SPECIALTY OPTICAL FIBERS FOR SENSING

FIBRAS ÓPTICAS ESPECIAIS PARA SENSORIAMENTO
UNIVERSIDADE ESTADUAL DE CAMPINAS
INSTITUTO DE FÍSICA “GLEB WATAGHIN”

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SPECIALTY OPTICAL FIBERS FOR SENSING

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FIBRAS ÓPTICAS ESPECIAIS PARA SENSORIAMENTO

Tese apresentada ao Programa de Pós-Graduação em Física do Instituto de Física “Gleb Wataghin” da Universidade Estadual de Campinas para obtenção do título de Doutor em Ciências.

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E ORIENTADA PELO PROF. DR. CRISTIANO MONTEIRO DE BARROS CORDEIRO

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CAMPINAS
2017
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Abstract

In this thesis, specialty optical fibers for sensing applications are investigated. Firstly, we propose the embedded-core capillary fiber structure for acting as a pressure sensor. Analytical and numerical studies were performed and showed that high pressure sensitivity could be achieved with this simplified fiber structure, which consists of a capillary structure with a germanium-doped core placed within the capillary wall. Experiments allowed measuring a sensitivity of $(1.04 \pm 0.01)$ nm/bar, which is high when compared to other microstructured optical fiber-based pressure sensors. Moreover, we studied the so-called surface-core optical fibers, which are fibers whose cores are placed at the external boundary of the fiber. In this approach, Bragg gratings were used to obtain refractive index – making use of the interaction between the guided mode evanescent field and the external medium – and directional curvature sensors – by exploring the off-center core position. The measured refractive index and the curvature sensitivities, respectively 40 nm/RIU around 1.41 and 202 pm/m$^{-1}$, compares well to other fiber Bragg grating-based sensors. Additionally, antiresonant polymer capillary fibers were investigated as temperature and pressure sensors. For the temperature sensing description, one used an analytical model to simulate the transmission spectra of such fibers and the dependence on temperature variations. Regarding the pressure sensing application, pressure-induced capillary wall thickness variations were analytically accounted and related to the system pressure sensitivity. In both these applications, experimental data were presented. Finally, additional opportunities using specialty optical fibers were presented, namely, a photonic-crystal fiber-based dual-environment pressure sensor, a three parameters sensor using Bragg gratings, tapered fibers and multimode interference, a liquid-level sensor based on Bragg gratings and multimode interference, and a temperature sensor based in an embedded-core fiber filled with indium. The results reported herein demonstrates the potential of optical fibers for providing sensing platforms to attain measurements of different sort of parameters with highly sensitivity and improved resolutions.

**Keywords**: specialty optical fibers, microstructured optical fibers, sensors, fiber optics
Nesta tese, fibras ópticas especiais são estudadas para fins de sensoriamento. Primeiramente, propomos a estrutura denominada fibra capilar com núcleo embutido (embedded-core capillary fibers) para realização de sensoriamento de pressão. Estudos numéricos e analíticos foram realizados e mostraram que altas sensibilidades a variações de pressão poderiam ser alcançadas com esta estrutura simplificada, que consiste de um capilar dotado de um núcleo, dopado com germânio, em sua parede. Experimentos permitiram medir uma sensibilidade de (1.04 ± 0.01) nm/bar, que é um valor alto quando comparado a outros sensores de pressão baseados em fibras microestruturadas. Ademais, estudamos fibras do tipo surface-core, que são fibras cujos núcleos são colocados na superfície externa da fibra. Nesta abordagem, redes de Bragg foram utilizadas para obter sensores de índice de refração – fazendo-se uso da interação entre o campo evanescente do modo guiado no núcleo e o ambiente externo à fibra – e de curvatura – ao se explorar o fato de que, nestas fibras, o núcleo se encontra fora do centro geométrico da mesma. As sensibilidades a variações de índice de refração e curvatura medidas, 40 nm/RIU em torno de 1.41 e 202 pm/m^{−1} compararam-se bem a outros sensores baseados em redes de Bragg. Outrossim, fibras capilares poliméricas foram investigadas como sensores de temperatura e pressão. Para a descrição do sensor de temperatura, usou-se um modelo analítico para simular o espectro de transmissão dos capilares e a sua dependência com as variações de temperatura. No que tange à aplicação de sensoriamento de pressão, variações nas espessuras dos capilares devido à ação da pressão foram calculadas e relacionadas à sensibilidade da medida de monitoramento. Nestas duas aplicações, realizações experimentais também são reportadas. Finalmente, oportunidades adicionais de sensoriamento ao se utilizar fibras ópticas especiais são apresentadas, a saber, um sensor de pressão para dois ambientes baseados em fibras de cristal fotónico, um sensor de três parâmetros baseado em redes de Bragg, fibras afinadas e interferência multimodal, um sensor de nível de líquido baseado em redes de Bragg e interferência multimodal e um sensor de temperatura baseado em fibras embedded-core preenchidas com índio. Os resultados aqui reportados demonstram o potencial das fibras ópticas em fornecerem plataformas de sensoriamento para alcançar medidas de diferentes tipos de parâmetros com alta sensibilidade e resolução adequada.

*Palavras-chave:* fibras ópticas especiais, fibras microestruturadas, sensores, fibras ópticas
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Table 5.1. Resolution limit comparison.
List of acronyms

**UV**: ultraviolet

**FBG**: fiber Bragg grating

**LPG**: long-period grating

**RIU**: refractive index unit

**MMI**: multimode interference

**SMS**: singlemode-multimode-singlemode

**SMF**: singlemode optical fiber

**MMF**: multimode optical fiber

**OSA**: optical spectrum analyzer

**NCF**: no-core optical fiber

**PCF**: photonic-crystal fiber

**ARROW**: antiresonant reflecting optical waveguide

**PC**: pressure chamber

**IF**: interferometric fringes

**FSR**: free spectral range

**FWHM**: full width at half maximum

**CCD**: charge coupled device

**FIB**: focused ion beam

**EDS**: energy-dispersive X-ray spectroscopy

**PMMA**: polymethylmethacrylate

**SH-PCF**: side-hole photonic-crystal fiber
Materials’ properties

Here we list some optical, mechanical and thermal properties of materials used along this thesis.

### Thermal and mechanical properties:

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### Elasto-optic properties:

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### Sellmeier Coefficients:

#### Silica

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#### Germania

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List of equipment

Here we list the main piece of equipment used in the experiments described throughout this thesis.

- Optical Spectrum Analyzer – OSA Ando AQ-6315
- Industrial BraggMETER, FiberSensing – FS2200
- Hot plate IKA®C-MAG HS7
- Laser for FBG inscription – 266 nm Quantel Q-Smart 450 laser
- SAFIBRA SLED Broadband optical light source
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Chapter 1

Introduction

Nowadays world’s dynamics probably wouldn’t be the same without fiber optics. The revolution in communications field provided by the boost in data transmission rates have allowed information exchange to happen at unthinkable velocities and quality levels. Additionally, optical fibers have been successfully inserted in several other fields such as imaging, biomedical laser delivery systems, military gyroscopic setups, automotive lightning and control. [1.1]

Moreover, optical fibers acquired great importance in sensing applications since they enabled high sensitivity measurements with very compact and robust setups. Besides, optical fiber sensors are immune to electromagnetic interference and can be used in harsh environments since they are usually made of silica. These advantages have motivated important progress in the optical fiber sensors’ market. Recent research reveals that, in the next five years, the market can grow at an annual rate of 10 percent and reach a size of 3.2 billion dollars in 2022. [1.2]

Several reports are available in the literature which demonstrate that optical fibers are a suitable platform for measurements of different sorts of parameters. Temperature, pressure, refractive index, strain and curvature are examples of parameters which can be successfully monitored by using fiber optics-based devices. In order to make fiber optics able to probe these broad diversity of parameters, numerous technologies can be employed to tailor the fiber’s properties. For instance, the use of Bragg and long-period gratings, rocking filters, metal-coated optical fibers, and special configurations such as in-fiber Fabry-Perot interferometer are possibilities of turning fibers sensitive to a parameter of interest.

Standard optical fibers used in both telecommunication and sensing fields are made of silica and formed basically of two regions: the core and the cladding. The core consists of a germanium-doped silica region located at the geometrical center of the fiber. Due to its doping, the core has a higher refractive index than the cladding (pure silica).
Figure 1.1a illustrates the standard optical fiber structure and Figure 1.1b its refractive index profile (step-index profile). \[1.3\]

![Figure 1.1. Standard optical fiber structure and refractive index profile. \(\Delta n\): refractive index contrast (Adapted from \[1.4\]).](image)

The refractive index contrast between core and cladding allows light to be guided by total internal reflection along its length. Light propagation characteristics along fiber optics can be studied by the employment of Maxwell equations. When boundary conditions are appropriately applied to the fiber structure, these equations allow obtaining well defined electric and magnetic field distributions on the cross-section of the fiber which propagate along the fiber length. These solutions are called optical modes and are associated to particular propagation constants and effective refractive indexes. \[1.3\]

Although standard optical fibers allow the realization of optical fiber sensing, the progressive need of manipulating the guided light properties have motivated the investigation in the field of the specialty optical fibers. Herein, one defines specialty fiber as any fiber structure which is different from the so-called standard optical fiber (as shown in Figure 1.1a and discussed in the last paragraphs). The difference can be related to, for example, the addition of a dopant in the fiber core (such as erbium-doped fibers) or to the material the fiber is made of (such as soft-glass and polymer-made optical fibers). Additionally, new fiber geometries can be obtained such as the solid-core and hollow-core photonic-crystal fibers, which provides a myriad of possibilities regarding the exploration of applications since fundamental science to applied fields. Furthermore, a number of other fiber structures are available as, for instance, fiber tapers (which are fibers processed in such a way that a well-defined section of it has its dimensions reduced), fibers with internal electrodes and multicore fibers. Figure 1.2 presents some examples of specialty optical fibers structures.
Figure 1.2. Examples of specialty optical fibers. (a) Solid-core [1.5] and (b) hollow-core photonic crystal fiber [1.6]; (c) negative-curvature hollow fiber [1.7]; (d) photonic-crystal fiber with electrodes next to the fiber microstructure [1.8]; (e) multicore optical fiber [1.9].

The exploration of the fiber optical response as a parameter of interest varies is the basis of optical sensing research. Some figures of merit are then appropriate to measure the performance of a certain sensor – namely sensitivity, resolution and dynamic range. The sensitivity is defined as the rate at which a specific optical parameter (e.g. wavelength, power, phase) is varied when an external parameter changes. In general, in this thesis, we are interested in spectral measurements. Therefore, in most cases, there will be a spectral feature (a dip, a peak, an interferometric pattern) whose spectral position is followed while an external parameter of interest (external medium refractive index, pressure, curvature or strain conditions) is varied. Thus, the sensitivity value is accounted by obtaining the slope of the line which provides the best fit to the experimental data of the wavelength shift as function of the external parameter (X) variation. Figure 1.3a is a schematic representation of the procedure for the sensitivity determination.

The resolution, in turn, is related to the detection limit of the system. In spectral measurements, it must be accounted by identifying the least detectable wavelength shift and, then, by associating this wavelength shift to the least amount of the external parameter which would be resolvable by the sensing system. It is directly associated to the spectral optical feature full width at half maximum (FWHM), what means that the
sharper the optical feature (lower FWHM value), the more improved will be the sensor resolution – see Figure 1.3b for a representation of this situation.

Finally, the dynamic range accounts for the largest interval in which the sensor can provide a correct and unequivocal reading of the monitored parameter. Specially, this figure is very important for measurements which are based on following the spectral position of interferometric fringes since, in this approach, the dynamic range is limited by the fringes’ spectral separation, i.e. its free spectral range (FSR) – Figure 1.3c. This limitation exists because, if the wavelength shift of a certain fringe is enough to reach a neighboring one, the interpretation of the sensor response can be mistaken. Therefore, one assume herein that the dynamic range is the variation of the external parameter which would provide a wavelength shift equal to the FSR value.

![Figure 1.3. Schematic representation of the sensor (a) sensitivity, (b) resolution and (c) dynamic range. ΔX: parameter under test variation; Δλ: wavelength variation; FWHM: full width at half maximum; FSR: free spectral range.](image)

In this thesis, we approach specialty fiber-based setups for sensing. Novel fiber designs are proposed, fabricated and tested. In addition, it is provided theoretical descriptions of the physical phenomena by presenting analytical and numerical simulations.

In Chapter 2, a new fiber structure, termed capillary embedded-core fiber, is proposed for providing pressure-sensing measurements with enhanced sensitivity.
Embedded-core fiber consists of a capillary fiber with a germanium-doped core placed within its wall. In order to understand the physical principle for pressure sensing, an analytical model for accounting the stresses in pressurized tubes is used to calculate the birefringence which is induced in the structure due to external pressure application. In sequence, fiber fabrication is reported and the experimental measurements are described.

In Chapter 3, we present the study of so-called surface-core fibers. In this sort of fibers, the core is placed on fiber’s external surface, what allows probing external refractive index and directional curvature variations. The reported research ranges from fiber fabrication and imprinting of Bragg gratings in the fibers to the performance of simulations and sensing measurements.

In Chapter 4, polymer antiresonant capillary fibers are studied for temperature and pressure sensing. Here, we coupled an analytical model for accounting capillary walls thickness changes for temperature and pressure variations to another one for recovering the spectral behavior of an antiresonant waveguide. In addition, characterization and sensing measurements are provided.

Finally, in Chapter 5, we present additional opportunities for sensing measurements using specialty optical fibers. Thus, a photonic-crystal fiber-based pressure sensor for dual environment monitoring, a three-parameter sensor based on Bragg gratings, tapered fibers and multimode interference, and an intensity-based liquid level sensor are described. Sensor’s operation descriptions and experimental realization of the same are presented in detail. Moreover, the use of metal-filled embedded-core fiber in temperature sensing measurements is presented.

In the following section, we present a set of technologies which can turn optical fibers able to act as sensors. Bragg and long-period gratings, rocking filters, fiber tapers and multimode interference are topics to be covered herein. Moreover, special fiber designs will be discussed.

1.1 Fiber Gratings

Optical fiber gratings consist of periodic longitudinal refractive index modulations in the fiber structure which allow coupling between optical modes. Experimentally, such modulations can be created either by shining an UV [1.10] or CO₂ [1.11] laser on an optical fiber or by applying electric arcs [1.12] on the fiber structure. Moreover, gratings
can be mechanically induced by, for instance, pushing a corrugated board against an optical fiber [1.13]. Depending on the grating period, which can range from hundreds of nanometers to millimeters, coupling can occur between different sort of modes (forward and backwards propagating core modes, cladding modes or core modes with different polarizations) when the difference between their propagation constants are equal to $2\pi/\Lambda$, where $\Lambda$ is the grating period – i.e. $\beta_2 - \beta_1 = \frac{2\pi}{\Lambda}$, where $\beta_1$ and $\beta_2$ are the propagation constants of the modes experiencing the coupling. This condition is referenced as the phase matching condition and allows recognizing that the coupling will be observed at specific wavelengths. [1.14]

If the grating period is in the order of hundreds of nanometers, coupling between forward propagating and backwards propagating core modes is observed – in this case, the grating is called a fiber Bragg grating or, simply, a FBG. For Bragg gratings, the phase matching condition can be written as in Eq. (1.1), where $\lambda_B$ is the wavelength at which mode coupling was observed (Bragg wavelength), $n_{\text{eff}}$ is the effective refractive index of the core mode and $\Lambda$ is the grating period. [1.14]

$$\lambda_B = 2 \Lambda n_{\text{eff}}$$

(1.1)

As in a Bragg grating the forward propagating core mode is coupled to a backwards propagating core mode, its optical response can be measured in reflection. Thus, when light from a broadband light source is launched in a fiber in which a Bragg grating was inscribed, a peak at the Bragg wavelength is seen in the reflected spectrum. If the response of the grating is measured in transmission, a dip at the Bragg wavelength is expected. Figure 1.4 illustrates a fiber Bragg grating operation.

**Figure 1.4.** Bragg grating operation illustration. (Adapted from [1.15])
The existence of a peak in the reflection spectrum of an FBG makes it suitable for the performance of sensing measurements. Besides, as can be seen in Eq. (1.1), the Bragg wavelength varies if the period of the grating is altered or if the effective refractive index suffers a variation. It makes straightforward thinking FBGs as temperature and strain sensors since both these parameters can cause \( \Lambda \) and \( n_{\text{eff}} \) values to vary (via thermal expansion, thermo-optic and strain-optic effects). Thus, for example, in temperature or strain sensing experiments, the Bragg peak spectral position can be followed as the temperature or the strain is changed. [1.16]

If the spatial periodicity of the grating is in the order of hundreds of micrometers, coupling between the fundamental core mode and cladding modes is possible. In this case, the grating is referenced as a long-period fiber grating (LPG) and the phase matching condition is written as in Eq. (1.2), where \( \lambda_i \) is the wavelength at which coupling is observed, \( n_{\text{core}} \) is the effective refractive index of the fundamental core mode, \( n_{\text{clad}}^i \) is the effective refractive index of a specific cladding mode and \( \Lambda \) is the grating period. [1.14]

\[
\lambda_i = (n_{\text{core}} - n_{\text{clad}}^i)\Lambda
\]  

(1.2)

Since the cladding modes present higher attenuation than the core mode, if broadband light is launched in a fiber with a long-period grating, the resulting transmission spectrum will be characterized by dips at the wavelengths at which coupling between core and cladding modes were attained (Figure 1.5). Moreover, as cladding modes effective refractive indexes are dependent on the refractive index of the medium that surrounds the fiber, long-period gratings are usually thought for setting up refractive index sensors. In this sort of application, the spectral position of the resonances can be followed as the refractive index of the external medium is changed. [1.17]

Figure 1.5. Long-period grating operation illustration. (Adapted from [1.15])
A third kind of fiber gratings also useful for the performance of sensing measurements is referenced as rocking filters. The rocking filter is a grating which is inscribed in a birefringent optical fiber with a period in the order of millimeters and provides coupling between core modes with different polarizations. The phase matching condition is expressed by Eq. (1.3), where $\lambda_R$ is the resonant wavelength, $B$ is the modal phase birefringence – defined by Eq. (1.4) – and $\Lambda$ is the grating period. In Eq. (1.4), $n_{\text{eff},x}$ and $n_{\text{eff},y}$ stands for the effective refractive index of the core mode with x and y polarizations respectively. [1.18]

$$\lambda_R = B \Lambda$$  \hspace{1cm} (1.3)

$$B = n_{\text{eff},x} - n_{\text{eff},y}$$  \hspace{1cm} (1.4)

It is noteworthy to observe that Eq. (1.2) and Eq. (1.3) are, in fact, different forms of writing the same phase matching condition: $\lambda_{\text{RES}} = \Delta N \Lambda$, where $\lambda_{\text{RES}}$ is the wavelength at which the coupling will occur, $\Lambda$ is the grating period and $\Delta N$ is the difference between the effective refractive indexes of the modes experiencing the coupling. Therefore, the difference between the magnitude order of the periods of the Bragg gratings, long-period gratings and rocking filters (respectively in the order of thousands of nanometers, hundreds of microns and millimeters) is explained by the distinctive values of $\Delta N$ in these gratings. For example, if one assumes the coupling to occur at the wavelength of 1550 nm, for the rocking filters one can find $\Delta N \sim 10^{-4}$, which is a reasonable value for the difference between the effective refractive indexes of the x- and y-polarized modes in birefringent optical fibers and, for the long-period gratings, $\Delta N \sim 10^{-3}$, which is refractive index difference usually observed between the fundamental core mode and the cladding modes.

The optical response of a rocking filter is measured by the employment of two polarizers, orthogonally or parallelly oriented with respect to each other (Figure 1.6). The first polarizer excites the core mode in the birefringent fiber on a particular polarization state (x or y). As the light travels along the rocking filter, coupling from the mode on the initial polarization state to a mode on the orthogonal polarization state is verified. If the second polarizer is parallelly oriented with respect to the first one, a spectral dip is
observed at $\lambda_R$ (Figure 1.6a). If, on the other hand, the second polarizer is orthogonally oriented with respect to the first one, a spectral peak is observed at $\lambda_R$ (Figure 1.6b).

![Rocking Filter Operation Illustration](image)

**Figure 1.6.** Rocking filter operation illustration with (a) parallel polarizers and (b) orthogonal polarizers. P$_1$ and P$_2$: polarizers. (Adapted from [1.15])

Rocking filters also allows the realization of sensing measurements. It is usually done by exploring fiber birefringence changes when an external parameter acts on the fiber. Hydrostatic pressure is an example of a parameter which can be monitored by rocking filter-based sensors. The application of pressure on fiber’s structure induces stresses within the same and, depending on fiber characteristics, its distribution can be asymmetric implying in birefringence changes (the relation between hydrostatic pressure variations and birefringence will be discussed in detail in Chapter 2). [1.18]

We can observe that fiber gratings can provide a wide range of possibilities when acting as sensing platforms. In the following chapters, we explore refractive index, curvature, temperature and strain Bragg gratings-based sensors.

### 1.2 Fiber tapers

Another interesting technology widely used to build up optical sensors are fiber tapers, which consist of optical fibers which have their dimensions controllably reduced. Large evanescent fields, strong confinement, configurability and robustness are some of fiber tapers properties which makes them attractive for the development of optical technologies from nonlinear optics to sensing applications. [1.19]
Tapers can be obtained by using the flame brushing technique \[1.20\]. In this method, a well-defined region of the fiber is heated by an oscillating flame as it is controllably stretched (Figure 1.7a). By mass conservation, the increase of fiber length cause its diameter to reduce. Therefore, fiber tapers comprehend two transition regions and a waist with uniform diameter. \[1.19\]

![Figure 1.7. (a) Flame brushing technique and a schematic of the final profile of a fiber taper with two transition regions and a uniform taper waist (adapted from \[1.20\]). (b) Representation of the Z-direction Poynting vector of a fiber taper guiding light. \[1.21\]](image)

If an optical mode is guided in the core of the optical fiber, it will be converted to cladding modes in the microfiber as it propagates along the transition region \[1.19\]. Due to the reduced diameter of the tapered region, a large portion of the evanescent field permeates the external medium (Figure 1.7b). It causes the characteristics of the mode guided in the tapered region to be strongly dependent on the surrounding medium properties. This property opened the possibility of the realization of a great variety of refractive index sensors based on optical fiber tapers. An example of a highly sensitive sensor – with sensitivity in the order of thousands of nanometers per RIU (refractive index unit) – was reported by our group in \[1.22\], where birefringent tapers were prepared from side-polished standard optical fibers and their optical response in a polarimetric measurement was accounted as a function of external refractive index variations.

Moreover, mechanical properties of the tapered fibers can be explored for sensing purposes. For instance, due to their reduced diameter – and, therefore, reduced cross-sectional area –, when a force is axially applied to an optical fiber, the strain level on the tapered region is higher than in the non-tapered region \[1.23\]. It allows obtaining, for
instance, strain sensors with enhanced sensitivity. A more detailed description of this effect is discussed in Chapter 5.

1.3 Multimode interference (MMI)

Multimode interference (MMI) is a phenomenon which can also be employed for obtaining fiber optics-based sensors. Usually, it is convenient to explore it in a configuration known as SMS structure (singlemode-multimode-singlemode). It comprehends a singlemode fiber (SMF), a multimode fiber (MMF) and another single mode fiber section set in sequence and fused to each other (Figure 1.8a).

![Figure 1.8](image_url)

**Figure 1.8.** (a) SMS structure and interference pattern inside the multimode fiber (colors represent the normalized electric field amplitude). SMF: singlemode fiber; MMF: multimode fiber. (adapted from [1.26]). (b) Representation of the typical optical response of an SMS structure (adapted from [1.27]).

In this sort of structure, the mode guided in the singlemode fiber is launched in the multimode region so that numerous modes are excited. Due to the different propagation constants of the modes inside the multimode fiber, they interfere with each other as they propagate (Figure 1.8a). As a result of interference, self-images of the input field (exact replica both in phase and amplitude) will be obtained along the multimode optical fiber. The lengths \( L \) (as respect to the point where the light is launched in the multimode fiber) at which the self-images will occur are described by Eq. (1.5), where \( n_{MMF} \) and \( D_{MMF} \) are respectively the effective refractive index and the diameter of the fundamental mode in the multimode fiber and \( \lambda \) is the wavelength. [1.24]
\[ L = \frac{4 n_{MMF} D_{MMF}^2}{\lambda} \] (1.5)

For measuring the optical response of an SMS structure, light from a broadband light source is coupled in the singlemode fiber and its transmission spectrum is measured in an optical spectrum analyzer (OSA). The typical spectrum consists of a peak centered at a wavelength \( \lambda_{SMS} \) (Figure 1.8b), which can be predicted by rewriting Eq. (1.5) as Eq. (1.6) for a multimode fiber with length \( L_{MMF} \). [1.25]

\[ \lambda_{SMS} = \frac{4 n_{MMF} D_{MMF}^2}{L_{MMF}} \] (1.6)

If the multimode fiber in the SMS structure is a silica rod (no-core fiber – NCF), the effective refractive index of the fundamental mode in the multimode fiber, \( n_{MMF} \), will be dependent on the refractive index of the external medium which surrounds the fiber (since, in this case, the interface silica-external medium provides the refractive index contrast for mode confinement). Thus, if the surrounding medium refractive index is altered, a spectral shift in the SMS optical response is expected. By calibrating this spectral shift as a function of the refractive index variations, it is possible, for instance, to obtain a SMS-based refractive index sensor.

This approach was employed in [1.28], where the authors characterized SMS structures with no-core fibers and tapered no-core fibers for refractive index sensing purposes. Furthermore, other possibilities regarding the application of SMS structures for temperature, refractive index, strain and liquid-level monitoring will be discussed in this thesis (Chapter 5).

### 1.4 Specialty fibers

Standard singlemode and multimode optical fibers can, as shown in the previous sections, be employed in sensing measurement if they are processed (imprinting of gratings, preparation of fiber tapers) or if they are set in specific configurations (as in SMS structure). However, there is not much liberty in the choice of fiber’s properties that can be optimized for sensing purposes. Essentially, the standard geometry only allows improvement in core size and its refractive index profile. Thus, specialty optical fibers
are a very interesting alternative for exploring optical fibers-based sensors. A wide range of possibilities are opened since new geometries can be thought, new wave guidance mechanisms can be exploited and, besides, different material can be integrated to optical fibers. In the following sections, specialty fibers examples are provided.

1.4.1 Birefringent fibers

As a first example of specialty optical fibers, we can cite the birefringent ones. As expressed in Eq. (1.4), the birefringence for a specific optical mode in a waveguide is defined as the difference between the effective refractive indexes of the modes with orthogonal polarizations.

Breaking core’s circular symmetry or providing an asymmetric stress distribution within the fiber are two possible routes for incorporating birefringence in an optical fiber. The first method for attaining a birefringent fiber can be exemplified by the elliptical-core optical fibers (Figure 1.9a). In this sort of fibers, the birefringence arises from the fact that the effective core diameter for optical modes with orthogonal polarization states are different [1.29]. As this birefringence is due to the geometric shape of the core, it is called form birefringence.

Tapered optical fibers can also present form birefringence, as it was reported by our group in [1.22]. To do this, a standard optical fiber can be side-polished (in order to break its circular symmetry – Figure 1.9b) and, in sequence, tapered down. As the asymmetry created by the polishing is maintained during the tapering process, the modes which are guided through the taper at different polarization states become characterized by different effective refractive indexes.

Additionally, for obtaining birefringent optical fibers via the creation of an asymmetric stress distribution within the fiber, boron-doped regions can be added to the fiber. So-called PANDA and bow-tie fibers (Figure 1.10) are examples of structures in which the birefringence is attained by following this route. In this sort of fibers, as the thermal expansion coefficient of the doped regions is different than the undoped region one, an asymmetric stress distribution is generated within the fiber structure. It implies the core material refractive index to be altered differently on horizontal and vertical directions. Thus, a birefringence level is induced. [1.29]
Figure 1.9. (a) Elliptical-core fiber structure representation. (b) Cross-section image of a side-polished optical fiber. Red circle helps identifying the asymmetry generated by the polishing process. [1.22]

Figure 1.10. (a) PANDA and (b) Bow-tie fibers structure representation.

Birefringent fibers are widely employed in sensing setups. Usually, the birefringence dependency on a specific parameter (temperature or pressure, for example) is studied. For instance, in [1.30] PANDA fibers temperature sensitivity was explored for demonstrating the operation of a dual-environment optical sensor and, in [1.23], birefringent microfibers were used for obtaining a very high sensitivity refractive index sensor.

1.4.2 Photonic-crystal fibers (PCFs)

Photonic-crystal fibers (PCFs) consist of a special sort of optical fibers endowed with air holes on its transversal cross-section which runs parallelly along its entire length. The air holes define a microstructure around the fiber core which determine the properties of the guided light. The freedom in choosing the microstructure geometry (and, therefore,
the fiber properties) allows the application of the photonic-crystal fibers in several fields which can range from nonlinear optics to sensing, study of fiber devices and material characterization. [1.31]

Solid-core and hollow-core photonic-crystal fibers are reported in literature – Figure 1.11a presents an example of solid-core photonic-crystal fiber and Figure 1.11b shows a hollow-core one. In solid-core fibers, light is guided by modified total internal reflection. In this mechanism, the cladding (holes microstructure) can be thought as having a lowered average refractive index when compared to the solid-core one. This refractive index contrast provides the condition for total internal reflection to occur in an analogous fashion as it occurs in standard optical fibers. As modified total internal reflection context is created by the microstructured cladding, the optical characteristics of the modes supported by the fiber are intrinsically dependent on the microstructure geometric characteristics. [1.33]

![Figure 1.11. (a) A solid-core and (b) a hollow-core photonic-crystal fibers. [1.32]](image)

In hollow-core fibers, however, total internal reflection is not possible since the fiber core has a lower refractive index than the cladding. Thus, the photonic bandgap or the inhibited coupling effect can be explored. In the photonic bandgap fibers, the cladding structure is such that a photonic bandgap is obtained and, in a certain wavelength range, there is no cladding mode to which the core mode can be coupled; in the inhibited coupling fibers, otherwise, the coupling from the core mode to the cladding modes is strongly minimized by lowering the spatial interaction between the core and the cladding modes or by having a strong mismatch between modes transverse spatial phases. [1.34]

Silica photonic-crystal fibers can be prepared by using a fiber drawing tower facility and by employing the stack-and-draw procedure [1.35]. In stack-and-draw
procedure, silica capillaries and rods are manually assembled in a preform stack whose structure corresponds to the one planned for the final fiber. The stack is then put into a jacketing tube and the resulting assembly is drawn in the tower facility to a microstructured preform (cane). Finally, the cane is drawn to fiber dimensions – in this final step, another tube can be used for jacketing the cane so the desired proportion between microstructured cladding, core and outer fiber sizes can be achieved. More details on the fabrication of photonic-crystal fiber procedure are available in Appendix A. [1.36]

Polymers such polymethyl methacrylate (PMMA) and polycarbonate, can also be used for obtaining photonic-crystal fibers. Although stack-and-draw technique can also be used for obtaining polymer optical fibers (POFs), the holes’ structure in polymer fiber preforms are usually obtained by drilling solid polymeric cylinders in driller machines (Figure 1.12a shows a typical PMMA preform after drilling process). This technique allows obtaining more complex holes’ arrangements, such as one exemplified in Figure 1.12b, where the authors obtained a graded-index cladding structure. [1.33]

The fiber drawing process follow the same steps as in silica fibers but with the important difference that, during drawing process, the furnace temperature is around 200 °C. It allows drawing fibers with dopants such as rhodamine (Figure 1.12c), what would be impossible for silica fibers (whose fabrication process occur at temperatures around 2000 °C). [1.33]

Figure 1.12. (a) PMMA fiber preform. (b) Graded-index cladding polymer fiber. (c) Rhodamine-doped polymer optical fiber. [1.33]
As demonstrated by the wide variety of photonic-crystal fiber-based sensors reported in literature, the application of photonic-crystal fibers in sensing measurements is very broad. For example, filling the photonic-crystal fiber holes with liquids [1.37] or gases [1.38] have shown to be a successful approach for obtaining sensors based on absorption, fluorescence and refractive index changes. Moreover, photo-elastic effect can be explored in birefringent photonic-crystal fibers pressure sensing [1.39]. In Chapter 5, a photonic-crystal fiber-based sensor for dual environment probing will be detailed.

1.4.3 Antiresonant reflecting optical waveguides (ARROW)

Besides photonic-crystal fibers that can guide light by modified total internal reflection or photonic bandgap guidance, an interesting class of specialty fibers is able to transmit light by the so-called antiresonant reflection mechanism. These fibers are classified as antiresonant reflecting optical waveguides (ARROW). [1.40]

Antiresonant reflection mechanism can occur when light propagates within a fiber structure in which the core refractive index is lower than the cladding’s one. Although it may resemble photonic bandgap guidance, in antiresonant reflecting waveguides the cladding periodicity does not determine the bands for light propagation in the waveguide and the guidance mechanism rely on the reflection characteristics of the waves that impinges on core-cladding boundary. [1.40]

The simplest example of an antiresonant optical fiber is a capillary fiber, as represented in Figure 1.13a (where $n_1$ is the core’s refractive index, $d$ is the capillary wall thickness and $n_2$ its refractive index). Guidance mechanism can be understood if the capillary wall is thought as a Fabry-Perot etalon. For wavelengths propagating in the core which correspond to Fabry-Perot etalon resonances (constructive interference in the capillary wall), high transmission through the cladding is observed and this is a wavelength of minimum transmission through the core. In contrast, for wavelengths experiencing low leakage through the wall (Fabry-Perot antiresonances; destructive interference in the capillary wall), a high transmission through the core will be observed (Figure 1.13b). [1.40]
The spectral positions of the minima, $\lambda_{min}$, can be found by using Eq. (1.7), where $n_1$ is the core’s refractive index, $n_2$ is the capillary wall’s one, $d$ is the capillary wall thickness and $m$ is the minimum order [1.40]. Thus, it is seen that if an external parameter is able to alter $n_1$, $n_2$ or $d$ values, a shift in the minimum spectral position will be verified and the configuration can act as a sensor. In [1.41], for instance, a capillary fiber antiresonance spectrum was monitored while the capillary wall was being chemically etched. Besides, in [1.42], the influence of the application of different internal pressure levels on the antiresonance spectrum of a silica capillary fiber was studied – this topic will be detailed in Chapter 4.

\[
\lambda_{min} = \frac{2 n_1 d}{m} \sqrt{\left(\frac{n_2}{n_1}\right)^2 - 1}
\]  

Antiresonant reflection can also be explored in more sophisticated fiber designs. A successful structure has been referenced as negative-curvature antiresonant fibers, which was firstly proposed in [1.43]. In this sort of fibers, the core is delimited by convex silica layers which define the so-called negative curvature of the core. Figure 1.14a and Figure 1.14b shows examples of negative-curvature antiresonant optical fibers. The fiber exposed in Figure 1.14a had its microstructured optimized so bending losses could be lowered and the fiber presented in Figure 1.14b, in turn, was designed for attaining low attenuation in the wavelength range between 3 µm and 4 µm.
Figure 1.14. Cross section of two successful negative curvature hollow-core optical fibers designs reported in literature. (a) Fiber design for lowering bending losses [1.44] and (b) for attaining lowered attenuation for wavelengths between 3 µm and 4 µm. [1.45]

As in negative-curvature fibers the light is guided through the hollow core, several interesting properties were verified. Low dispersion, low nonlinear response, high damage threshold and low loss in wavelength ranges in which silica is opaque are some of the appealing properties of this kind of fiber. Moreover, it is seen that negative-curvature fiber’s microstructure is much simpler than photonic bandgap fiber’s ones, what makes it easier to fabricate. All these appealing properties allowed antiresonant optical fibers to become a very fruitful field of research in the latest years. In addition, several important research groups are devoting their attention to this topic, what allows predicting that it will remain very productive in the following years. [1.46, 1.47]
Chapter 2

Simplifying the design of microstructured fiber pressure sensors: embedded-core fiber

As discussed in the last chapter, the application of optical fibers in sensing has been broadly investigated in recent years. The development of optical fiber-based pressure sensors, in particular, is very desirable because they potentially offer elegant solutions for a wide and varied range of applications. For example, they have been employed to monitor pressure variations in downhole [2.1], medical [2.2] and aerodynamics applications [2.3].

Several fiber optics-based technologies such as long-period [2.4] and Bragg gratings [2.5] are reported to be able to detect pressure variations. In these examples, the achieved sensitivities were as high as 5.1 pm/bar [2.4] and 0.4 nm/bar [2.5]. Another important technology for building optical fiber-based pressure sensors which can provide ultrahigh sensitivities (in the order of hundreds or even thousands of nanometers per bar) are the Fabry-Perot interferometers. They are often prepared by processing the optical fiber tip by adding a diaphragm on it (which can be made of polymer-metal composite materials [2.6] or graphene [2.7], for example) in such a manner that a cavity is created between the fiber tip and the diaphragm. External pressure variations cause the diaphragm to displace and, therefore, vary the cavity length. The changes in the interferometer characteristic spectral pattern (usually measured in reflection) due to the pressure variations are used to define the system sensitivity. However, the structural robustness of these Fabry-Perot-based sensors are poor, limiting their application when high pressure sensing is targeted. Very recent research has demonstrated the possibility of making nanodiaphragms made of silica [2.8]. The authors of these research claim it means an important step towards the improvement of the robustness of these sensors.

Due to their design versatility, microstructured optical fibers are a suitable platform for obtaining pressure sensors [2.9-2.11]. In general, to achieve optimized pressure sensitivity, their structures are designed in such a manner that the application of hydrostatic pressure induces asymmetric stress distributions in the fiber. As these fibers
are, in general, birefringent, variations in its birefringence are observed due to the photoelastic effect [2.12] and the optical response of these fibers become sensitive to pressure variations.

In this context, photonic-crystal fibers [2.13] and fibers with sophisticated microstructure geometries (as the fiber reported by A. Anuszkiewicz et al., whose structure is endowed with a triangular-shaped pattern of air holes [2.10]) have been investigated to act as pressure sensors. Additionally, side-hole optical fibers have been shown to be an interesting kind of fiber for pressure sensing [2.14, 2.15]. Figure 2.1 show examples of microstructured fibers whose optical responses were studied and tested as a function of hydrostatic pressure variations. Although these fibers allow the realization of optimized pressure sensing measurements and are an important platform to do so, the fabrication process of such fibers is complicated, time-consuming and demands much technical effort.

![Figure 2.1. Examples of microstructured optical fibers explored in pressure sensing applications: (a) a photonic-crystal fiber [2.13]; (b) and (c) microstructured fiber endowed with a triangular lattice of air holes. [2.10]; Side-hole fibers with (d) a germanium doped-core [2.14] and (e) a photonic-crystal structure [2.15].](image-url)
To characterize the sensitivity of the fibers as the one shown in Figure 2.1 to external pressure variations, usually the so-called polarimetric wavelength scanning method [2.16] is employed. In this method, a broadband light source (for example, a supercontinuum source – SC) launches light into the optical fiber. A first polarizer ($P_1$) is used to excite the two orthogonal modes of the birefringent fiber. A second polarizer ($P_2$) is employed to allow the recombination and interference between the orthogonal optical modes that traveled along the fiber, which is seen as an interferometric pattern measured by an optical spectrum analyzer (OSA). To experimentally maximize the interferometric fringes visibility, the polarizers angles are tuned while observing the resulting spectrum; theoretically, the maximum visibility of the interferometric fringes are attained when the first polarizer is oriented at 45 degrees with respect to the principal axes of the birefringent fiber and the second polarizer is oriented at 0 or 90 degrees with respect to the first polarizer. Additionally, a pressure chamber (PC) is used to subject the fiber to different external pressure levels. A representation of the described experimental setup is available in Figure 2.2.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure2.png}
\caption{Experimental setup for pressure-sensing measurements. SC: supercontinuum source; $P_1$ and $P_2$: polarizers; $O_1$ and $O_2$: objective lenses; OSA: optical spectrum analyzer; PC: pressure chamber; $L$: fiber length; $L_p$: pressurized fiber length.}
\end{figure}

As said in the last paragraph, the recombination and interference of light in the second polarizer produces spectral fringes in the transmission spectrum. Since the birefringence of the fibers as the ones shown in Figure 2.2 is altered when pressure is applied, the spectral positions of these fringes are dependent on the external pressure level. Therefore, it is useful to define a sensitivity coefficient, $C_S$, to account for the spectral displacement of the interferometric fringes (IF) due to pressure changes, $C_S \equiv \frac{d\lambda_{IF}}{dP}$. The $C_S$ value can also be written as a function of the wavelength $\lambda$, fiber group birefringence, $G$, and the phased birefringence derivative with respect to pressure,
\[
\frac{\partial B_{\text{modal}}}{\partial P}, \text{ as can be seen in Eq. (2.1) [1.17]. Thus, the } C_S \text{ value can be obtained either by following the spectral positions of the interferometric fringes as the external pressure is varied or by estimating the fundamental properties of the fiber such as } G \text{ and } \frac{\partial B_{\text{modal}}}{\partial P}.
\]

\[
C_S \equiv \frac{d\lambda_{IF}}{dP} = \frac{\lambda}{G} \frac{\partial B_{\text{modal}}}{\partial P}
\tag{2.1}
\]

\(C_S\) value (or the pressure sensitivity, as commonly referenced) is, therefore, an important figure of merit for comparing the performance of the sensors. For example, H. Y. Fu et al. showed 0.342 nm/bar for a commercial all-silica photonic-crystal fiber [2.13] and T. Martynkien et al. reported 0.30 nm/bar and 0.52 nm/bar for specially designed microstructured fibers [2.18, 2.19].

Moreover, by using Eq. (2.1), it is possible to estimate the fiber birefringence derivative with respect to pressure, \(\frac{\partial B}{\partial P}\), which also consist of an important parameter for comparing the sensor’s responses. For instance, G. Statkiewicz-Barabach et al. reported, for a photonic-crystal fiber, the value \(\frac{\partial B}{\partial P} = 2.52 \times 10^{-7} \text{ bar}^{\text{-1}}\) [2.9] and A. Anuskiewicz et al. attained, for a specially designed fiber endowed with a triangular lattice of holes, the value \(\frac{\partial B}{\partial P} = 8.89 \times 10^{-7} \text{ bar}^{\text{-1}}\) [2.10].

Also, it is demonstrated in the literature that the use of rocking filters inscribed in fibers such as the ones shown in Figure 2.1 allows measuring pressure variations with very high sensitivity. For example, A. Anuskiewicz et al. measured sensitivities as high as 17.7 and 13.2 nm/bar for the fibers shown in Figure 2.1b and Figure 2.1d, respectively [2.10, 2.14].

However, as already mentioned, the special fibers able to monitor pressure variations reported up to date are very sophisticated, what makes their fabrication complicated from a technical point of view. In this chapter, the use of a simplified specialty optical fiber structure – the embedded-core capillary fiber – in hydrostatic pressure measurement is proposed. The embedded-core fiber consists of a silica capillary structure endowed with a germanium-doped region (the fiber core) placed within the capillary wall. As it is discussed in the following, the fabrication of this fiber is straightforward and is accomplished in a single-step fiber drawing process.
2.1 Pressure-induced material birefringence in capillary fibers

When hydrostatic pressure is applied to capillary fibers (Figure 2.3a), their walls displace. It entails stress induction within the capillary structure [2.20]. Because the material birefringence is dependent on the induced stress within a fiber structure, its value is expected to be altered if the fiber is under pressure. Eq. (2.2) shows the material birefringence, \( B_{\text{mat}} \), dependence on the pressure-induced stresses in the horizontal \((\sigma_x)\) and vertical \((\sigma_y)\) directions [2.21]. In Eq. (2.2), \( C_1 \) and \( C_2 \) identify the elasto-optic coefficients \((C_1 = -0.69 \times 10^{-12} \text{ Pa}^{-1} \text{ and } C_2 = -4.19 \times 10^{-12} \text{ Pa}^{-1} \text{ for silica [2.22]})\); \( n_{x0} \) and \( n_{y0} \) are the material refractive indexes under no stress. The elasto-optic coefficients accounts for the refractive index variations due to the existence of stresses within the material: \( n_x = n_{x0} + C_1 \sigma_x + C_2 \sigma_y \) and \( n_y = n_{y0} + C_1 \sigma_y + C_2 \sigma_x \).

\[
B_{\text{mat}} = n_{x0} - n_{y0} + (C_2 - C_1)(\sigma_x - \sigma_y) \quad (2.2)
\]

The pressure-induced material birefringence profile inside the wall of capillary fibers can be analyzed by using the Lamé solution for the stresses within pressurized thick-walled tubes [2.20]. As already mentioned, the stresses inside the capillary fiber walls arise from the displacements they experience when pressure is applied to them. For a radial position \( r \) within the capillary wall, one can obtain the displacement, \( u(r) \), by using Eq. (2.3) – where \( r_{\text{in}} \) and \( r_{\text{out}} \) are, respectively, the inner and outer radii of the tube, \( \nu \) and \( E \) are the capillary material Poisson ratio and Young’s modulus (for silica, \( \nu = 0.165 \) and \( E = 72.5 \text{ GPa [2.4, 2.23]} \)), \( p_{\text{in}} \) and \( p_{\text{out}} \) are the internal pressure applied to the fiber, respectively. Due to the symmetry of the problem, the displacement is not dependent on the azimuthal coordinate and is a function of the radial position only [2.20]. The demonstration of the Lamé equations is provided in Appendix B.

\[
u(r) = \frac{1}{E\left[1 - \left(\frac{r_{\text{in}}}{r_{\text{out}}}\right)^2\right]^2}\left\{1 - \nu\left[p_{\text{in}} \left(\frac{r_{\text{in}}}{r_{\text{out}}}\right)^2 - p_{\text{out}}\right]r + (1 + \nu)(p_{\text{in}} - p_{\text{out}})\frac{r_{\text{in}}^2}{r}\right\} \quad (2.3)
\]

Figure 2.3b presents the displacement profile in the wall of a silica capillary (with \( r_{\text{in}}/r_{\text{out}} = 0.5 \)) when it is under an external pressure level of 50 bar (5 MPa) and the internal pressure is assumed to be 1 bar (0.1 MPa). In the simulation shown, \( r_{\text{in}} = 40 \mu\text{m} \).
By observing Figure 2.3b plot, it is seen that, in the studied situation, the displacement at the inner radius is, in modulus, lower than the one at the outer radius position. It implies a decrease in capillary wall thickness as it is schematized in Figure 2.3c (in which the inner and the outer wall displacements are represented).

The displacements of the mass elements in the capillary wall allow calculating the strains into the structure, which are the derivative of the total deformation to the initial dimension of the material body. According to Lamé description, the radial strain, $\varepsilon_r(r)$, is obtained by solving Eq. (2.4) and the azimuthal strain, $\varepsilon_\theta(r)$, is accounted by solving Eq. (2.5), where $u(r)$ is the displacement as shown in Eq. (2.3) – see Appendix B for a detailed explanation. Assuming a capillary with $r_{in} = 40 \mu m$ and $r_{out} = 80 \mu m$ undergoing an external pressure level of 50 bar, we can obtain the results shown in Figure 2.4a, where it can be observed that the radial strain can be either tensile ($\varepsilon_r(r) > 0$) or compressive ($\varepsilon_r(r) < 0$). Moreover, we can identify a point of zero radial strain — $r_{\varepsilon_r=0}$, given by Eq. (2.6) —, which, for the situation studied in Figure 2.4a ($r_{in} = 40 \mu m$, $r_{out} = 80 \mu m$, $p_{in} = 1$ bar, $p_{out} = 50$ bar and $\nu = 0.165$), is calculated to be 46.9 $\mu m$. Additionally, it is observed that the azimuthal strain is always compressive ($\varepsilon_\theta(r) < 0$).

$$\varepsilon_r(r) = \frac{du(r)}{dr} \quad (2.4)$$

$$\varepsilon_\theta(r) = \frac{u(r)}{r} \quad (2.5)$$
\[ r_{\varepsilon_r=0} = r_{in} \sqrt{\frac{(1+v)(p_{out}-p_{in})}{(1-v)}} \left[ p_{out} - p_{in} \left( \frac{r_{out}}{r_{in}} \right)^2 \right]^{-1} \]  

(2.6)

Figure 2.4. (a) Strain and (b) stress as a function of the radial position inside a capillary with \( r_{in} = 40 \mu m \) and \( r_{out} = 80 \mu m \) (\( p_{in} = 1 \) bar and \( p_{out} = 50 \) bar). Green triangles and dark red circles are the data obtained from the COMSOL® numerical model.

Furthermore, the Lamé solution allows to determine the radial (\( \sigma_r \)) and azimuthal (\( \sigma_\theta \)) stresses which are induced inside the tube wall when hydrostatic pressure is applied to the fiber (details in Appendix B). The stresses are a measure of the internal forces per unit area that the neighboring volume elements exert on each other. The expressions for the stresses are shown in Eq. (2.7) and Eq. (2.8), where \( r_{in} \) and \( r_{out} \) are the inner and outer radii of the tube; \( p_{in} \) and \( p_{out} \) are the internal and external pressure, respectively.

\[
\sigma_r(r) = \frac{1}{1 - \left( \frac{r_{in}}{r_{out}} \right)^2} \left[ p_{in} \left( \frac{r_{in}}{r_{out}} \right)^2 - p_{out} - (p_{in} - p_{out}) \left( \frac{r_{in}}{r} \right)^2 \right] 
\]

(2.7)

\[
\sigma_\theta(r) = \frac{1}{1 - \left( \frac{r_{in}}{r_{out}} \right)^2} \left[ p_{in} \left( \frac{r_{in}}{r_{out}} \right)^2 - p_{out} + (p_{in} - p_{out}) \left( \frac{r_{in}}{r} \right)^2 \right] 
\]

(2.8)

Figure 2.4b presents the results for the radial and the azimuthal stresses behaviors along the tube wall (between \( r_{in} = 40 \mu m \) and \( r_{in} = 80 \mu m \)) for the situation in which the
fiber is subjected to an external pressure of 50 bar and an internal pressure of 1 bar. As expected, the absolute value of the radial stress at the outer radius assumes the external pressure value \( p_{\text{out}} = 50 \text{ bar} = 5 \text{ MPa} \), while, at the inner radius position, the radial stress assumes the internal pressure value \( p_{\text{in}} = 1 \text{ bar} = 0.1 \text{ MPa} \), which are boundary conditions of the problem. Additionally, numerical results obtained from a finite-element-based model built using the COMSOL® software are also exposed in Figure 2.4b (green triangles and dark red circles). Analytical and numerical results are seen to be very similar.

The stresses expressed in polar coordinates \((\sigma_r, \sigma_\theta)\) can be readily written in rectangular coordinates \((\sigma_x, \sigma_y)\) by using the transformations presented in Eq. (2.9) and Eq. (2.10) \[2.20\]. To obtain \(\sigma_x\) and \(\sigma_y\) along the horizontal axis, we simply set \(\theta = 0\) to conclude that \(\sigma_r = \sigma_x\) and \(\sigma_\theta = \sigma_y\).

\[
\sigma_x = \sigma_r \cos^2 \theta + \sigma_\theta \sin^2 \theta \tag{2.9}
\]

\[
\sigma_y = \sigma_r \sin^2 \theta + \sigma_\theta \cos^2 \theta \tag{2.10}
\]

Therefore, by recognizing that, along the horizontal axis, \(\sigma_x\) is expressed by Eq. (2.7) and \(\sigma_y\) by Eq. (2.8), and by substituting these results into Eq. (2.2), we can write Eq. (2.11), which accounts for the material birefringence at a position \(x\) along the horizontal axis inside the capillary fiber wall. To obtain Eq. (2.11), it was assumed that \(n_{x0}\) and \(n_{y0}\) are equal (no birefringence under no stress). Moreover, we have defined the gauge pressure as \(p_{\text{gauge}} \equiv p_{\text{out}} - p_{\text{in}}\).

\[
B_{\text{mat}}(x) = 2(C_2 - C_1)p_{\text{gauge}} \left[1 - \left(\frac{r_{\text{in}}}{r_{\text{out}}}\right)^2\right]^{-1} \frac{r_{\text{in}}^2}{x^2} \tag{2.11}
\]

Figure 2.5a is obtained by plotting, for \(p_{\text{gauge}} = 50\) bar, the material birefringence absolute value as a function of the position on the horizontal axis for capillaries with different \(r_{\text{in}}/r_{\text{out}}\) ratio values (but with the same value for the inner radius, 40 \(\mu\text{m}\)). Results show that when the fiber is subjected to external pressure, the induced material birefringence values are greater for thin-walled capillary fibers. Moreover, it can be observed that higher material birefringence values are obtained for positions which are closer to the inner radius.
Figure 2.5b shows the material birefringence modulus as a function of the position on the horizontal axis for a capillary with \( r_{in} = 40 \) µm and \( r_{out} = 80 \) µm subjected to four different pressure levels (20, 30, 40 and 50 bar). It can be observed that, although the material birefringence increases for all positions within the capillary wall, the increase occurs at different rates – being higher for positions closer to the inner radius and lower towards the capillary external side.

![Figure 2.5b](image)

The different slopes of the material birefringence variation due to external pressure application are observed in Figure 2.5c, where we have plotted the material birefringence as a function of the pressure for the inner radius \( (r_{in} = 40 \) µm), outer radius \( (r_{out} = 80 \) µm) and middle point of the capillary wall \( (r_{1/2} = 60 \) µm). The slopes ranged from \( 9.3 \times 10^{-12} \text{ bar}^{-1} \) to \( 2.3 \times 10^{-12} \text{ bar}^{-1} \) along the capillary wall. Additionally, as
exposed in Figure 2.5d, the material birefringence was plotted as a function of the applied external pressure for capillary fibers with \( r_{in} = 40 \, \mu m \) but with different \( r_{in}/r_{out} \) values. This graph allows observing that \( dB_{mat}/dP \) is higher for greater \( r_{in}/r_{out} \) values. Therefore, we can conclude that the material birefringence variations are greater for positions closer to the inner side of the capillary and for tubes with thinner walls.

### 2.2 Modal birefringence dependence on applied pressure

To study the birefringence dependence on the applied pressure in practical applications, we explored a configuration in which a high refractive index core is embedded into the capillary wall, as presented in Figure 2.3a – the *embedded-core capillary fiber*. The core is a germanium-doped region and has an elliptical shape. Even though the material birefringence was investigated in the previous section, it is necessary to study its modal behavior. Therefore, the embedded-core fiber structure was simulated in COMSOL® and its modal birefringence dependency on the applied pressure was attained. The numerical results were obtained in collaboration with Prof. Dr. Marcos A. R. Franco and Mr. Valdir A. Serrão from the Institute for Advanced Studies (IEAv).

A capillary fiber with \( r_{in} = 40 \, \mu m \) and \( r_{out} = 67.5 \, \mu m \) was studied in the numerical model. The core was considered to be an ellipse with dimensions of 5.7 \( \mu m \) and 11.4 \( \mu m \). In the simulations, the effective refractive indexes of the x- and y-polarized core modes were obtained for different pressure conditions. It allowed to numerically obtain the modal birefringence derivative as a function of the applied pressure, \( dB_{modal}/dP \). We have performed the calculation of \( dB_{modal}/dP \) for several positions within the capillary fiber wall, as it can be observed in Figure 2.6. The blue region indicates for the capillary the capillary wall region and the yellow ellipses stand for the area. Additionally, the insets in Figure 2.6 show the core position (dark blue ellipses) inside the capillary wall for selected points in Figure 2.6 plot.

In Figure 2.6, it is seen that when the entire core area is inside the capillary wall, the \( dB_{modal}/dP \) behavior is analogous to that of the material birefringence case – increasing values towards the inner side of the capillary. As the core approaches the inner or outer wall, part of its area can be outside the capillary structure (see representations in Figure 2.6 insets). It entails decreasing \( dB_{modal}/dP \) values. Therefore, it is recognized that, to obtain an optimized birefringence dependence on pressure variations, it is crucial to
totally embed the core region inside the capillary fiber wall. As we could predict from the analytical simulations, the greatest $dB_{\text{modal}}/dP$ values are obtained for core positions closer to the inner wall.

![Figure 2.6. Modal birefringence derivative with respect to pressure, $dB_{\text{modal}}/dP$, as a function of the core position inside the capillary wall. The blue region stands for the capillary wall regions and the yellow ellipses illustrates the core area. The insets represent the core location inside the capillary fiber.](image)

2.3 Fiber fabrication

To obtain an experimental realization of the proposed structure, a capillary fiber with an embedded core was fabricated (embedded-core fiber). To obtain such a fiber, initially, a germanium doped rod is reduced from its initial diameter (21 mm) to the thickness of 0.8 mm (Figure 2.7a). In sequence, the thinned germanium doped rod is merged to a silica tube, by using a flame from a blowtorch (Figure 2.7b). The resulting preform is inserted into a jacketing tube as it is represented in Figure 2.7c, causing the core region to be located in between the inner tube and the jacketing one. In the last step, the resulting fiber preform is directly drawn to fiber’s final diameter in an optical fiber tower drawing facility. All the fabrication steps were performed by us at Unicamp.

During the fiber drawing process, vacuum is applied in the space between the tubes, allowing them to merge. In the merging process, the core is compressed and, in the final fiber, it acquires an elliptical shape. When preparing the preform, an adequate choice
of the germanium-doped rod and tubes dimensions allows attaining the desired core position within the capillary wall.

![Figure 2.7. (a) Germanium-doped silica preform. (b) Merging and (c) jacketing procedure diagram.](image)

Figure 2.8a shows the cross-section of the embedded-core fiber obtained by following the steps described above. The capillary diameters are 40 µm and 100 µm, the distance between the center of the fiber and the core position is 35 µm and the core dimensions are 11 µm and 3.5 µm. To obtain such a fiber, one employed, in the preform preparation process, an inner tube with dimensions of 9.5 mm × 11.5 mm and a jacketing tube with dimensions of 18 mm × 20 mm.

Additionally, to have another fiber for comparison, we have performed the fabrication of a fiber in which the core was placed on the fiber outer surface – this structure was named surface-core fiber. In this fiber, the capillary inner diameter is 80 µm, the outer diameter is 140 µm and the core dimensions are 6 µm and 9 µm. Its cross-section is presented in Figure 2.8b. To obtain the surface-core fiber, the jacketing procedure is not necessary and the fiber is drawn directly from the preform obtained after merging the germanium-doped core to the supporting tube. In Chapter 3, one will discuss the surface-core fiber in detail and its application in refractive index and directional curvature sensing.
It is worth emphasizing that all the steps in embedded-core and surface-core fiber fabrication procedures are straightforward. It allows recognizing that these fibers fabrication process is much simpler than the ones for other specialty fibers such as photonic-crystal fibers. As mentioned in Chapter 1, for example, to obtain photonic-crystal fibers, stack-and-draw procedure is often employed. In this technique, numerous tubes and rods are drawn and, in sequence, manually assembled in a preform stack. The following steps comprehend jacketing processes which are done to obtain the desired proportion between core and cladding sizes. Therefore, although convenient, stack-and-draw procedure is very time consuming and demands much technical effort.

2.4 Pressure-sensing measurements and performance analysis

To characterize the sensitivity of the fibers to external pressure variations, we have used the so-called polarimetric wavelength scanning method [2.16]. As explained in the first part of this chapter, in this method, a broadband light source is used for launching light into the optical fiber and two polarizers are used for exciting the two orthogonal modes of the birefringent fiber and for recombining the orthogonal optical modes that
traveled along the fiber. An optical spectrum analyzer is used to measure the transmitted light and a pressure chamber is used to subject the fiber to different external pressure levels. Here, we used the experimental setup schematized in Figure 2.2.

In order to measure the sensitivity coefficient, $C_S$, for the embedded-core capillary fiber, the spectral response of the embedded-core fiber was measured as it was subjected to pressure variations. Figure 2.9a shows the resulting spectra. It can be observed that the fringes blueshift when the pressure is increased. In Figure 2.9b, the wavelength shift due to pressure application to the embedded-core fiber is presented as blue squares. In the measurements, the embedded-core fiber length was $(36.0 \pm 0.1)$ cm and the pressurized fiber length was $(12.0 \pm 0.1)$ cm. The red circles in Figure 2.9b represents the pressure-sensing results for the surface-core fiber. In the experiments with the surface-core fiber, the fiber length was $(32.0 \pm 0.1)$ cm and the pressurized fiber length was $(12.0 \pm 0.1)$ cm. The measured data, allowed obtaining, after fitting the experimental points, a sensitivity coefficient $C_S^{\text{experiment}} = (0.345 \pm 0.002)$ nm/bar for the embedded-core fiber and a sensitivity coefficient $C_S^{\text{experiment}} = (0.160 \pm 0.004)$ nm/bar for the surface-core fiber.

Before performing the comparison between the experimental sensitivity values expressed above, it is necessary to correct them by a factor $L_P/L$ ($L$: fiber length; $L_P$: pressurized fiber length) \cite{2.24}. It must be made since $C_S$ value refers to a situation in which the whole fiber length is pressurized. As one has pressurized a fraction of the fiber length, $L_P$, this correction necessary. Therefore, after performing the correction, we could
obtain the following sensitivity coefficients ($C_{S}^{corrected}$): (1.04 ± 0.01) nm/bar for the embedded-core fiber and (0.43 ± 0.01) nm/bar for the surface-core fiber.

By observing the results, we can realize that an enhancement in fiber pressure sensitivity was achieved when the core was placed within the capillary wall. Comparing the two corrected values, it is seen that the embedded-core fiber sensitivity is 2.4 times higher than the one presented by the surface-core fiber. It corroborates our simulation results: a maximized sensitivity could be obtained for a fiber in which the core was placed inside the capillary fiber structure.

As the sensing measurements are based on accounting the spectral dips’ shift as a function of the applied pressure, we can analyze that the dynamic range of the sensor is determined by the dips spectral separation, i.e. its free spectral range (FSR). It is because, in a practical measurement, if a dip reaches the spectral position of a neighboring one, misinterpretation in sensor reading can occur. In the measurement presented in Figure 2.9a, the free spectral range can be estimated to be FSR = 14.2 nm. This would be the maximum wavelength shift that, in a practical application and without any extra data processing, could provide an unequivocal response for the sensor. Using the sensitivity coefficient $C_{S}$ accounted directly in the measurement, one can estimate the measurement dynamic range as approximately 42 bar – what could make the sensor suitable for submarine measurements at depths variations up to ~400 m. In this context, it is worth emphasizing that although we estimate a 42 bar dynamic range for practical applications, data up to 80 bar could be measured since, in our experiments, we carefully followed the dips spectral position as a function of pressure.

Moreover, it should be analyzed that the measurement dynamic range can be tuned by adjusting the fiber length. It happens because, in the polarimetric wavelength scanning method, the increase in fiber length causes the dips to be spectrally closer in the transmission spectrum (thus reducing the FSR and the dynamic range). Alternatively, if a shorter fiber is used, the FSR will be greater and, therefore, the dynamic range too. For example, if in a specific application fiber length was 2 cm, its dynamic range would be in the order of 300 bar. In this configuration, the sensor could be appropriate for petroleum exploration applications.

To illustrate the variation of the dips spacing for varying fiber lengths, we provide in the following the results for the transmission spectrum accounted by using Jones matrices formalism for predicting the system’s optical response [2.24]. In the simulations, the output power, $P_{out}$, is obtained by calculating $P_{out} = |P_{A}(\theta) . P_{2}(\alpha) . E_{in}|^{2}$, where
$P_1$ and $P_2$ are the matrices which represent the first and second polarizers – $P_i = R^{-1}(\delta) \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix} R(\delta)$, with $R(\delta) = \begin{pmatrix} \cos \delta & \sin \delta \\ -\sin \delta & \cos \delta \end{pmatrix}$, where $i = 1, 2$ and $\delta = \theta, \alpha$ (the polarizer angles). The $F$ matrix represents the birefringent fiber and is calculated by making $F = \begin{pmatrix} 1 & 0 \\ 0 & \exp \left[i \left(\frac{2\pi LG}{\lambda}\right)\right] \end{pmatrix}$, where $L$ is the fiber length, $G$ is the group birefringence and $\lambda$ is the wavelength; $E_{in}$ represents the electric field of the input light, taken as $\begin{pmatrix} 1 \\ 0 \end{pmatrix}$. The results for the transmission spectrum as the fiber length is varied are shown in Figure 2.10. It is seen that if the fiber length is decreased, the dips’ separation enhances. [2.24]

![Figure 2.10](image)

Figure 2.10. Jones matrices-based simulation results for sensor transmission spectra for varying fiber lengths.

Regarding sensor’ resolution, it can be observed that it is determined by the widths of the spectral dips observed in the polarimetric measurement. In the measurement shown in Figure 2.9a, the dip’s FWHM (full width at half maximum) can be estimated as $\Delta \lambda = 6$ nm. Assuming one can resolve two spectral dips if they are, at least, $\Delta \lambda / 50 \approx 0.1$ nm apart from each other, the sensor resolution limit can be estimated as 0.3 bar (calculated by multiplying the least resolvable wavelength shift by the sensitivity coefficient $C_S$ accounted directly in the measurement).
We simulated, using Jones matrices formalism, this wavelength shift ($\Delta \lambda/50$) for a 12 cm long fiber (FWHM $\approx 20$ nm) and for a 5 cm long one (FWHM $\approx 50$ nm). Results are shown in Figure 2.11. Using the simulated data, the resolution limit for the 12 cm long fiber can be calculated to be 0.4 bar while for a 5 cm long it is 1.0 bar (here, the $\Delta \lambda/50$ wavelength shift was multiplied by the experimental $C_S$ value).

Additionally, numerical simulations on the fiber sensitivities were performed. The simulated sensitivity values for the embedded-core and surface-core fiber were attained by using COMSOL® mechanical and optical analyses. To obtain the most verisimilar analysis possible, realistic models based on microscopy images were created.

Initially, based on the obtained effective refractive indexes for the orthogonal modes in the fiber core, we calculated the fiber group birefringence dependence on the applied pressure, $\frac{\partial B_{modal}}{\partial P}$. Moreover, the fiber group birefringence, $G$, were estimated by using $G = B - \lambda \frac{\partial B}{\partial \lambda}$, where $B$ is the phase birefringence and $\lambda$ is the wavelength. The attained values for $\frac{\partial B_{modal}}{\partial P}$ and $G$ were substituted in Eq. (2.1) and the sensitivity coefficient could be calculated to be 0.89 nm/bar for the embedded-core fiber and 0.50 nm/bar for the surface-core fiber. We could, therefore, observe a good agreement between simulated and experimental data – (1.04 ± 0.01) nm/bar for the embedded-core fiber and (0.43 ± 0.01) nm/bar for the surface-core fiber.

Moreover, as the proposed fibers are endowed with a germanium-doped region which acts as the fiber core, temperature sensitivity is expected in these fibers. It arises from the fact that undoped and doped silica present different thermal expansion

![Figure 2.11. $\Delta \lambda/50$ wavelength shifts for fibers (a) 12 cm and (b) 5 cm long.](image-url)
coefficients. Thus, temperature variations induce stresses within the fiber structure leading to birefringence variations \([2.13]\). To estimate their temperature sensitivity, the fibers were subjected to temperature variations whereas their spectral response were measured according to the wavelength scanning method. Measurement allowed to determine \( \frac{\partial B_{modal}}{\partial T} = (2.8 \pm 0.1) \times 10^{-7} \, ^\circ \text{C}^{-1} \) for the birefringence derivative with respect to temperature in the embedded core fiber and \( \frac{\partial B_{modal}}{\partial T} = (4.0 \pm 0.4) \times 10^{-7} \, ^\circ \text{C}^{-1} \) in the surface-core fiber. The obtained results are similar to the ones reported for commercial polarization maintaining fiber such as PANDA \((4.0 \times 10^{-7} \, ^\circ \text{C}^{-1})\) and Bow-tie fiber \((3.6 \times 10^{-7} \, ^\circ \text{C}^{-1})\) \([2.25]\). However, embedded-core and surface-core fibers’ \( \frac{\partial B_{modal}}{\partial T} \) values are higher than the ones reported for specially designed microstructured fibers with incorporated germanium-doped core employed in pressure monitoring measurements \((1.7 \times 10^{-7} \, ^\circ \text{C}^{-1})\) \([1.18]\) and for all-silica photonic-crystal fibers \((1.1 \times 10^{-9} \, ^\circ \text{C}^{-1})\) \([1.13]\).

Therefore, if a practical application is targeted, a temperature compensation system would be of interest. It could be accomplished, for example, by performing the fabrication of an embedded-core fiber with two cores – placed at different radial positions inside the capillary wall – and by imprinting a Bragg grating in each of them. As the core of the embedded-core fiber is obtained from a standard optical fiber preform, we can expect a Bragg grating temperature sensitivity in the order of \(10 \, \text{pm/}^\circ \text{C}\) for both cores, as in typical Bragg grating temperature sensors \([2.26]\). Besides, numerical simulations show that, for a capillary structure with 40 \(\mu\text{m}\) inner radius and 62.5 \(\mu\text{m}\) outer radius, if one of the cores has its center placed 2.5 \(\mu\text{m}\) from the inner wall (so most of the core area is inside the capillary structure; core dimensions: 5.7 \(\mu\text{m}\) and 11.4 \(\mu\text{m}\)) and the other core is placed on the fiber external surface, the pressure sensitivity of a Bragg grating inscribed in the core closer to the inner radius would be approximately twice the pressure sensitivity for the core on the fiber external surface. Thus, by taking into account the shifts in Bragg peaks and associating them to the different pressure sensitivities and similar temperature sensitivities, temperature variations could be calculated and the pressure measurement from the polarimetric measurement (as described in the paper) could be corrected.

Moreover, the off-center position of the core makes necessary to conduct further studies on splicing methods and, if practical applications are targeted, additional studies on sensor packaging would be necessary. A possible alternative would be inserting the sensing fiber into a hollow metallic tube with transversal holes on its side. It would protect
the fiber and would still allow the pressure from the external environment to act on the fiber.

### 2.5 Sensitivity comparison and prospects on sensor improvement

The reported results on the embedded-core optical fiber pressure sensitivity allows demonstrating that this geometry can be seen as a novel route towards the simplification of microstructured optical fiber-based pressure sensors. The measured sensitivity – (1.04 ± 0.01) nm/bar – is higher than that of other fiber-based sensors that also uses polarimetric measurements. For example, H. Y. Fu et al. showed 0.342 nm/bar for a commercial all-silica photonic-crystal fiber [2.13] and T. Martynkien et al. reported 0.30 nm/bar and 0.52 nm/bar for specially designed microstructured fibers [2.18, 2.19].

Moreover, by using Eq. (2.1), it is possible to estimate the embedded-core fiber birefringence derivative with respect to pressure, \( \frac{\partial B}{\partial P} \), to be (2.33 ± 0.02) \times 10^{-7} \text{ bar}^{-1}. This value is on the same magnitude order as the ones attained for sophisticated microstructured fibers whose designs were optimized for pressure sensing. As one mentioned in the first part of this chapter, G. Statkiewicz-Barabach et al. reported, for a photonic-crystal fiber, the value \( \frac{\partial B}{\partial P} = 2.52 \times 10^{-7} \text{ bar}^{-1} \) [2.9] and A. Anuskiewicz et al. attained, for a specially designed fiber endowed with a triangular lattice of holes, the value \( \frac{\partial B}{\partial P} = 8.89 \times 10^{-7} \text{ bar}^{-1} \) [2.10]. The fabrication procedure of these fibers, however, is considerably more complex than the one used for obtaining the embedded-core fiber, which involves a relatively simple fiber drawing process. Table 2.1 presents a comparison between the parameters of special birefringent optical fibers used for pressure sensing purposes.

Additionally, we can observe that there is still room for enhancing the pressure sensitivity by working on the embedded-core geometric dimensions of the non-optimized fiber reported herein. To provide a prediction on the sensitivity enhancement, we performed analytical simulations of an embedded-core capillary fiber with 70 \( \mu \text{m} \) and 100 \( \mu \text{m} \) inner and outer diameters, respectively, and with the core placed 42.5 \( \mu \text{m} \) away from the fiber center (at the middle point of the capillary wall) – all very realistic geometric parameters. The calculated material birefringence derivative with respect to
pressure was 3.4 times the value expected for an embedded-core fiber with the same dimensions as the one we fabricated.

Table 2.1. Sensing parameters of selected specialty optical fibers used in pressure sensing measurements.

| Reference | Fiber structure | $|dB_{\text{modal}}/dP| \times 10^{-7}$ bar$^{-1}$ | Sensitivity coefficient, $|C_S|$ (nm/bar) | Resolution (bar) | Dynamic range (bar) |
|-----------|----------------|---------------------------------|---------------------------------|----------------|-------------------|
| Embedded-core fiber | ![Embedded-core fiber](image) | $(2.33 \pm 0.02)$ | $(1.04 \pm 0.01)$ | 0.3 | 42 |
| [2.9] | ![Fiber structure](image) | 2.52 | 0.614 | $0.07^*$ | ** |
| [2.10] | ![Fiber structure](image) | 8.89 | 17.8 | $0.01^*$ | ** |
| [2.13] | ![Fiber structure](image) | 1.71 | 0.342 | 0.03 | 15$^*$ |
| [2.18] | ![Fiber structure](image) | 2.3 | 0.30 | ** | ** |

*estimated by us; **information not available.

To evaluate the influence of the elliptical shape on the birefringence and sensor’s performance, we performed supplementary numerical simulations using a capillary structure with inner radius 40 µm and outer radius 67.5 µm and the core placed at the middle point within the capillary wall. In the simulations, the core dimensions were varied and the birefringence values were accounted. Moreover, we calculated the modal birefringence derivative with respect to pressure, $\frac{\partial B_{\text{modal}}}{\partial P}$, and the sensitivity coefficient – $C_S$, as in Eq. (2.1) – for each situation. The results are shown in Table 2.2, where we see that the alteration in core eccentricity does not imply in considerable $\frac{\partial B_{\text{modal}}}{\partial P}$ variation.
Table 2.2. Simulated values for phase birefringence ($B$), group birefringence ($G$), phase derivative with respect to pressure ($dB_{modal}/dP$) and sensitivity coefficient ($C_S$). The values were calculated at $\lambda = 1150$ nm, compatible with the spectral range measured in the experiments. In the simulations, the capillary structure was assumed to have 40 µm inner radius and 67.5 µm outer radius. The core was placed at the middle point within the capillary wall.

| Core dimensions (µm) | Core eccentricity | Phase birefringence, $|B|$ ($\times 10^{-4}$) | Group birefringence, $|G|$ ($\times 10^{-3}$) | $|dB_{modal}/dP|$ ($\times 10^{-7}$ bar$^{-1}$) | Sensitivity coefficient, $|C_S|$ (nm/bar) |
|----------------------|-------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|
| 4 × 12               | 0.33              | 1.63                            | 2.46                            | 5.72                            | 2.7                             |
| 4 × 8                | 0.50              | 0.95                            | 1.67                            | 5.81                            | 4.0                             |
| 4 × 5                | 0.80              | 0.24                            | 0.41                            | 5.88                            | 16.5                            |

The sensitivity coefficient ($C_S$), however, can be increased if the fiber core is more symmetric and presents a lower group birefringence – as expected from Eq. (2.1). As can be observed in Table 2.2, the $C_S$ value for a core with dimensions 4 µm × 5 µm is estimated to be approximately 6 times higher than the $C_S$ value for a core with dimensions 4 µm × 12 µm (data found for an embedded-core fiber with inner radius 40 µm, outer radius 67.5 µm and the core placed at the middle point within the capillary wall). Additional experimental work should be performed in order to obtain cores with lower geometric asymmetry. A possible approach would be to include, during the embedded-core fiber preform preparation, additional silica rods between the inner tube and the jacketing tube – Figure 2.12. It would possibly avoid the core compression during the fiber fabrication and, therefore, allow to obtain embedded-core fibers with less asymmetric cores.

Figure 2.12. Proposal for the jacketing procedure to obtain less asymmetric embedded-core fibers with less asymmetric cores.
Therefore, one can underline that, in this chapter, a new route for the simplification of microstructured optical fiber-based sensor was proposed by studying the photoelastic effect in capillary fibers. Initially, we have provided an analytical description of the pressure-induced material birefringence inside the walls of the capillary fibers, whose results showed that the material birefringence dependence on pressure is enhanced for thinner capillaries and for positions closer to their inner walls. Moreover, numerical simulations were performed and the obtained data confirmed the analytical model predictions and showed the crucial role performed by the capillary structure in \( \frac{\partial B}{\partial P} \) enhancement.

Furthermore, the fabrication of an embedded-core fiber was reported. In sequence, the fiber was characterized in pressure-monitoring experiments and showed sensitivity levels which are similar to the ones reported for complicated and specially designed fiber structures. It allows visualizing the embedded-core fiber as a very interesting platform able to considerably simplify the design of microstructured optical fiber pressure sensors.

The results from the investigation described in this chapter were presented at the IX Iberoamerican Optics Meeting & XII Latinoamerican Meeting on Optics, Lasers and Applications (RIAO/OPTILAS) [2.27] and were published as a journal paper in Scientific Reports (Nature Group) [2.28]. Moreover, a Brazilian patent will be written on this topic.

Additional developments on the use of the embedded-core fiber for temperature sensing (by performing a metal-filling post-processing) were also studied in collaboration with Mr. Giancarlo Chesini and the results were presented in the III International Conference on Applications of Optics and Photonics [2.29]. Additionally, a journal article will be submitted to IEEE Sensors Letters [2.30]. A description of this research is presented in Chapter 5.
Chapter 3

Sensing with surface-core fibers

In the last chapter, we proposed the embedded-core fiber as a new platform to significantly simplify the design of microstructured fiber-based pressure sensors. When analyzing the performance of the sensors, we studied a structure denominated surface-core fiber (which references a structure in which the core is placed on the external surface of the fiber) to provide a comparison between the pressure sensitivities. In the present chapter, we propose additional sensing opportunities for the surface-core fibers by employing them in refractive index and curvature sensing. As it will be discussed in the following, the core position allows the interaction between the guided mode’s evanescent field and the external medium, causing the fiber to be sensitive to external refractive index changes. Additionally, off-center core position allow curvature probing as will be described in the following.

Several fiber sensors have already been described to be able to sense refractive index variations. Long-period gratings \[3.1, 3.2\], multimode interferometers \[3.3, 3.4\] and birefringent microfibers \[3.5, 3.6\] are some examples of technologies which can be employed to turn optical fibers sensitive to refractive index changes in the external medium. Sensitivity values ranging from hundreds to thousands of nanometers per refractive unit (nm/RIU) are reported for fiber sensors based in these techniques.

Regarding curvature measurements, long-period gratings and multimode interferometers are once again useful technologies \[3.7, 3.8\]. Besides, it is also possible to employ Bragg gratings inscribed in multicore fibers to turn the optical response of the setups sensitive to curvature orientation \[3.9-3.11\].

In this chapter, a study on Bragg gratings inscribed in surface-core optical fibers and the application of the same in refractive index and curvature sensing is described. To our knowledge, near-surface-core fibers have been reported for the first time in \[3.12\] by C. Guan et al., who theoretically studied its sensitivity to external refractive index variations (Figure 3.1a and Figure 3.1b shows pictures of the fibers studied by C. Guan et al in \[3.12\]) by approaching the interaction between the guided mode evanescent field
and the external medium. In the investigation reported in [3.12], there was no study on the inscription of Bragg gratings in surface-core fibers. An analogous configuration for studying the interaction of the optical mode evanescent field and samples of interest for sensing purposes uses a hollow fiber (eccentric-suspended-core hollow fiber), as presented Figure 3.1c [3.13]. In this configuration, the sample under test can be confined inside the fiber, what can be useful for gas sensing [3.13].

![Figure 3.1.](image)

**Figure 3.1.** (a) and (b) Near-surface-core fibers studied by C. Guan et al. (Adapted from [3.12]). (c) Eccentric-suspended-core hollow fiber [3.13].

The investigation which will be reported in this chapter ranges from fiber fabrication and characterization to the performance of simulations, the imprinting of Bragg gratings and the realization of experimental measurements for refractive index and curvature sensing. For the refractive index sensing experiments, sensitivities as high as 40 nm/RIU were attained for refractive index variations around 1.42 RIU. Other refractive index fiber Bragg gratings-based sensors described in literature, for example, reports sensitivity values which ranges from 15 nm/RIU to 30 nm/RIU [3.14-3.16].

Moreover, it will be reported that the optical response of the Bragg gratings in surface-core fibers is dependent on curvature magnitude and direction. For curvature monitoring measurements, a maximum sensitivity of $202 \pm 3 \text{ pm/m}^{-1}$ was obtained. This value is two times larger than the value reported for similar fiber Bragg gratings-based sensors reported in literature [3.9-3.11].

**3.1 Fiber Fabrication**

In surface-core fibers’ design, the core region is placed on fiber’s external surface. The fabrication of the fiber is simple and follows the same process described in the last
chapter. As in this chapter one targets the realization of refractive index measurements, we carried on an additional step for getting rid of the silica layer in the germanium-doped silica preform (see Figure 2.7a). It is done by inserting the preform in a hydrofluoric acid (HF) bath. During the etching process, the diameter decreases from 0.8 mm to 0.65 mm, what causes the silica layer (represented in Figure 2.7a) to be removed. Getting rid of the silica layer is important for refractive index sensing tests because, in the final fiber, the guided mode will directly interface the external medium and, therefore, a more effective interaction between the same and the external medium will be observed. The following steps are the same that the ones described in Chapter 2. Figure 3.2a shows the surface-core fiber cross-section and Figure 3.2b shows a zoom in the core region.

![Figure 3.2. (a) Surface-core fiber cross-section. (b) Zoom in the core region.](image)

### 3.2 Fiber Bragg gratings in surface-core fibers

Bragg gratings were imprinted in surface-core fibers by the employment of phase-mask technique. In this method, light from an UV laser (in our laboratory, at 266 nm) is shone on a phase-mask and an interferometric pattern is created on the fiber (Figure 3.3a). As the germanium doped region of the fiber (the core) is photosensitive (i.e. its refractive index is permanently altered when it is exposed to light at an appropriate wavelength), a longitudinal modulation in fiber core’s refractive index can be obtained and, thus, the condition for obtaining a Bragg grating can be achieved. [3.18]

Figure 3.3b illustrates the setup for obtaining Bragg gratings and for monitoring its spectral response in reflection. It is worth observing that a cylindrical lens is used to focus the UV laser beam on the fiber during the grating inscription process. To monitor the Bragg grating spectrum in real-time, a connectorized singlemode fiber was butt-
coupled to the surface-core fiber. A small amount of glycerin was used in the coupling for reducing Fresnel’s reflections at the fiber ends so the background noise could be lowered. In addition, a CCD camera was used to image the fiber end to observe the illumination conditions. By observing the CCD camera image, it was possible to find the core position and to optimize the coupling of light to the surface-core fiber.

**Figure 3.3.** (a) Representation of the interferometric pattern generated by the phase mask for Bragg gratings imprinting [3.17]. (b) Schematic diagram of the grating imprinting setup and for optical response monitoring. M1 and M2: mirrors; CL: cylindrical lens; PM: phase mask; OL: objective lens.

The Bragg gratings were imprinted with enough reflectivity to be observed in reflection. Figure 3.4a presents the spectrum (measured by using a FS2200 Industrial BraggMETER from FiberSensing) of a FBG imprinted in a surface-core fiber by the employment of a phase mask with pitch 1062.65 nm (the spectrum is normalized for better visualization). The tested fibers were maintained under tension during the performance of the experiments. During the development of the research project, the gratings were imprinted by Mr. Ricardo Oliveira (from the Institute of Telecommunications, IT, Aveiro, Portugal) and Mr. Stenio Aristilde (IFGW, Unicamp).

### 3.3 Refractive index sensing

As in surface-core fibers light propagation takes place at fiber external boundary, the guided mode evanescent field permeates the medium which surrounds the fiber. Therefore, one can expect the core mode effective refractive index to be dependent on external refractive index changes. Since the Bragg peak spectral position is determined, besides grating pitch, by the effective refractive index of the optical mode – see
Eq. (1.1) –, Bragg peak shifting is expected if the external refractive index is altered. Hence, by monitoring Bragg peak spectral position as a function of the external refractive index, a refractive index sensor can be attained.

For testing Bragg gratings in surface-core fibers sensitivity to external refractive variations, the fibers were immersed in solutions of water and glycerin at different concentrations and the Bragg peak spectral position was monitored. Experiments demonstrated, however, a very low sensitivity to external refractive index changes (0.07 nm/RIU). It can be verified by observing the very small wavelength shift in Bragg grating spectral peak shown in Figure 3.4a. Thus, to enhance the configuration’s sensitivity, tapers from surface-core fibers were prepared prior to Bragg gratings inscription. The tapered fibers were prepared by ‘flame-brushing’ technique, as described in Chapter 1, and the grating imprinting was performed by using the same phase-mask technique.

The reduction in fiber diameter causes the mode area to increase and, therefore, the mode effective refractive index value will be more sensitive to external refractive index variations [3.15]. Thus, Bragg gratings in tapers with diameters 80 µm and 20 µm were prepared. The resulting reflection spectra for varying external refractive indexes, $n_{\text{ext}}$, are shown in Figure 3.4b and Figure 3.4c (spectra are normalized for better visualization). It is worth emphasizing that a phase mask with pitch 1075.34 nm was used for imprinting the grating in the 80 µm thick fiber taper and a phase mask with pitch 1071.2 nm was used for inscribing the grating in the 20 µm taper. It implied in different spectral positions for the Bragg peak in the tapers spectra. Furthermore, as the core mode in the 20 µm taper has a greater portion of its evanescent field in the external medium than the 80 µm taper, the mode in the 20 µm taper has a lower effective refractive index than the mode in the 80 µm taper [3.15]. For a mode with lower effective refractive index, its correspondent Bragg peak is expected to appear at a lower wavelength, as can be verified by Eq. (1.1).

Additionally, in the spectra shown in Figure 3.4b, we can observe two peaks separated by a spectral distance of 0.23 nm. As a hypothesis, we can propose that it may have happened due to a possible geometric deformation of the fiber during the tapering process, which may have induced a birefringence level to the fiber. If this hypothesis is right, one could estimate a birefringence of $2.1 \times 10^{-4}$ for this sample.
In Figure 3.4d, the Bragg wavelength shift as a function of the external refractive index is shown (for untapered and tapered fibers). Data for the untapered fiber is presented as black circles and the results for the 80 µm and 20 µm tapers as red triangles and blue squares, respectively. It can be noted a greater wavelength shift for the tapered fibers due to the more significant interaction between the core mode evanescent field and the external medium. The sensitivity value for refractive index variations around 1.42 RIU could be measured as 8 nm/RIU for the 80 µm taper and 40 nm/RIU for the 20 µm taper (Figure 3.4d). Furthermore, it is possible to estimate, if an optical spectrum analyzer with 10 pm spectral resolution is employed, the maximum resolution of $2.5 \times 10^{-4}$ RIU.

The maximum sensitivity attained in the experiments reported in this chapter, 40 nm/RIU for a Bragg grating inscribed in a 20 µm thick fiber taper, compares well with other results published by authors who also studied the FBG’s fundamental mode peak wavelength shifts. In [3.14], for example, the authors reported a sensitivity of 15 nm/RIU for a Bragg grating inscribed in a taper 6 µm thick tested in the refractive index range.
between 1.326 and 1.378 RIU. In addition, in [3.15], a 30 nm/RIU sensitivity was found for an 8.5 µm taper in the same refractive index range. Thus, we can observe that we could achieve similar sensitivity values for thicker fiber tapers, which implies in sensor robustness enhancement. It is worth saying that we could obtain this sensitivity values with thicker tapers because, in fact, although the taper structure is thicker, the core region dimension is comparable to the sensors reported by other authors (in the 20 µm thick surface core fiber taper we reported herein, we estimate that the core diameter is around 2 µm).

Greater sensitivity values (in the order of hundreds or thousands of nanometers per RIU), however, are reported in the literature for setups which employ other fiber optics technologies such as interferometers [3.19, 3.20] and plasmonic devices [3.21]. Furthermore, other researchers also explored Bragg gratings in microfibers and published the results in the literature. For instance, in [3.22] and [3.23], FBG’s higher order modes peaks were monitored and sensitivities as high as 92 nm/RIU and 102 nm/RIU, respectively, could be measured around 1.38 RIU. In [3.22], the authors employed a fiber taper 7 µm thick and, in [3.23], a 6 µm taper was used. Besides, a sensitivity of 660 nm/RIU around 1.39 RIU could be found in [3.24], where the researchers analyzed a FIB-milled Bragg grating in a 0.9 µm taper (FIB: focused ion beam). All these results were obtained, however, for very thin fiber tapers, which reduces sensor robustness.

3.4 Fiber simulation

The fiber structure was numerically simulated for corroborating the experimental results. Initially, the fiber cross-section was drawn in a vector graphics editor (CorelDraw) so one could obtain a realistic reproduction of the surface-core fiber geometric characteristics. In sequence, the drawing was imported into a commercial finite-element-based software (COMSOL®) for optical mode analysis.

Surface-core fibers’ core region is germanium-doped and the refractive index profile is graded. In order to characterize the germanium concentration along the core, energy-dispersive X-ray spectroscopy (EDS) was performed. The right axis of the graph shown in Figure 3.5a shows the results for germanium concentration along the core obtained from EDS technique (Appendix C describes the procedure for attaining this measurement in detail).
To account for the refractive index profile along the core, we have employed Eq. (3.1), which allows obtaining the refractive index, \( n \), of a germanium-doped silica glass at a concentration \( X \) and at a wavelength \( \lambda \) \([3.25]\). \( SA_i \) and \( SL_i \) are the Sellmeier coefficients for silica (SiO\(_2\)) and \( GA_i \) and \( GL_i \) are germanium dioxide’s (GeO\(_2\)) ones. \( SA_i \), \( SL_i \), \( GA_i \) and \( GL_i \) values can be found in Table 3.1.

\[
n^2 = 1 + \sum_{i=1}^{3} \frac{[SA_i+X(GA_i-SA_i)]\lambda^2}{\lambda^2-[SL_i+X(GL_i-SL_i)]^2}
\]  

(3.1)

**Table 3.1.** Sellmeier coefficients for silica (\( SA_i \) and \( SL_i \)) and for germanium dioxide (\( GA_i \) and \( GL_i \)) [[2.25]].

<table>
<thead>
<tr>
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<th></th>
<th>( SL_1 ) (( \mu m^2 ))</th>
<th>( SL_2 ) (( \mu m^2 ))</th>
<th>( SL_3 ) (( \mu m^2 ))</th>
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<tr>
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<td>( GA_2 )</td>
<td>( GA_3 )</td>
<td>( GL_1 ) (( \mu m^2 ))</td>
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</tr>
<tr>
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<td>0.06897260</td>
<td>0.15396605</td>
<td>11.841931</td>
</tr>
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By employing Eq. (3.1) and considering the germanium concentration distribution obtained from EDS technique, we could obtain the core refractive index profile, as shown in the left axis in Figure 3.5a. A Gaussian function was chosen to fit the experimental data and the adjusted curve (red line in Figure 3.5a) was used to define the core refractive index in simulations.
In the simulations, we obtained the effective refractive index of the fundamental core mode as a function of the external refractive index. Figure 3.5b shows the simulated data for the core mode effective refractive index in the untapered surface-core fiber and in the 80 µm and 20 µm tapers. Data from Figure 3.5b allows predicting, via the Bragg grating phase matching condition – Eq. (1.1) – the Bragg wavelength shift as the refractive index of the external refractive medium is varied. This calculation results are show as dashed lines in Figure 3.4d, where a good agreement between simulated and experimental data can be verified.

3.5 Directional curvature sensing

As in surface-core fibers the core region is out of fiber’s center of symmetry, directional curvature sensing can be thought as an additional opportunity for the use of surface-core fibers. Directional curvature monitoring is possible since, depending on curvature orientation, the fiber core experiences compression or expansion (Figure 3.6a). Thus, to attain a configuration in which curvature variations could be measured, a setup as represented in Figure 3.6b was employed. Firstly, the surface-core fiber with a Bragg grating was fixed between two rotator fiber holders under a straight condition. One of the supports on which the fiber was fixed was coupled to a motorized stage. The linear movement of the motorized stage towards the fixed one allowed the creation of curvature increments.

Curvature bending, $C$, is obtained by taking the inverse of the curvature radius, $R$, as shown in Eq. (3.2). Moreover, Eq. (3.2) also shows that the radius of curvature can be associated to the displacement from the straight position, $h$. Here, we consider that the length of the bent fiber section is $2L$ [3.26]. In Figure 3.6b, a representation of the geometric parameters for curvature characterization can be observed.

$$C = \frac{1}{R} \approx \frac{2h}{h^2 + L^2} \quad (3.2)$$

In order to measure directional curvature variations, one took care in order to ensure that curvature increments were being generated in the right direction. Thus, one limited the fiber movement to be described along a single axis by keeping the fiber in between two plastic boards, following the procedure described in [3.26]. In addition, care
was also taken to define the core orientation for the measurements. It was done by projecting the core image into a CCD camera associated to a beam profiler software. By monitoring the core image while the two fiber holders were rotated by the same angle, the core orientation could be adjusted conveniently (Figure 3.6b).

![Diagram](image.png)

**Figure 3.6.** (a) Depending on curvature direction, the FBG is submitted to extension or compression situations. (b) Curvature measurement setup. $R$: curvature radius; $2L$: bent fiber length; $h$: distance from the straight position.

Both compression and expansion of the core introduces strain levels in the core. The induced strain, $\varepsilon$, is directly proportional to the curvature magnitude, $C$, for a specific distance $y$ from the neutral axis (geometric center of the structure), as can be observed in Eq. (2.3) [3.27]. Negative sign for the strain value represents compression and positive sign stands for expansion. A demonstration for Eq. (3.3) can be found in Appendix D.

$$\varepsilon = y C$$

(3.3)

As the introduction of a strain level in a fiber structure imply in variations in both its refractive index (via strain-optic effect) and length, the spectral response of a Bragg grating shifts when the fiber is subjected to strain increments, as can be expected from Bragg gratings phase matching condition – Eq. (1.1). By working out the derivative of Eq. (1.1) with respect to the strain – see Appendix D –, we can find Eq. (3.4), which accounts for the spectral shift of the Bragg peak, $\Delta \lambda_B$, as a function of the applied strain, $\varepsilon$. In Eq. (3.4), $P_\varepsilon$ is silica photoelastic coefficient ($P_\varepsilon = 0.22$), $\lambda_B$ is the Bragg peak spectral position, $C$ is the curvature and $y$ the position from fiber’s neutral axis. We can, therefore, expect that curvature increments will cause the Bragg peak to shift proportionally. [3.28]
\[
\Delta \lambda_B = (1 - P \varepsilon) \lambda_B \varepsilon = [(1 - P \varepsilon) \lambda_B \varepsilon] C
\]

(3.4)

For probing the optical response of Bragg gratings inscribed in surface-core fibers to curvature increments, four configurations were tested. The configurations differed from each other by core orientation and curvature direction, as summarized in Figure 3.7. Data represented as green squares references the situation in which the grating was under expansion and data represented as blue triangles stands for the situation in which the grating was compressed due to curvature. Data presented as red circles and pink rhombs were measured for the situation in which the fiber was rotated by 90 degrees from initial position.

![Figure 3.7](image.png)

**Figure 3.7.** Directional curvature sensing results. Green squares stand for the FBG under extension and blue triangles for the FBG under compression. Red circles and pink rhombs represents de results measured after the fiber were rotated by 90 degrees. \( R \): curvature radius. Spectra show the Bragg peak behavior in expansion (top spectra) and compression (bottom spectra) experiments.

By observing Figure 3.7, it is possible to check that grating expansion caused, as expected, the Bragg peak spectral position to redshift (shift towards longer wavelengths; positive wavelength shift). Grating compression, in turn, causes Bragg peak position to blueshift (shift towards lower wavelengths; negative wavelength shift). The difference between wavelength shifting behavior shows the possibility of employing Bragg gratings in surface-core fibers for directional curvature monitoring.
Results obtained for the situation in which the fiber was rotated (red circles and pink rhombs in Figure 3.7) followed the expected behavior as well, since no curvature sensitivity is expected when the core is on the fiber’s neutral axis [3.26]. The small wavelength shift one have observed (0.35 nm) are due to possible misalignments between the core position and bending plane.

By fitting a linear function to the measured data, \((188 \pm 5) \text{ pm/m}^{-1}\) and \((-202 \pm 3) \text{ pm/m}^{-1}\) sensitivities could be obtained. The obtained values are high when compared to other fiber Bragg gratings-based curvature sensors described in literature – which ranges from 50 pm/m\(^{-1}\) to 100 pm/m\(^{-1}\) [3.9-3.11]. Furthermore, the attained sensitivity values are higher than the one obtained for Bragg gratings imprinted in eccentric core polymer optical fibers – 63.3 pm/m\(^{-1}\) [3.26].

In other configurations not based in Bragg gratings, higher sensitivity values can be reached. For instance, two and three cores optical fibers are reported to provide sensitivities as high as hundreds of nanometers per inverse meter [3.29, 3.30]. However, by the data reported in [3.29] and [3.30], one can see that the spectral features whose wavelength shift is followed in the sensing experiment (spectral dips originated from mode coupling between the cores) are much broader than the Bragg peak used herein. The spectral dips in [3.29] and [3.30] have full width at half maximum (FWHM) around 75 nm and 50 nm respectively. The FWHM of the Bragg peak shown in Figure 3.7 is, on the other hand, 0.25 nm.

This large difference between the FWHM has an important impact on the sensor resolution. By the data reported by the authors of [3.29], for example, it is possible to estimate a resolution limit of 0.01 m\(^{-1}\). Based in our sensor’s results, a resolution limit of 0.02 m\(^{-1}\) can be calculated. Therefore, it is possible to conclude that the surface-core fiber-based curvature sensor reported here, although considerably less sensitive than the sensor reported in [3.29], provides a similar resolution limit when compared with the optical sensor based on a fiber with two cores reported by the authors of [3.29].

The results reported in this chapter were presented in the 24\(^{th}\) International Conference on Optical Fiber Sensors [3.31], where it was laureated with the “Best Brazilian Student Paper Award”. Moreover, the results were published as a journal article in Optical Fiber Technology [3.32].
Chapter 4

An even simpler structure: antiresonant capillary fibers

In the previous chapters, we demonstrated that embedded-core and surface-core fibers are interesting platforms for the development of microstructured optical fiber-based sensors with simplified designs. In the current chapter, it is our intention to approach an even simpler structure: the capillary fibers. Here, differently from the fiber structures studied in Chapter 2 and Chapter 3, we studied the transmission of light through the capillary fiber hollow core and explored such structure in temperature and pressure sensing measurements.

As commented in Chapter 1, transmission of light through the hollow core of capillary fibers occur via the antiresonant reflection mechanism. In this context, the capillary wall is thought as a Fabry-Perot resonator. For wavelengths which experiences constructive interference in the capillary wall (Fabry-Perot resonances), high transmission through the cladding is observed and low transmission through the hollow core is, therefore, verified. On the other hand, for wavelengths experiencing destructive interference in the capillary wall (Fabry-Perot antiresonances), low leakage through the wall is observed and high transmission through the core will be attained. \[4.1\]

The wavelength of minimum transmission can be estimated by using Eq. (1.7),

\[ \lambda_{\text{min}} = \frac{2 n_1 d}{m} \sqrt{\left(\frac{n_2}{n_1}\right)^2 - 1} \]

as shown in Chapter 1. Analogously, it is possible to obtain Eq. (4.1), which accounts for the wavelengths that experiences maximum transmission. In Eq. (4.1), \( n_1 \) is the core’s refractive index, \( n_2 \) is the capillary wall’s one, \( d \) is the capillary wall thickness and \( m \) is the order of the maximum – a demonstration for Eq. (4.1) is provided in Appendix D. \[4.1\]

\[ \lambda_{\text{max}} = \frac{4 n_1 d}{(2m+1)} \sqrt{\left(\frac{n_2}{n_1}\right)^2 - 1} \quad (4.1) \]
As the spectral minima and maxima positions are dependent on the hollow core and capillary wall refractive indexes, and on the capillary wall thickness, external parameters able to alter \( n_1, n_2 \) or \( d \) values can be monitored by the observation of the changes verified in the capillary fibers spectral responses. For example, a recent report on the use of silica capillaries for probing the pressure level in the capillary fiber hollow core is available in [4.2]. Additionally, antiresonant silica capillaries have also been used for liquid level sensing, as reported by S. Liu et al. in [4.3].

Here, we present the use of polymethylmethacrylate (PMMA)-made capillary fibers in temperature and external pressure sensing. To study the capillaries as temperature sensors, an analytical model was used to describe the spectral response of the fibers when subjected to temperature variations. In the pressure sensing studies, we employed the Lamé solution for pressurized vessels (as in Chapter 2), to account for capillaries thickness variations when pressure is applied to them. Additionally, temperature and pressure sensing measurements are provided and the results are compared to the predicted by the analytical models.

### 4.1 Antiresonant capillaries spectrum – analytical model

To study the capillary fibers transmission spectral characteristics, we have employed the analytical model described in [4.4], which allows obtaining the power transmitted through the capillary as a function of the wavelength. It is worth observing that this same model has already been used in [4.5] and [4.6] to account for capillary fibers optical losses in visible and terahertz spectral ranges.

In Figure 4.1a, we represent the capillary structure, which consists simply of a tube. \( D_{\text{in}} \) and \( D_{\text{out}} \) are the inner and outer capillary diameters; \( n_1 \) and \( n_2 \) are the core and the capillary refractive indexes. The model considers that each leaky mode supported by the capillary hollow core can be described as a light ray that impinges on the capillary wall with an angle of incidence \( \theta_1 \) – Figure 4.1b –, which can be accounted by Eq. (4.2), where \( n_{\text{eff}} \) is the effective refractive index of the mode [4.4]. The effective refractive index of a specific mode in the capillary hollow core can be obtained by Eq. (4.3), where \( \lambda \) is the wavelength and \( u_{\mu\nu} \) is a root for the equation \( J_{\nu-1}(u_{\mu\nu}) = 0 \) – where \( J \) is the Bessel function. [4.7]
Figure 4.1. (a) Capillary fiber cross-section representation; \( n_1 \) and \( n_2 \): core and capillary refractive indexes; \( D_{in} \) and \( D_{out} \): inner and outer diameter of the capillary fiber. (b) Light ray schematic of the propagating wave along the core. White arrows represent refracted light through the capillary wall.

\[
\theta_1 = \sin^{-1}\left(\frac{n_{eff}}{n_1}\right) \quad (4.2)
\]

\[
n_{eff} = 1 - \frac{1}{2} \left(\frac{\mu \nu \lambda}{\pi D_{in}}\right)^2 \quad (4.3)
\]

The optical power transmitted through the capillary can be estimated from the determination of the incidence angle \( \theta_1 \), as expressed in Eq. (4.4), where \( P_{in} \) is the power of the light launched in the capillary hollow core and \( P_{out} \) is the transmitted power after propagating a distance \( L \) along the capillary, \( d \) is the capillary wall thickness, \( a \) is the hollow core diameter, and \( \Gamma \) is the Fresnel reflection coefficient – Eq. (4.5), written for a TE polarized wave [4.4]. The demonstration for Eq. (4.4) is provided in Appendix E.

\[
P_{out} = P_{in} \exp\left\{ \left(\frac{L}{\tan \theta_1}\right) \ln\left[ 1 - \frac{(1-\Gamma^2)^2}{(1-\Gamma^2)^2 + 4\Gamma^2 \sin^2 \left(\frac{2\pi n_2 d}{L} \sqrt{1 - \left(\frac{n_1}{n_2}\right)^2 \sin^2 \theta_1}\right)}\right] \right\} \quad (4.4)
\]

\[
\Gamma = \frac{\sqrt{1-\sin^2 \theta_1 - \frac{n_2}{n_1}} \left(1-\frac{n_1}{n_2}\right)^2 \sin^2 \theta_1}{
\sqrt{1-\sin^2 \theta_1 + \frac{n_2}{n_1}} \left(1-\frac{n_1}{n_2}\right)^2 \sin^2 \theta_1}
\quad (4.5)
\]

Figure 4.2a presents the simulated transmission spectrum for a 2 cm long PMMA capillary fiber with \( D_{in} = 160 \mu m \) and \( D_{out} = 240 \mu m \), where the characteristic spectrum
of a antiresonant reflecting waveguide can be checked. In Figure 4.2b, it is showed the transmission spectrum between 1558.5 nm and 1562 nm for better visualization of the 56th order transmission minimum – \( m = 56 \) in Eq. (1.7). For this minimum, one calculates, by Eq. (4.2) and Eq. (4.3), \( n_{\text{eff}} = 0.99997 \) and \( \theta_1 = 89.6^\circ \). In the simulations, PMMA dispersion was taken into account by using the Sellmeier coefficients reported in [4.8].

![Figure 4.2](image)

**Figure 4.2.** (a) Simulated transmission spectrum for a capillary with inner diameter 160 \( \mu \)m, outer diameter 240 \( \mu \)m and length 2 cm. (b) Transmission spectrum between 1558.5 nm and 1562 nm for better visualization of the 56th order minimum (\( n_{\text{eff}} = 0.99997 \) and \( \theta_1 = 89.6^\circ \)).

### 4.2 Temperature sensing with PMMA antiresonant capillary fibers

As mentioned, we can expect from Eq. (1.7), \( \lambda_{\text{min}} = \frac{2 n_1 d}{m} \sqrt{\left(\frac{n_2}{n_1}\right)^2 - 1} \), spectral shifting on the minima positions if the capillary wall thickness or refractive index are varied. As temperature variations induce changes in both these parameters, capillary fibers show itself as an interesting platform for the realization of temperature sensing measurements.

To investigate the capillaries transmission spectrum dependence on temperature variations, we evaluated thermal expansion and thermo-optic effect influences separately and the resulting effect when they act together. It was performed by including, in Eq. (4.4), the capillary wall thickness variation due to thermal expansion (\( \Delta d = d \alpha \Delta T \); \( d \): capillary wall thickness; \( \alpha \): PMMA thermal expansion coefficient, \( 5.5 \times 10^{-5}^\circ \text{C}^{-1} \) [4.9]; \( \Delta T \): temperature variation) and the refractive index change due to thermo-optic effect (assuming the PMMA thermo-optic coefficient as \( -1.3 \times 10^{-4}^\circ \text{C}^{-1} \) [4.9]).
In Figure 4.3a, it is presented the behavior of the spectral transmission minimum of a 2 cm long PMMA capillary fiber with $D_{in} = 160$ µm and $D_{out} = 240$ µm, when only thermal expansion is considered. It can be observed that the spectral position of the minimum redshifts as the temperature is increased. In contrast, Figure 4.3b exposes the shifting of the same minimum when only the thermo-optic effect is considered – thermal expansion neglected. In this situation, there is a blueshift of the minimum spectral position for increasing values of temperature.

Figure 4.3. Capillary transmission spectra when considering (a) thermal expansion only, (b) thermo-optic effect only and (c) both thermal expansion and thermo-optic effect ($D_{in} = 160$ µm; $D_{out} = 240$ µm; $L = 2$ cm). (d) Wavelength shift as a function of the temperature variation.

Additionally, in Figure 4.3c, one shows the situation in which both thermal expansion and thermo-optic effect were considered. In this context, blueshift of the minimum spectral position is verified. It allows concluding that the thermo-optic effect has a greater contribution on the minimum shifting than thermal expansion – which is due to the high PMMA thermo-optic coefficient, approximately 15 times higher than silica’s one [4.9].
Furthermore, in Figure 4.3d, a plot of the minimum wavelength shift as a function of the temperature variation is presented. Here, we show the wavelength shift when only the thermal expansion is considered (red line), when only the thermo-optic effect is considered (blue line) and when both the effects are taken into account (purple line). By Figure 4.3d, one can predict the temperature sensitivity to be -141.8 pm/°C.

To accomplish an experimental realization of the configuration studied herein, we assembled an experimental setup as depicted in Figure 4.4a. A broadband light source (BLS) is coupled to a multimode fiber (MMF) which launches the optical signal into the capillary fiber hollow core. A second multimode fiber section is placed at the end of the capillary fiber for collecting the light transmitted through the capillary. The power of the transmitted signal is measured in an optical spectrum analyzer (OSA). The capillary fibers used in this investigation have $D_{in} = 160 \mu m$ and $D_{out} = 240 \mu m$ (cross-section in Figure 4.4b) and were produced by Mr. Thiago H. R. Marques in the polymer optical fiber tower facility available in our laboratory (Laboratório de Fibras Especiais – LaFE).

![Figure 4.4. (a) Experimental setup schematic. BLS: broadband light source; MMF: multimode fiber; OSA: optical spectrum analyzer. (b) Capillary fiber cross section.](image)

The transmitted power spectrum for a 13 cm long PMMA capillary fiber is presented in Figure 4.5a, where the transmission dips can be noted. In Figure 4.5b, we present the experimental (red line) and the analytically simulated (blue line) transmission spectra in the range between 1500 nm and 1600 nm. It is seen that, in the simulations, the minima widths are much thinner than that in the experimental spectrum. We believe the
difference in the widths should be due to the multimode characteristics of the capillary fiber hollow core – not considered in the analytical model –, and, as the launching of light in the capillary is made by using a multimode fiber, the excitation of multiple modes can be favored. Additionally, the analytical model does not consider possible geometrical imperfections in the capillary fiber (ellipticity and capillary wall thickness variations, for example). Further studies are, therefore, necessary to confirm these hypotheses.

Figure 4.5. (a) Experimental transmission spectrum for a 13 cm long capillary fiber with $D_{in} = 160$ µm and $D_{out} = 240$ µm. (b) Experimental (red line) and analytically simulated (blue line) transmission spectra between 1500 nm and 1600 nm. (c) Wavelength shift as a function of the temperature variation.

To obtain the temperature sensitivity value, we placed the capillary fiber on a hotplate and the temperature was controllably varied while the spectral response was monitored and the dips shifting was accounted. Figure 4.5c presents the wavelength shift as a function of the temperature variation. By fitting a linear function to the experimental points, we obtained a temperature sensitivity of (140 ± 6) pm/°C. This result is in good proximity to the one expected from the analytical simulations (141.8 pm/°C, as shown in Figure 4.3d) and is around 14 times higher than typical Bragg gratings-based temperature sensors [4.10].
Therefore, it is possible to identify the antiresonant capillary fibers as interesting platforms for the realization of temperature sensing measurements. This research was presented at the 25th International Conference on Optical Fiber Sensors [4.11].

4.3 Pressure sensing with PMMA antiresonant capillary fibers

Another possibility of the use of antiresonant capillary fibers in sensing the employment of this sort of fibers in pressure measurements. This possibility arises from the fact that, as described in Chapter 2, the application of pressure induces displacements in the capillary fiber which are dependent on the radial position – Eq. (2.2). As capillary wall thickness variations entail shifting in antiresonance characteristic spectrum, sensing measurements can be performed.

4.3.1 Pressure-induced capillary wall thickness variations

Consider that a capillary has an initial wall thickness $d = r_{\text{out}} - r_{\text{in}}$, where $r_{\text{in}}$ and $r_{\text{out}}$ are the inner and outer radii respectively. When pressure is applied, the capillary wall thickness will vary and assume a new value $d'$, which can be obtained by Eq. (4.5), where $u(r_{\text{in}})$ and $u(r_{\text{out}})$ are the displacements at the inner and outer radius positions. By calculating $u(r_{\text{in}})$ and $u(r_{\text{out}})$ using Eq. (2.2), one obtains Eq. (4.6), which expresses the new capillary wall thickness as a function of the inner and outer radius ($r_{\text{in}}$ and $r_{\text{out}}$), internal and external pressure levels ($p_{\text{in}}$ and $p_{\text{out}}$), the capillary material Young modulus ($E$) and Poisson ratio ($\nu$).

$$d' = [r_{\text{out}} + u(r_{\text{out}})] - [r_{\text{in}} + u(r_{\text{in}})] = d + u(r_{\text{out}}) - u(r_{\text{in}})$$  \hspace{1cm} (4.5)

$$d' = d + \frac{r_{\text{out}}}{E(1+\nu)} \left\{ (1-\nu) \left[ p_{\text{in}} \left( \frac{r_{\text{in}}}{r_{\text{out}}} \right)^2 - p_{\text{out}} \right] + (1+\nu)(p_{\text{out}} - p_{\text{in}}) \left( \frac{r_{\text{in}}}{r_{\text{out}}} \right) \right\}$$  \hspace{1cm} (4.6)

If we assume that the capillary thickness change is exclusively due to external pressure variations, Eq. (4.7) can be obtained for expressing the thickness derivative with respect to the external pressure, $\frac{\partial d'}{\partial p_{\text{out}}}$. By observing Eq. (4.7), it can be noted that $\frac{\partial d'}{\partial p_{\text{out}}}$ sign is dependent on $\frac{r_{\text{in}}}{r_{\text{out}}}$ values. For $\frac{r_{\text{in}}}{r_{\text{out}}} < \frac{1-\nu}{1+\nu}$, the value of $\frac{\partial d'}{\partial p_{\text{out}}}$ is negative and the
model predicts that the capillary wall will be thinner when pressure is applied to the fiber. Alternatively, if \( \frac{r_{in}}{r_{out}} > \frac{1-v}{1+v} \), the value of \( \frac{\partial d'}{\partial p_{out}} \) will be positive, what means that the capillary wall thickness will increase due to pressure application. It is worth underlining that if \( \frac{r_{in}}{r_{out}} = \frac{1-v}{1+v} \), one will have \( \frac{\partial d'}{\partial p_{out}} = 0 \) and, therefore, no thickness variation will be expected. Figure 4.6a shows a schematic representation of \( \frac{\partial d'}{\partial p_{out}} \) sign as a function of the ratio between the inner and the outer radii.

\[
\frac{\partial d'}{\partial p_{out}} = \frac{r_{out}(1+v)}{E(1+\frac{r_{in}}{r_{out}})} \left[ \frac{r_{in}}{r_{out}} - \frac{(1-v)}{(1+v)} \right] 
\]

(4.7)

Figure 4.6. (a) Schematic representation of \( \frac{\partial d'}{\partial p_{out}} \) sign as a function of \( \frac{r_{in}}{r_{out}} \). (b) \( \frac{\partial d'}{\partial p_{out}} \) as a function of \( \frac{r_{in}}{r_{out}} \) for PMMA capillaries with different external radius values.

Moreover, by Eq. (4.7), it is seen that materials with lower Young modulus should present increased \( \frac{\partial d'}{\partial p_{out}} \) values. Therefore, in the investigation reported herein, one focused our study on PMMA capillaries instead of silica ones (PMMA Young modulus: 3 GPa [4.12]; silica Young modulus: 72.5 GPa [4.13]).

Figure 4.6b presents the behavior of \( \frac{\partial d'}{\partial p_{out}} \) values as a function of \( \frac{r_{in}}{r_{out}} \) for PMMA capillaries with different external radius (PMMA Poisson ratio: 0.345 [4.12]). As expected, capillaries with greater external radii have, in modulus, higher \( \frac{\partial d'}{\partial p_{out}} \) values. Additionally, it is seen in Figure 4.6b that depending on the \( \frac{r_{in}}{r_{out}} \) ratio value, the capillary
wall thickness can either increase or decrease when external pressure is applied to the same. Furthermore, for PMMA capillaries, one can observe that if \( \frac{r_{in}}{r_{out}} = 0.487 \), no thickness variation is predicted.

### 4.3.2 Pressure sensitivity and measurements

As it will be discussed in the following, the pressure sensing measurement was performed by following the spectral transmission minima positions as a function of the pressure variation. Therefore, to account the pressure sensitivity we have taken the total derivative of Eq. (1.7), \( \lambda_{min} = \frac{2n_1d}{m} \sqrt{\left(\frac{n_2}{n_1}\right)^2 - 1} \), with respect to the external pressure, \( i.e., \frac{d\lambda_{min}}{dp_{out}} \). As both the capillary wall thickness, \( d = r_{out} - r_{in} \), and the refractive index of the capillary, \( n_2 \), vary if the pressure is changed, \( \frac{d\lambda_{min}}{dp_{out}} \) should be written an in Eq. (4.8). By using Eq. (4.7) and performing the derivatives in Eq. (4.8), one obtains Eq. (4.9). It is worth noting that \( \frac{dn_2}{dp_{out}} \) is the elasto-optic coefficient of the material the capillary is made of. For PMMA, \( \frac{dn_2}{dp_{out}} = -4.49 \times 10^{-11} \text{ Pa}^{-1} \). [4.12]

\[
\frac{d\lambda_{min}}{dp_{out}} = \left( \frac{\partial \lambda_{min}}{\partial d} \right) \frac{d(d)}{dp_{out}} + \left( \frac{\partial \lambda_{min}}{\partial n_2} \right) \frac{dn_2}{dp_{out}} \tag{4.8}
\]

\[
\frac{d\lambda_{min}}{dp_{out}} = \frac{2n_1r_{out}}{m} \sqrt{\left(\frac{n_2}{n_1}\right)^2 - 1} \left\{ \frac{(1+\nu)}{\nu} \left( \frac{r_{in}}{r_{out}} \right) - \left( \frac{1-\nu}{1+\nu} \right) \right\} + \frac{n_2}{(n_2^2-n_1^2)} \left( 1 - \frac{r_{in}}{r_{out}} \right) \frac{dn_2}{dp_{out}} \tag{4.9}
\]

Figure 4.7 presents the results for the pressure sensitivity, \( \frac{d\lambda_{min}}{dp_{out}} \), as a function of the ratio between the inner and outer radii, \( \frac{r_{in}}{r_{out}} \), for different external radius values. By analyzing the graph shown, we can recognize a similar behavior as that observed in Figure 4.6 – sensitivity values can assume both negative and positive values depending on \( \frac{r_{in}}{r_{out}} \). The situation of zero pressure sensitivity, however, is predicted to occur at \( \frac{r_{in}}{r_{out}} = 0.58 \). It is different from the point at which \( \frac{\partial d'}{dp_{out}} \) is zero – \( \frac{r_{in}}{r_{out}} = 0.478 \), see Figure 4.6. It happens due to the consideration of the photoelastic effect in Eq. (4.8),
which add its contribution to the pressure sensitivity and shifts the point of zero sensitivity.

Figure 4.7. Analytically calculated pressure sensitivity as a function of \( \frac{r_{\text{in}}}{r_{\text{out}}} \) for capillary fibers with different external radii.

As an experimental realization of the proposed sensor, we have tested a PMMA capillary with inner radius 125 µm and outer radius 175 µm. To subject the capillary to pressure variations, the capillary fiber was inserted into a gas pressure chamber connected to a nitrogen tank. A valve was used to control the amount of gas inside the chamber and, therefore, the pressure to which the capillary fiber was subjected. A super-luminescent light emitting diode (SLED) was used as the light source and the transmitted signal was measured by an optical spectrum analyzer (OSA) – Figure 4.8. To avoid the nitrogen to enter the capillary hollow part, we have closed its ends using glue.

Figure 4.8. Experimental setup for the realization of the pressure sensing experiment.

Figure 4.9a shows the capillary spectral response as a function of the external pressure level. It is seen that the transmission dips redshift as the external pressure is increased. This behavior, \( i.e. \) a positive pressure sensitivity, agrees to what would be
expected from the simulation results shown in Figure 4.7. Additionally, in Figure 4.9b, it is shown the average wavelength shift (considering all transmission dips shown in the Figure 4.9a plot) as a function of the external pressure. Data from this plot allows calculating a pressure sensitivity of $(18.3 \pm 0.4)$ pm/bar. This result is approximately 50% higher than the expected one (12 pm/bar), as can be observed in the simulated plot presented in Figure 4.9c. Further studies on this topic needs to be performed to better understand the difference between the predicted and experimental sensitivity values. We believe it may be related to the alteration of PMMA mechanical properties when pressurized [4.14]. Additionally, during the realization of the experiments, we have noted an important hysteresis behavior – i.e. a different behavior when raising or decreasing the pressure levels – in the sensor response, which should also be addressed in further studies.

The results of this research were presented at the III International Conference on Applications of Optics and Photonics [4.15].

Figure 4.9. (a) Experimental transmission spectrum for a capillary with $r_{in} = 125$ µm and $r_{out} = 175$ µm at different pressurization conditions. (b) Wavelength shift as a function of the external pressure. (c) Analytically calculated pressure sensitivity as a function of $\frac{r_{in}}{r_{out}}$ for a capillary fiber with $r_{out} = 175$ µm.
Chapter 5

Additional sensing opportunities using specialty optical fibers

In this chapter, we present additional opportunities in sensing that were also studied during the graduation period. Namely, research on the application of photonic-crystal fibers (PCFs) in pressure probing measurements and on the employment of Bragg gratings in standard and tapered fibers and multimode interference setups for refractive index, strain and temperature monitoring were developed. Moreover, metal-filled embedded-core fibers were explored as temperature sensors.

Regarding the research on photonic-crystal fibers, a dual-environment pressure sensing application was studied. To do this, two sections of a side-hole birefringent photonic-crystal fiber were spliced together in an in-series configuration and the response of each section was individually evaluated by using a technique we developed some years ago [5.1]. Making use of the side-hole PCF pressure sensitivity, we could monitor pressure variations in two disconnected environments.

Concerning the use of Bragg gratings in standard and tapered fibers and of multimode interference devices, we studied a three-parameters sensor and an intensity-based liquid-level sensor. In the first application, a Bragg grating inscribed in a standard fiber, a Bragg grating inscribed in a tapered fiber and a singlemode-multimode-singlemode (SMS) structure were concatenated and temperature, strain and external refractive index variations were probed. In the second investigation, a SMS structure followed by a Bragg grating is used to probe liquid level variations. Here, the SMS structure optical response acts as a filter for the Bragg grating reflected power. The study of the power variation as the system was immersed in water allowed the characterization of the sensor.

Finally, we report the embedded-core fiber acting as a temperature sensor when it is filled with metal. In this application, we make use of the fact that the embedded-core central region is hollow and that metal can be inserted in it. The resulting structure
becomes highly sensitive to temperature variations since the metal expansion inside the fiber induces stresses within the silica region and alters the core birefringence.

5.1 Dual-environment pressure sensing with a photonic-crystal fiber

Due to the photonic-crystal fibers’ design versatility, this sort of fibers can be visualized as an excellent platform for building up sensors. By conveniently choosing fiber’s microstructure, fiber properties can be optimized so it can be employed in sensing measurements of a parameter of interest. Thus, photonic-crystal fibers have shown its potential to allow monitoring measurements of a great variety of physical parameters such as hydrostatic pressure [5.2], strain [5.3] and curvature [5.4].

Photonic-crystal fiber structure can be designed so its optical properties are sensitive to pressure variations. In general, photoelastic effect is explored by adequately planning PCF microstructure geometry characteristics. A usual approach consists of using birefringent photonic-crystal fibers with microstructure designs which can provide an asymmetric stress distribution within the fiber core when the fiber is put under pressure. It causes fiber birefringence to alter and allows the realization of pressure sensing measurements. [5.5, 5.6]

Here, we explored the pressure sensitivity of a side-hole photonic-crystal fiber (SH-PCF), which is characterized by the existence of longitudinal large holes placed next to the fiber microstructure, and employed it to probe hydrostatic pressure variations in two disconnected environments. To obtain the sensor, we employed a simple technique, developed by us, which allows accessing the individual responses of two birefringent fibers set in an in-series configuration. In this technique, we use an input and an output polarizer with orientations chosen so the first and second fiber’s responses can be independently measured [5.1]. By taking into account the fibers’ optical responses as a function of the applied pressure, we could demonstrate the operation of a photonic-crystal fiber-based sensor for dual-environment monitoring.

5.1.1 Fiber characterization

As mentioned above, we have chosen a side hole photonic-crystal fiber to attain hydrostatic pressure measurements in two separate environments. The cross-section of
the side-hole PCF is presented in Figure 5.1 – inset shows a zoom in the microstructured region. Hole diameter \( d = 1.7 \, \mu m \) and their separation distance \( \Lambda = 2.8 \, \mu m \) are also represented in Figure 5.1.

![Figure 5.1](image)

**Figure 5.1.** (a) SH-PCF cross-section. Inset provides a zoom in the microstructured region. Hole diameter, \( d = 1.7 \, \mu m \), and separation, \( \Lambda = 2.8 \, \mu m \) are represented. (b) Experimental setup diagram for fiber characterization. SC: supercontinuum from a photonic-crystal fiber; \( P_1 \) and \( P_2 \): polarizers; SMF: standard single mode fiber; SH-PCF: side-hole photonic-crystal fiber; OSA: optical spectrum analyzer.

To experimentally characterize the fiber, a setup as depicted in Figure 5.1b was assembled. The side-hole photonic-crystal fiber was initially spliced to standard single mode fibers and put into a pressure chamber. Light from a broadband light source (supercontinuum from a photonic-crystal fiber – SC) passes through a first polarizer (\( P_1 \)) and is launched into the birefringent SH-PCF so both orthogonal modes are excited. Second polarizer (\( P_2 \)) allows the light from the orthogonal modes to recombine and interfere. The optical response is measured by an optical spectrum analyzer (OSA). A typical spectrum is presented in Figure 5.2a. It worth observing that the curvatures in the standard fiber sections were minimal to avoid the polarization state degradation of the light to be launched in the side-hole photonic-crystal fiber.

Fiber group birefringence \((G)\) can be measured from Figure 5.2a spectrum by making \( G = \frac{\lambda^2}{S} \), where \( \lambda \) is the wavelength, \( S \) is the spectral distance between two
consecutive dips in the spectrum and $L$ is the fiber length \([5.6]\). Phase birefringence ($B$), in turn, can be calculated by Eq. (5.1), where $\gamma$ is a fitting parameter accounted for by the empirical relation shown in Eq. (5.2) and whose value is found by carrying on a self-consistency method ($A$ is also a fitting constant) \([5.7]\). Black dots in Figure 5.2b and Figure 5.2c show the experimental results for group and phase birefringence as a function of wavelength.

$$
B = \frac{\lambda}{2L} \left[ \left( 1 + \frac{S}{\lambda} \right)^{-1} - 1 \right]^{-1}
$$

(5.1)

$$
B = A\lambda^\gamma
$$

(5.2)

![Figure 5.2](image)

**Figure 5.2.** (a) Typical SH-PCF transmission spectrum. (b) Group birefringence, (c) phase birefringence and (d) sensitivity coefficient $C_S$ experimental and simulated results as a function of wavelength.

As referenced in Chapter 2, pressure sensitivity in polarimetric measurements can be accounted by a sensitivity coefficient $C_S \equiv \frac{\Delta\lambda}{\Delta P} = \frac{\lambda}{\gamma} \frac{\partial B}{\partial P}$ – Eq. (2.1) in Chapter 2. Thus, by measuring the SH-PCF spectra as a function of the applied pressure (using the configuration schematically represented in Figure 5.1b) and following the resulting wavelength shift of a spectral dip, experimental $C_S$ values as a function of the wavelength
could be determined. These results are shown as black dots in Figure 5.2d. Additionally, theoretical values for $B$, $G$ and $C_S$ were calculated by using a commercial finite-element method-based software (COMSOL®). Red lines in Figure 5.2b, Figure 5.2c and Figure 5.2d show the simulated data for $B$, $G$ and $C_S$ as a function of the wavelength.

Moreover, the blue line in Figure 5.2d shows simulated $C_S$ values for a commercial photonic-crystal fiber usually tested in pressure monitoring experiments (PM-1550-01 by NKT Photonics). It is seen that the side-hole fiber studied herein has higher sensitivity coefficients than the commercial PCF. For example, at $\lambda = 1550$ nm, SH-PCF’s sensitivity coefficient is about 2.8-fold the one found for the commercial PCF. Besides, we have calculated the $C_S$ value for the fiber reported in [5.7] and found it is 1.34 times the value we measured for our SH-PCF. In addition, in [5.8], a very high sensitivity value was measured – 17.7 nm/bar.

### 5.1.2 Dual-environment hydrostatic pressure measurements

After performing the characterization of the side-hole photonic-crystal fiber, we have employed it to obtain a sensor able to monitor pressure variations in two disconnected environments. To achieve this goal, we used a technique, recently reported by us [5.1], where two birefringent fibers are set in an in-series configuration so their principal axes are rotated in relation to each other. In experimental setup (Figure 5.3), the optical response is obtained by using a broadband light source (supercontinuum from a photonic-crystal fiber), an input and an output polarizer ($P_1$ and $P_2$) and an optical spectrum analyzer.

![Figure 5.3. Experimental setup schematic diagram for dual environment pressure monitoring. $L_1$ and $L_2$: fiber lengths; $L_{P1}$ and $L_{P2}$: pressurized fiber lengths.](image)

Although the fibers are spliced, we can obtain individual fiber responses by adequately tuning polarizer’s angles. As it is described in [5.1], in order to obtain the first
fiber response, the second polarizer must be adjusted so its orientation coincides to one of the principal axes of the second fiber. Analogously, for obtaining the optical response of the second fiber, light must be launched in the first fiber with a polarization orientation along one of its principal axes.

To provide an experimental realization regarding the use of the proposed configuration for the dual-environment pressure probing, two sections of the side-hole PCF – with lengths \( L_1 = (22.5 \pm 0.2) \) cm and \( L_2 = (58.5 \pm 0.2) \) cm – were spliced and placed into pressure chambers as can be observed in Figure 5.3. Initially, the first fiber response was obtained (Figure 5.4a) and the wavelength shift of the interferometric fringes were accounted while the fiber was subjected to pressure variations. In sequence, the second fiber response was obtained (Figure 5.4b) and, again, the interferometric fringes spectral positions were followed as a function of the applied pressure.

Figure 5.4c presents the wavelength shift of a particular dip as a function of the pressure for the first and second fiber pressure probing experiments. Sensitivities coefficients, \( C_S \), were measured as \( C_{S1} = (0.169 \pm 0.004) \) nm/bar for the first fiber and \( C_{S2} = (0.222 \pm 0.004) \) nm/bar for the second fiber. The difference in the measured
sensitivity values are due to the fact that, in the pressure sensing experiments, different lengths of the fibers were pressurized – for the first fiber, the pressurized length was $L_{P1} = (2.0 \pm 0.1) \text{ cm}$ and, for the second fiber, the pressurized length was $L_{P2} = (8.0 \pm 0.1) \text{ cm}$.

In [5.1], we demonstrated that the ratio between the measured sensitivities, $R$, could be obtained by Eq. (5.3). According to this equation, the predicted value for the ratio between the sensitivities (taking into account the total fiber lengths and the pressurized fiber lengths) is calculated to be $R_{predicted} = (0.65 \pm 0.08)$. By using the experimentally measured sensitivities, we calculate $R_{experimental} = (0.76 \pm 0.03)$. Therefore, we can analyze that the predicted and experimental values for $R$ are consistent and that the operation of a dual-environment pressure sensor based on a side-hole photonic-crystal fiber was demonstrated.

$$ R \equiv \frac{C_{S1}}{C_{S2}} = \frac{L_{P1} L_2}{L_{P2} L_1} \quad (5.3) $$

The results from this research were published in [5.9] and were obtained in collaboration with Mr. Juliano G. Hayashi (who performed the fiber characterization experiments) and Mr. Yovanny A. V. Espinel (who contributed with the simulations). My contributions involved the realization of the splicing between standard and photonic-crystal fibers, assembly of the pressure chamber, the performance of the dual-environment pressure sensing experiments and data analysis.

5.2 Three-parameter sensor based on Bragg gratings, multimode interference and fiber tapers

In addition to the research on the photonic-crystal fiber-based pressure sensor, a configuration for three parameter sensing were also investigated. The configuration comprehends a fiber Bragg grating inscribed in a standard fiber, a Bragg grating on a tapered fiber and a SMS structure (formed by a no-core fiber – i.e. a simple silica rod – spliced in between two standard optical fibers) set in an in-series setup. By accounting the spectral responses of each part of the sensor, one could, simultaneously, discriminate temperature, strain and refractive index variations.
5.2.1 Experimental setup and principle of operation

In order to simultaneously measure temperature, strain and refractive index variations, one have used two fiber Bragg gratings – one in a standard fiber and other in a tapered one – and a SMS structure as it is schematically represented in Figure 5.5. To obtain the setup, a standard single-mode fiber was tapered down by using the flame brushing technique, as already described in this thesis. The resulting fiber taper was endowed with two transition regions and a uniform waist 50 µm thick and 10 mm long. The taper diameter was chosen so it could provide the desired optical/mechanical response – as will be detailed in the following – and the adequate robustness level for resisting manipulation during grating inscription and sensing measurements.

![Figure 5.5. Schematic diagram for the three-parameter sensor. FBG1 and FBG2 are, respectively, the Bragg gratings in the standard fiber and in the tapered fiber. NCF: no-core fiber.](image)

To imprint the gratings, we have employed an UV laser at 266 nm together with a phase mask, whose period was chosen in such a manner it could induce Bragg gratings in the infrared spectral region with suitable separation between them. It allowed to easily recognize the individual optical responses for sensing data acquisition.

The SMS structure, in turn, was built by using a no-core fiber (NCF), which consists of a simple silica rod with 125 µm diameter, spliced in between two standard single mode fibers. As explained in Chapter 1, multimode interference takes place in the no-core fiber and self-images of the input field are observed at a specific wavelength ($\lambda_{SMS}$) for a certain multimode fiber length ($L_{MMF}$). The relation between $\lambda_{SMS}$
and $L_{MMF}$ was expressed in Eq. (1.5): \( \lambda_{SMS} = \frac{4n_{MMF}D_{MMF}^2}{L_{MMF}} \), where $n_{MMF}$ and $D_{MMF}$ are respectively the effective refractive index and the diameter of the fundamental mode in the multimode fiber. As described in Chapter 1, the optical response of the SMS structure is characterized by a transmission peak at $\lambda_{SMS}$.

When the refractive index of the medium that surrounds the configuration is altered by an amount $\Delta n$ or the fiber is subjected to temperature or strain conditions variations ($\Delta T$ and $\Delta \varepsilon$, respectively), the spectral responses of each part of the sensor will experience wavelength shifts at their characteristic peaks with different sensitivities. It allows obtaining a 3×3 linear system – as shown in Eq. (5.4) – for associating the wavelength shifts to the external parameters variations. In Eq. (5.4), $\Delta \lambda_{FG1}$ and $\Delta \lambda_{FG2}$ represents for the wavelength shifts of the Bragg peaks from the FBGs in the untapered and tapered fiber and $\Delta \lambda_{MMI}$ is the wavelength shift of the MMI transmission spectrum. $K_\varepsilon$, $K_T$ and $K_n$ are the strain, temperature and refractive index sensitivity coefficients respectively. Subscripts FBG1, FBG2 and MMI reference, respectively, the FBG in the untapered fiber, in the tapered fiber and for the SMS structure contributions. If the sensitivity coefficients matrix is known, strain, temperature and external refractive index variations can be independently calculated by simply solving the linear system in Eq. (5.4).

\[
\begin{pmatrix}
\Delta \lambda_{FBG1} \\
\Delta \lambda_{FBG2} \\
\Delta \lambda_{MMI}
\end{pmatrix} =
\begin{pmatrix}
K_{\varepsilon,FBG1} & K_{T,FBG1} & K_{n,FBG1} \\
K_{\varepsilon,FBG2} & K_{T,FBG2} & K_{n,FBG2} \\
K_{\varepsilon,MMI} & K_{T,MMI} & K_{n,MMI}
\end{pmatrix}
\begin{pmatrix}
\Delta \varepsilon \\
\Delta T \\
\Delta n
\end{pmatrix} \tag{5.4}
\]

### 5.2.2 Simultaneous measurement of strain, temperature and external refractive index variations

In order to experimentally characterize the sensor’s response, the sensitivities coefficients $K_\varepsilon$, $K_T$ and $K_n$ were individually measured by varying a specific parameter (strain, temperature or external refractive index) while the other two were maintained constant. To obtain $K_\varepsilon$ values, the sensor was subjected to strain increments (at fixed temperature and refractive index) and the FBGs’ and MMI’s peaks wavelength shifts were accounted. Figure 5.6a and Figure 5.6b show the spectral response for the FBG in
the untapered (FBG1) and in the tapered fiber (FBG2) and for the SMS structure when the sensor was subjected to different strain levels. Figure 5.6c shows the wavelength shift as a function of the strain and the measured sensitivity values ($K_{\varepsilon, FBG1} = 0.91$ pm/µε, $K_{\varepsilon, FBG2} = 5.88$ pm/µε, $K_{\varepsilon, MMI} = -1.37$ pm/µε).

![Figure 5.6](image)

**Figure 5.6.** Spectral responses of the (a) FBGs and (b) SMS structures as a function of the applied strain. (c) Wavelength shift as a function of the applied strain.

The different strain sensitivities measured for the FBG in the untapered and in the tapered fiber are due to the fact that, when longitudinal force is applied to the fiber, the stress (force over area) is different for the untapered and for the tapered fiber. The strain on the untapered fiber, $\varepsilon_{fiber}$, the strain on the tapered fiber, $\varepsilon_{taper}$, and the correspondent cross-sectional areas ($A_{fiber}$ for the untapered fiber and $A_{taper}$ for the tapered fiber) can be related by Eq. (5.5). The results found in the measurements are in good agreement with the relation expressed in Eq. (5.5) since $\varepsilon_{fiber}/\varepsilon_{taper} \sim 0.15$ and $A_{taper}/A_{fiber} \sim 0.16$. [5.10]

$$\frac{\varepsilon_{fiber}}{\varepsilon_{taper}} = \frac{A_{taper}}{A_{fiber}}$$  \hspace{1cm} (5.5)
To characterize the system’s sensitivity to external refractive index variations, the sensor was immersed in isopropanol-water solutions at different concentrations, while the strain level and the temperature were maintained constant. Again, the spectral shifting in Bragg gratings’ and SMS structure’s responses were accounted as the external refractive index was varied. Figure 5.7a and Figure 5.7b show the spectral data (reflected and transmitted spectra respectively) for different external refractive indexes. Figure 5.7c presents the peak wavelength shift as a function of the external refractive index for the three parts of the sensor. The refractive index of the isopropanol-water solutions were measured by using a commercial refractometer.

**Figure 5.7.** Spectral responses of the (a) FBGs and (b) SMS structure as a function of the external refractive index. (c) Wavelength shift as a function of the external refractive index.

By observing the data exposed in Figure 5.7c, we can observe that the refractive index sensitivity for the Bragg gratings in both untapered and tapered fiber is virtually zero ($K_{n,FBG1} = K_{n,FBG2} = 0$). It was expected since the fundamental mode in the untapered and 50 µm thick tapered fiber is strongly confined to the fiber core and, because of this, its evanescent field does not effectively interact with the external medium. Alternatively, in the no-core fiber (NCF), the external medium acts as the fiber cladding and, therefore, the modes guided in the NCF have their characteristics strongly dependent on the
surrounding medium refractive index. Thus, a redshift was observed in the MMI peak position. It allowed estimating a $K_{n,\text{MMI}} = 98.646 \text{ nm/RIU}$ refractive index sensitivity.

In order to account for the sensor’s temperature response, the system was immersed in water and the solution was heated. Spectral responses were observed while the temperature was varied and the resulting spectra are shown in Figure 5.8a (for the Bragg gratings) and Figure 5.8b (for the SMS structure). Shifts in the FBGs spectra, shown in Figure 5.8c, are seen to be similar and the correspondent sensitivities coefficients were measured to be $K_{T,\text{FBG1}} = 9.2 \text{ pm/ºC}$ and $K_{T,\text{FBG2}} = 8.4 \text{ pm/ºC}$.

![Figure 5.8](image)

**Figure 5.8.** Spectral responses of the (a) FBGs and (b) SMS structure as a function of the temperature. (c) Wavelength shift as a function of the temperature.

Additionally, the shifts in the SMS structure’s spectrum allows estimating the sensitivity coefficient to be $-7.2 \text{ pm/ºC}$. However, as in the temperature characterization experiments the sensor was put under a water bath and the no-core fiber spectrum is dependent on the surrounding medium refractive index, it should be noted that this sensitivity value refers to both temperature and refractive index variations contributions. It happens because temperature changes cause the water refractive index to change due to thermo-optic effect. Therefore, the measured sensitivity coefficient must be corrected, since $K_T$ value should describe the sensitivity to temperature variations only.
As the maximum in the SMS structure transmission spectrum has its spectral position dependent on both temperature, \(T\), and surrounding medium refractive index, \(n_{\text{ext}}\), we should account its shift due to temperature variations as a total derivative \(-\frac{d\lambda_{\text{SMS}}}{dT}\) in Eq. (5.6). Note that \(\frac{d\lambda_{\text{SMS}}}{dT} \equiv K_{T,n,\text{MMI}}\) is the experimentally measured sensitivity, \(K_{T,n,\text{MMI}} = -7.2\) pm/°C.

\[
\frac{d\lambda_{\text{SMS}}}{dT} = \frac{\partial \lambda_{\text{SMS}}}{\partial T} + \frac{\partial \lambda_{\text{SMS}}}{\partial n_{\text{ext}}} \frac{dn_{\text{ext}}}{dT} \tag{5.6}
\]

The right-hand side first term in Eq. (5.6), \(\frac{\partial \lambda_{\text{SMS}}}{\partial T}\), represents the shift due to temperature variation only. Hence, it can be identified as the \(K_T\) coefficient for the SMS structure, \(i.e., \frac{\partial \lambda}{\partial T} = K_{T,\text{MMI}}\). Similarly, \(\frac{\partial \lambda_{\text{SMS}}}{\partial n_{\text{ext}}}\) is the wavelength shift due to external refractive index variations only and, therefore, can be identified as the \(K_{n,\text{MMI}}\) coefficient (98.646 nm/RIU). Additionally, \(\frac{dn_{\text{ext}}}{dT} \equiv \Theta_{\text{ext}}\) is the external medium’s thermo-optic coefficient (-2 × 10^{-4} °C⁻¹ for water) \([5.11]\).

Furthermore, Eq. (5.6) can be rewritten as shown in Eq. (5.7), to explicitly show how it is possible to obtain \(K_{T,\text{MMI}}\) value from the experimentally measured cross temperature-refractive index sensitivity \(K_{T,n,\text{MMI}}\), refractive index sensitivity \(K_{n,\text{MMI}}\) and surrounding medium’s thermo-optic coefficient \(\Theta_{\text{ext}}\). By using \(K_{T,n,\text{MMI}} = -7.2\) pm/°C, \(K_{n,\text{MMI}} = 98.646\) pm/RIU and \(\Theta_{\text{ext}} = -2 \times 10^{-4}\) °C⁻¹, one can calculate \(K_{T,\text{MMI}} = 12.5\) pm/°C.

\[
K_{T,\text{MMI}} = K_{T,n,\text{MMI}} - K_{n,\text{MMI}}\Theta_{\text{ext}} \tag{5.7}
\]

Finally, the obtained sensitivity values can be used to fulfill the sensitivity coefficients matrix in Eq. (5.4). It allows entailing Eq. (5.8), which allows obtaining strain, temperature and refractive index variations by simply solving a 3 × 3 linear system.

\[
\begin{pmatrix}
\Delta \lambda_{FBG1} \\
\Delta \lambda_{FBG2} \\
\Delta \lambda_{\text{MMI}}
\end{pmatrix} = 
\begin{pmatrix}
0.91\ \text{pm}/\mu\varepsilon & 9.2\ \text{pm}/°C & 0\ \text{pm}/\text{RIU} \\
5.88\ \text{pm}/\mu\varepsilon & 8.4\ \text{pm}/°C & 0\ \text{pm}/\text{RIU} \\
-1.37\ \text{pm}/\mu\varepsilon & 12.5\ \text{pm}/°C & 98.646\ \text{pm}/\text{RIU}
\end{pmatrix}
\begin{pmatrix}
\Delta \varepsilon \\
\Delta T \\
\Delta n
\end{pmatrix} \tag{5.8}
\]
Considering an optical spectrum analyzer with 10 pm wavelength resolution, the resolution limit for three-parameter sensor described herein can be calculated, using Eq. (5.8), to be 0.17 µε, 1.1 ºC and 3.2 × 10⁻⁵ RIU. In Table 5.1, the obtained resolutions are compared to three other fiber sensors which also allows to simultaneously measure temperature, strain and refractive index variations. It is seen the achieved resolution is improved when compared to the sensors reported by J. Mau et al. in [5.12] (Sensor 1) and by N. J. Alberto et al. in [5.13] (Sensor 2). Additionally, it can be observed that the resolution limit for the sensor reported herein compares well to the one reported by S-M Lee et al. in [5.14].

Table 5.1. Resolution limit comparison.

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<tbody>
<tr>
<td>Strain (µε)</td>
<td>0.17</td>
<td>7.71</td>
<td>140.77</td>
<td>1.96</td>
</tr>
<tr>
<td>Temperature (ºC)</td>
<td>1.1</td>
<td>4.02</td>
<td>15.38</td>
<td>0.69</td>
</tr>
<tr>
<td>Refractive index</td>
<td>3.2 × 10⁻⁵</td>
<td>2.5 × 10⁻²</td>
<td>5.9 × 10⁻³</td>
<td>9.0 × 10⁻⁴</td>
</tr>
</tbody>
</table>

Therefore, we could obtain a sensor which allows the realization of simultaneous and independent measurements of temperature, strain and refractive index variations. The system is very simple since its obtained by splicing the sensing parts all together. It makes this configuration a promising platform towards the development of multiparameter sensors.

The results from this research were published in [5.15] and were obtained in collaboration with Mr. Ricardo Oliveira and Mr. Stenio Aristilde (who performed the experimental characterization of the sensor). My contributions were the proposal of the sensor (together with Prof. Cristiano M. B. Cordeiro) and the performance of data and error analysis (together with Mr. Ricardo Oliveira).

### 5.3 Intensity-based liquid-level sensor using multimode interference and Bragg gratings

Another application we have approached was to obtain a liquid-level sensor based on multimode interference and Bragg gratings. Liquid-level monitoring is important in several fields such as fuel storage and chemical processing. Ultrasonic [5.16] and
capacitive sensors [5.17] are examples of technologies which can be employed to obtain liquid-level sensors. However, their high maintenance cost, susceptibility to electromagnetic interference and low resistance to harsh environments appear as disadvantages which can limit the application of such configurations. Hence, optical fiber-based sensors rise as a promising technology for transposing these limits by offering compact, robust and highly sensitive liquid-level sensors.

Several liquid-level optical fiber-based sensors have already been reported in literature. A very useful approach is to explore the interaction between the evanescent field of the optical mode guided through the optical fiber and the external medium. It was successfully done by employing long-period gratings [5.18], D-shaped fibers [5.19] and by using unclad multimode optical fibers [5.20]. However, the measurements usually demand a system for performing spectral measurements, which causes the detection system to be expensive.

In the investigation reported herein, one propose the combination of a SMS structure (a no-core fiber spliced in between two standard singlemode fibers) and a Bragg grating for measuring liquid level. As it will be explained in the following, the SMS’ characteristic spectrum acts as a filter over the FBG’s one. It allowed measuring the FBG’s reflected peak power as a function of the length of fiber immersed in liquid and characterizing an intensity-based liquid level sensor.

5.3.1 Experimental setup and principle of operation

Figure 5.9 shows a schematic for the experimental setup employed in the measurements. The sensor is composed by a SMS structure (no-core fiber, NCF, spliced in between two standard singlemode fibers) followed by a fiber Bragg grating (FBG1). To perform the liquid-level sensing experiments, the sensor was connected to a motorized stage which could immerse the sensor into the liquid at controlled steps. Moreover, a hot plate was used to maintain the system at constant temperature during the experiments and an additional Bragg grating (FBG0) is used for monitoring possible power fluctuations in the optical light source.
As discussed in the last section in this chapter, multimode interference happen in the no-core fiber and self-images of the input field are observed at a specific wavelength ($\lambda_{SMS}$) given by $\lambda_{SMS} = \frac{4 n_{MMF} D_{MMF}^2}{L_{MMF}}$, where $L_{MMF}$ is the multimode fiber length and $n_{MMF}$ and $D_{MMF}$ are respectively the effective refractive index and the diameter of the fundamental mode in the multimode fiber. The optical response of the SMS structure is manifested as a transmission peak at $\lambda_{SMS}$.

When the SMS structure is completely immersed in a liquid, both effective refractive index and the diameter of the fundamental mode in the multimode fiber are altered (since, in the no-core fiber, the optical mode interfaces the external medium and, therefore, its evanescent field strongly interacts with the surrounding medium). It entails a shift in SMS structure’s transmission peak.

In particular, if only a part of the no-core fiber is immersed in a liquid, the resulting spectral response will be a combination of the influences of emerged and submerged parts of the sensor. The spectral position of SMS structure’s transmission peak can be predicted by considering the different effective refractive indexes and diameters of the fundamental mode in air and in the liquid ($n_{MMF,\text{air}}, D_{MMF,\text{air}}, n_{MMF,\text{liq}}, D_{MMF,\text{liq}}$) and by pondering $\lambda_{SMS}$ expression by the emerged and submerged fiber lengths ($L_{MMF,\text{air}}$ and $L_{MMF,\text{liq}}$). The spectral position of the partially immersed SMS structure, $\lambda_{SMS}'$, can be calculated by Eq. (5.9). [5.20]

$$\lambda_{SMS}' = \frac{4 n_{MMF,\text{air}} D_{MMF,\text{air}}^2}{L_{MMF}} \left(\frac{L_{MMF,\text{air}}}{L_{MMF}}\right) + \frac{4 n_{MMF,\text{liq}} D_{MMF,\text{liq}}^2}{L_{MMF}} \left(\frac{L_{MMF,\text{liq}}}{L_{MMF}}\right)$$  (5.9)
Therefore, it is possible to probe liquid level variations by following the shift in SMS structure’s transmission peak. It was demonstrated by J. E. Antonio-Lopez et al. in [5.20] and [5.21] and by Y. Luo et al. in [5.22]. However, in these reports, expensive detection systems are needed for spectrally interrogating sensor response. Additionally, the broad width of SMS structure’s transmission peak can limit the use of these sensors in applications which demand sensors with optimized resolution levels.

Here, the MMI spectral response is used as a filter over a Bragg grating spectrum. The FBG has its peak centered at an adequate spectral position so shifting in the SMS structure spectral response entails power variation in the Bragg grating reflection peak as a function of the immersed fiber length. It allowed us to characterize an intensity-based liquid-level sensor which can provide opportunities for assembling less expensive systems for practical applications.

5.3.2 Sensing measurements

To define the Bragg grating central wavelength which would maximize power variations on Bragg peak due to liquid-level variations, we studied the optical response of the SMS structure as a function of the submerged no-core fiber length (Figure 5.10a). By subtracting the spectra in two extreme conditions (no-core fiber completely emerged and completely submerged) one obtain the plot shown in Figure 5.10b, which allows identifying that the greater power variation happen around 1556 nm. It is worth underlining that, in the reported experiments, the no-core fiber total length was 58.2 mm.

The Bragg grating used in the experiments was inscribed so that its Bragg peak was centered around 1551.5 nm. In Figure 5.11a, it is seen that the immersion of the sensor in water implies power variations in the Bragg peak because the MMI spectra acts as a filter on it. Additionally, it can be verified that the Bragg peak spectral position is maintained whereas the setup is immersed. It was expected because, in the singlemode fiber in which the Bragg grating was inscribed, the core mode is well confined within the core of the fiber and, therefore, its corresponding evanescent field doesn’t interact with the external medium. Additionally, Figure 5.11b shows the Bragg peak power as a function of the immersion depth (liquid-level). A sensitivity of 0.25 dBm/mm could be measured.
Figure 5.10. (a) MMI spectra for different submerged NCF length. (b) Resulting data from subtraction between completely submersed no-core fiber spectrum (submerged NCF length: 60 mm) and completely emerged no-core fiber spectrum (submerged NCF length: 0 mm).

Figure 5.11. (a) FBG spectral response as a function of the immersed length (liquid-level). (b) Bragg peak power as a function of liquid-level.

Therefore, we could propose and demonstrate the operation of a simple liquid-level sensor based on multimode interference and a Bragg grating. As the sensing measurement is based on the reflected optical power from the Bragg peak, the setup does not demand the employment of expensive spectral optical analyzers and could be assembled by using a cost effective light source (for example, a light-emitting diode, LED with an emission wavelength centered at the FBG spectral response) together with a photodetector.

The results from this investigation were published in [5.21] and were obtained in collaboration with Mr. Ricardo Oliveira and Mr. Stenio Aristilde (who performed the experimental characterization of the sensor). As in the three-parameter sensor, my contributions were the proposal of the sensor (together with Prof. Cristiano M. B.
Cordeiro) and the performance of data and error analysis (together with Mr. Ricardo Oliveira).

5.4 Metal-filled embedded-core fiber for temperature sensing

Here, we demonstrate that the embedded-core fiber proposed in Chapter 2 can also be used as a highly sensitive temperature sensor if metal is inserted into its hollow part in a post-processing procedure. As it will be shown in the following, the sensor operation is based on the metal thermal expansion inside the fiber which causes the induction of stresses within the capillary wall. It generates changes in core birefringence and allows measuring the temperature sensitivity in a wavelength scanning measurement. The achieved sensitivity, \((14.4 \pm 0.7) \text{ nm/°C}\) is among the highest ones reported in literature for special birefringent optical fibers.

5.4.1 Temperature-induced birefringence in capillary fibers filled with metal

As discussed in Chapter 2, the material birefringence can arise from the existence of asymmetric stresses distributions in a material and can be accounted by Eq. (2.2). Herein, we propose the study of a configuration which consists of a capillary fiber filled with metal (Figure 5.12). When the structure is subjected to temperature variations, due to thermal expansion, displacements are observed in the metal and silica regions. It entails birefringence variations within the silica region due to the induction of an asymmetrical distribution of stresses.

To describe such a problem, it is necessary to be aware that, as the thermal expansion coefficients of the metal and silica are different (metal’s one is larger), free expansion do not occur inside the structure. Therefore, the displacements experienced by the mass elements inside the composite structure are constrained.
Figure 5.12. Diagram for the Metal-filled capillary fiber with embedded core. $r_{in}$: inner radius; $r_{out}$: outer radius.

The displacements for the metal and silica regions – $u_1(r)$ and $u_2(r)$ respectively – can be calculated from Eq. (5.10) and Eq. (5.11). These equations are obtained by imposing three boundary conditions, namely, the continuity of the radial displacement, the continuity of the radial stress and free expansion at the fiber outer surface [5.22] – more details in Appendix G. Moreover, we have considered the plane strain approximation because the fiber length is much larger than the cross-sectional dimensions. In Eq. (5.10) and Eq. (5.11), $\Delta T$ is the temperature variation, $r_{in}$ and $r_{out}$ are respectively the capillary inner and outer radius, $\nu$ is the Poisson ratio, $E$ is the Young modulus and $\alpha$ is the thermal expansion coefficient (index 1 stands for the filling metal and index 2 stands for silica). The parameter $\delta$ is accounted by Eq. (5.12).

$$u_1(r) = \Delta T \left[ \frac{\delta}{E_1} (1 - \nu_1) \left( \frac{1}{2} \right) + (1 + \nu_1) \alpha_1 \right] r$$ \hspace{1cm} (5.10)

$$u_2(r) = \Delta T \left\{ \left( 1 + \nu_2 \right) \left[ \frac{\delta}{E_2} \left( \frac{1}{2} \right) \right] + (1 + \nu_2) \alpha_2 \right\} r + \frac{\delta r_{out}^2}{E_2}$$ \hspace{1cm} (5.11)

$$\delta = \frac{(1+\nu_2)\alpha_2 - (1+\nu_1)\alpha_1}{\frac{(1+\nu_1)}{E_1} \left( \frac{1}{2} \right) \left( 1 - \frac{r_{out}^2}{r_{in}^2} \right) + \frac{(1+\nu_2)}{E_2} \left( \frac{1}{2} \right) \frac{r_{out}^2}{r_{in}^2}}$$ \hspace{1cm} (5.12)

The solid red line in Figure 5.13 presents the analytical results, calculated by using Eq. (5.10) and Eq. (5.11), for the displacements as a function of the radial position for a silica capillary fiber filled with indium with inner radius 20 $\mu$m and outer radius 50 $\mu$m for a temperature variation of 50 °C. Indium was chosen to be the filling metal because it
has a considerably high thermal expansion coefficient when compared to silica (32.1 × 10⁻⁶ °C⁻¹ for indium and 0.55 × 10⁻⁶ °C⁻¹ for silica [5.23]) and its low melting point (156 °C [5.23]), which simplifies the metal-filling process from an experimental point of view.

![Graph showing displacement as a function of the position](image)

**Figure 5.13.** Displacement as a function of the position for a solid cylinder (blue dashed line), indium-filled silica capillary (solid red line) and a hollow silica capillary (green dotted line). Temperature variation: 50 °C. Numerical results for the indium-filled capillary are presented as blue circles.

In Figure 5.13, it is seen that the displacement raises linearly as a function of the radial position in the metal region (up to 20 µm) and, in the silica region, assumes a decaying profile. For comparison, it is also shown in Figure 5.13 the displacement which would be expected for a solid indium cylinder with radius 20 µm undergoing free expansion for the same temperature variation (blue dashed line). Under free expansion, the displacement at 20 µm is 46.5 nm and, in the restricted expansion, the displacement is 30.3 nm at the same radial position. Therefore, it is observed that the silica capillary constrains the metal thermal expansion reducing the displacement it would be able to undergo if the expansion was free.

Additionally, it is shown in Figure 5.13 the displacement of the mass elements in a hollow silica capillary with inner radius 20 µm and outer radius 50 µm for a temperature variation of 50 °C (green dotted line). At the radial position of 20 µm, the calculated displacement is 0.6 nm. Thus, one can visualize that, when the capillary is filled with metal, the inner capillary wall is pushed further it would displace if it was hollow.

Furthermore, the indium-filled capillary fiber was numerically simulated by using a model in COMSOL® and the resulting data is presented as blue circles in Figure 5.13.
By observing the results, one concludes that the analytical and numerical results are identical. In these simulations, 12.74 GPa and 72.5 GPa were used, respectively, as indium and silica Young moduli \([5.24, 5.25]\), and 0.45 and 0.165 were used as indium and silica Poisson ratios \([5.24, 5.26]\).

According to \([5.22]\), the radial and azimuthal stresses \((\sigma_r \text{ and } \sigma_\theta)\) at a temperature \(T\) and at a radial position \(r\) into the silica region can be written as in Eq. (5.13) and Eq. (5.14), where \(T_0\) is the temperature at which there is no stress in the composite structure and \(\delta\) is calculated by Eq. (5.12). As shown in Chapter 2, if the radial and azimuthal stresses are written in rectangular coordinates along the horizontal axis, one can obtain \(\sigma_r = \sigma_x\) and \(\sigma_\theta = \sigma_y\). Therefore, by substituting these results in Eq. (2.2) in Chapter 2 (which allows obtaining the material birefringence from the stresses along the horizontal and vertical directions) and then taking the derivative of the resulting expression with respect to the temperature, one can find Eq. (5.15), which allows calculating the material birefringence derivative with respect to the temperature, \(\frac{dB_{mat}}{dT}\), for a position \(x\) in the horizontal axis. It is worth underlining that we assumed no birefringence under no stress (i.e. \(B_0 = 0\)).

\[
\sigma_r = \delta(T - T_0) \left(1 - \frac{r_{out}^2}{r} \right) \tag{5.13}
\]

\[
\sigma_\theta = \delta(T - T_0) \left(1 + \frac{r_{out}^2}{r} \right) \tag{5.14}
\]

\[
\frac{dB_{mat}}{dT} = -2\delta(C_2 - C_1) \frac{r_{out}^2}{x^2} \tag{5.15}
\]

In Figure 5.14, we present a graph for the absolute value of the material birefringence derivative with respect to the temperature as a function of the position within the metal-filled silica capillary fiber wall. Again, we have assumed capillaries with inner radius 20 \(\mu m\) and outer radius 50 \(\mu m\). In this plot, for comparison, we have assumed the filling metal to be indium, tin or bismuth – the choice of these metals was based on their low melting points: 156 \(^\circ\)C for indium \([5.23]\), 231.9 \(^\circ\)C for tin and 271.3 \(^\circ\)C for bismuth \([5.27]\).
The results exposed in Figure 5.14 shows that $\left| \frac{dB_{\text{mat}}}{dT} \right|$ values are greater for the indium-filled capillary. Although the Young modulus and Poisson ratio values contributes for accounting $\left| \frac{dB_{\text{mat}}}{dT} \right|$, we can observe that the main parameter which allows obtaining higher $\left| \frac{dB_{\text{mat}}}{dT} \right|$ values is the larger indium thermal expansion coefficient ($32.1 \times 10^{-6} \text{oC}^{-1}$ [5.23]) when compared to the other metals under study ($23 \times 10^{-6} \text{oC}^{-1}$ for tin and $13.3 \times 10^{-6} \text{oC}^{-1}$ for bismuth [5.25]). Moreover, by analyzing Figure 5.14, we observe that greater $\left| \frac{dB_{\text{mat}}}{dT} \right|$ values are attained for positions closer to the inner radius (a similar behavior as that observed in the pressurized embedded-core fibers described in Chapter 2). In the presented simulations, one used 0.36 and 0.33 as tin and bismuth Poisson ratios [5.26], and 42 GPa and 34 GPa as tin and bismuth Young moduli [5.28, 5.29].

### 5.4.2 Experimental results

To experimentally measure the sensitivity of the proposed configuration, the embedded-core was filled with indium by melting the metal and by applying an external pressure level of 8 bar to push it into the fiber [5.23]. Figure 5.15a presents the embedded-core fiber used in this research and Figure 5.15b shows the embedded-core fiber filled with indium.
The wavelength scanning method was used to obtain the spectral response of the sensor. As explained in Chapter 2, in this method, a broadband light source is used to launch light into the fiber and two polarizers are employed for exciting and recombining the orthogonal modes of the birefringent fiber. The resulting spectrum is measured in an optical spectrum analyzer where interferometric fringes can be observed. The temperature sensitivity is obtained by following the fringes spectral position as a function of the temperature variation. To perform the temperature sensitivity tests, the fiber was immersed in water and its temperature was carefully varied. Figure 5.16 shows the experimental setup employed in the experiments.

Figure 5.17a presents the spectra of the indium-filled embedded-core fiber for different temperature levels. Figure 5.17b shows, in turn, the wavelength shift as a function of the temperature, which allows obtaining, after performing an appropriate average on the heated fiber length and on the fiber total length \([5.1]\), a sensitivity of \((14.7 \pm 0.7) \text{ nm/}^\circ \text{C}\).
Figure 5.17. (a) Indium-filled embedded-core fiber spectra for different temperature levels and (b) the wavelength shift as a function of the temperature.

The achieved temperature sensitivity is considerably higher than the sensitivity value usually achieved in typical Bragg gratings-based sensors (in the order of 0.01 nm/°C) [5.30] and interferometric schemes such as fiber loop mirrors (in the order of 1 nm/°C) [5.31]. Moreover, it is also higher than the sensitivities reported for specialty optical fibers filled with metals such as the values 6.3 nm/°C and 9.0 nm/°C reported in [5.23] and [5.32], respectively. Although we have achieved a very large temperature sensitivity, it is worth saying that there is still room for optimization of the fiber structure for achieving even greater values – for instance, by placing the core even nearer to the capillary inner wall.

The results from this research were presented in the III International Conference on Applications of Optics and Photonics [5.33] and will be submitted as a journal article in IEEE Sensors Letters [5.34]. The results were obtained in collaboration with Mr. Giancarlo Chesini, who performed the metal-filling process and the temperature sensing measurements. My contributions in this investigation involved the fiber fabrication, the development of the analytical model and the discussions on the experimental results.
Chapter 6

Conclusions and future perspectives

In this thesis, our research on specialty optical fibers for sensing applications is presented. Initially, a presentation of the wide diversity of optical fiber-based sensor technologies was performed and the main achievements in the area were shown. There, we emphasized the great interest on the development of optical fiber-based systems able to provide monitoring measurements of different parameters with high sensitivity and improved resolution.

Regarding our contributions, we firstly presented the proposal of the so-called embedded-core capillary fiber for pressure sensing. As the novel geometry consist of a simple silica tube with a germanium-doped core embedded inside its wall, we claimed this geometry as a new route for the development of highly sensitive microstructured optical fiber-based pressure sensors. With this simplified structure, we could, even with a non-optimized fiber, attain high values for the polarimetric spectral sensitivity coefficient, $C_S$, and for $\frac{dB}{dP}$ – respectively $(1.04 \pm 0.01)$ nm/bar and $(2.33 \pm 0.02) \times 10^{-7}$ bar$^{-1}$ –, which are similar to that reported for sophisticated fiber structures which were optimized for the performance of pressure sensing measurements. Therefore, embedded-core fibers can be seen as a new important platform for the realization of highly sensitive pressure probing measurements.

As a future perspective regarding the improvement of embedded-core fiber-based pressure sensors, we can propose the study of a new fiber which would allow to temperature compensate the system response – since, as mentioned in Chapter 2, the germanium-doped core entails an important pressure-temperature cross-sensitivity. This modified embedded-core structure could be a capillary fiber with two cores placed at different radial positions within the capillary wall. To attain a temperature-compensated mechanism, we propose the inscription of Bragg gratings in each one of the cores of the proposed fiber. As the core of the embedded-core fiber is obtained from a standard optical fiber preform, we can expect a Bragg grating temperature sensitivity in the order of $10$ pm/$^\circ$C for both cores. Numerical simulations show that, for a capillary structure with
40 µm inner radius and 62.5 µm outer radius, if one of the cores has its center placed 2.5 µm from the inner wall and the other core is placed on the fiber external surface, the pressure sensitivity of a Bragg grating inscribed in the core closer to the inner radius would be approximately twice the pressure sensitivity for the core on the fiber external surface. Thus, by considering the shifts in Bragg peaks and associating them to the different pressure sensitivities and similar temperature sensitivities, the temperature variations could be calculated and the pressure measurement from the polarimetric measurement (as described in Chapter 2) could be corrected. Additionally, the study of the fiber response for internal pressure level variations is also another research opportunity.

Moreover, we reported the study of surface-core fibers (which differ from embedded-core fibers because their core is placed on the fiber external boundary) in refractive index sensing. To do that, we imprinted Bragg gratings in the core of such fibers and performed refractive index measurements. To enhance sensor sensitivity, fiber tapers were prepared and Bragg gratings were imprinting in them. A maximum sensitivity of 40 nm/RIU was measured for a 20 µm thick taper around 1.42 RIU. This result compares well to other Bragg gratings-based sensors.

Further development on thinner tapers and on evaluating core modes of higher orders may be desirable for sensitivity enhancement. Additionally, it would be of interest to test the surface-core fibers as a platform for obtaining sensors based on surface plasmon resonance. It could be done, for instance, by preparing a film of gold on the surface-core fiber (Figure 6.1a for a representation). Preliminary simulations showed that the sensitivity could be in the order of 2000 nm/RIU in this configuration. Moreover, surface-core fibers with two cores (Figure 6.1b) can also be seen as an additional opportunity for the realization of sensing measurements using this sort of structure – in this case, for example, the coupling between the modes in the two cores could be evaluated as the refractive index of the external medium is varied.

Surface-core fibers were also used for directional curvature sensing. It was motivated by the fact that the off-center position of the fiber core allows a Bragg grating inscribed in the fiber core to be compressed or extended depending on the curvature direction. It caused the Bragg gratings response to acquire different behavior depending on the curvature orientation. The maximum sensitivity attained was (-202 ± 3) pm/m⁻¹, which is a high value regarding Bragg gratings-based curvature sensors.
As an even simpler technology, we studied polymer antiresonant capillary fibers. Light guidance through the hollow core of the capillaries occurs via antiresonant reflection and, due to that, dips are seen in the capillary fibers transmission spectra. Thus, as the transmission dips’ spectral positions depend on the capillary wall thickness, we explored such structures as temperature and pressure sensors (since both parameters are able to provide variations in capillary wall thickness). Analytical and experimental studied were performed and demonstrated the feasibility of using antiresonant capillary fibers as temperature and pressure sensors. The realization of additional studies to provide a better understanding of the differences between the simulated and measured antiresonant dips bandwidth and of the possible alterations on PMMA mechanical properties when pressurized would be worthy.

Finally, we presented additional opportunities for sensing using special optical fibers. Under this topic, a side-hole photonic-crystal fiber pressure sensor was investigated and applied for dual environment monitoring. Additionally, a three-parameters sensor based on Bragg gratings, multimode interference and fiber tapering, and an intensity-based liquid-level sensor based on multimode interference and Bragg gratings were presented. Future investigative directions could employ the knowledge developed in these sensors in tilted fiber Bragg gratings-based setups for the performance of multi-parameters, refractive index or liquid level with improved resolution.

Furthermore, the application of metal-filled embedded-core fibers in temperature sensing was demonstrated. An analytical description of the structure behavior under temperature variations and an experimental realization of the sensor was provided. The measured temperature sensitivity – (14.7 ± 0.7) nm/°C – is among the highest values

**Figure 6.1.** (a) Representation of the surface-core fiber with a gold film for external refractive index ($n_{ext}$) sensing using surface plasmon resonance. (b) Surface-core fiber with two cores as a new sensing platform.
reported in literature for temperature sensors based on birefringent specialty optical fibers.

In conclusion, we could expose along this text our research on different technologies regarding specialty optical fibers for sensing. Theory and experiments were approached and the results demonstrated the sensors to act efficiently. Furthermore, sensors performance was analyzed in detail and prospects on sensors improvement were exposed. The investigation reported herein confirm optical fiber technology as a very suitable solution for the realization of sensing measurements with excellence quality and demonstrate the wide field of applications of optical fibers in sensing field.
References

Chapter 1


Chapter 2


Chapter 3


Chapter 4


Chapter 5


**Appendix A**


**Appendix B**


**Appendix C**

Appendix D


Appendix E


Appendix F

Appendix G


**Appendix A**

*Fabrication of microstructured optical fibers*

Silica microstructured fibers can be prepared by using a fiber drawing tower facility and by employing the stack-and-draw procedure [A.1]. The tower facility (Figure A.1) comprehends a feeding system, which inserts the glass (preform) into a furnace at a controlled speed. The furnace raises the preform temperature (for silica, up to a temperature of around 1900 °C) so it can be drawn by the tractor system – also at a controlled speed level. In order to increase the resulting fiber mechanical strength, a polymeric coating can be put on the fiber by passing it through a polymer bath in the coating cone. In sequence, the polymer is cured by a UV lamp. A spooling wheel can be used to coil the fiber conveniently. [A.2]

![Diagram](image)

**Figure A.1.** Schematic diagram for a fiber drawing tower facility and for photonic-crystal fiber fabrication. [A.1]
In stack-and-draw procedure, initially silica capillaries and rods are drawn by using the tower facility. Afterwards, as mentioned in Chapter 1, the silica capillaries and rods are manually assembled in a preform stack whose structure corresponds to the one planned for the final fiber (Figure A.2a). In sequence, the stack is inserted into a jacketing tube (Figure A.2b) and the resulting assembly is drawn in the tower facility to a microstructured preform (cane).

![Figure A.2. (a) A preform stack and (b) a preform stack inserted into a jacketing tube.](image)

In the following step, the cane is drawn to the fiber dimensions. It is worth saying that, in this last step, an additional tube can be used for jacketing the cane so the desired proportion between microstructured cladding, core and outer fiber sizes can be accomplished. In addition, it is worth emphasizing that furnace temperature, preform feed and drawing speeds and the pressure inside the preform can be tuned in order to control the resulting fiber geometry during the drawing process. [A.2]

Therefore, we can observe that the fabrication process of microstructured optical fibers is very demanding from a technical point of view since it comprehends steps which must be performed very carefully. As it is shown in Chapter 2 in this thesis, the proposal of the embedded-core appears as a new route for the simplification of microstructured optical fibers-based sensors since the stacking process is avoided.
Appendix B

Displacements, strains and stresses within pressurized capillary tubes

In this appendix, we approach the equations for accounting the stresses within pressurized capillary fibers as presented in Chapter 2. The expressions to be exposed herein are usually referenced as the Lamé solution for thick cylinders under pressure \([B.1]\). Thus, consider a tube with inner radius \(r_{in}\) and outer radius \(r_{out}\) which is subjected to an inner pressure level \(p_{in}\) and outer pressure \(p_{out}\). If a volume element within the capillary is studied, stresses along the radial direction and azimuthal direction, as shown in Figure B.1a, can be defined. Moreover, if we assume the volume element is under equilibrium, Eq. (B.1) can be written for the balance of forces along the radial direction. In Eq. (B.1), \(\sigma_{r}\) and \(\sigma_{\theta}\) are, respectively, the stresses on the radial and azimuthal directions; \(r\) is the radial distance between the capillary center and the volume element; \(\theta\) is the azimuthal coordinate and \(z\) references the coordinate along the capillary axis. Simplification in Eq. (B.1) allows obtaining Eq. (B.2), which exposes the relationship between radial and azimuthal stresses. \([B.1]\)

\[
\sigma_{r} r \, d\theta dz + 2\sigma_{\theta} \left(\frac{d\theta}{2}\right) dr dz = (\sigma_{r} + d\sigma_{r})(r + dr) d\theta dz \tag{B.1}
\]

\[
\frac{d\sigma_{r}}{dr} + \frac{(\sigma_{r} + \sigma_{\theta})}{r} = 0 \tag{B.2}
\]

Strains can also be defined for the volume element within the capillary structure. Suppose that the employment of pressure on the capillary tube caused the volume element boundaries to displace as represented in Figure B.1b. The radial deformation for an element with initial thickness \(dr\) is \((u + du - u)\). Therefore, the radial strain, \(\varepsilon_{r}\), is found to be described by Eq. (B.3). Besides, the arc on the azimuthal direction varies its length from \(r \, d\theta\) to \((r + u) \, d\theta\). Hence, one can find Eq. (B.4) for describing the azimuthal strain, \(\varepsilon_{\theta}\). \([B.1]\)
Figure B.1. Representation for the (a) stresses and (b) displacements experienced by a volume element within a pressurized capillary structure. $p_{in}$: internal pressure; $p_{out}$: external pressure.

\[ \varepsilon_r = \frac{u + du - u}{dr} \Rightarrow \varepsilon_r = \frac{du}{dr} \quad (B.3) \]

\[ \varepsilon_\theta = \frac{(r + u)d\theta - r d\theta}{rd\theta} \Rightarrow \varepsilon_\theta = \frac{u}{r} \quad (B.4) \]

Stresses and strains can be related by Hooke law. Neglecting the stresses along the cylinder axis and, therefore, considering that all stresses happen on the capillary cross-section, one finds Eq. (B.5) and Eq. (B.6) for the relationship between radial and azimuthal strain and stresses – $E$ stands for the material Young modulus and $\nu$ represents the Poisson ratio. [B.1]

\[ \varepsilon_r = \frac{1}{E} (\sigma_r - \nu \sigma_\theta) \quad (B.5) \]

\[ \varepsilon_\theta = \frac{1}{E} (\sigma_\theta - \nu \sigma_r) \quad (B.6) \]
By substituting Eq. (B.3) in Eq. (B.5) and Eq. (B.4) in Eq. (B.6), one can find Eq. (B.7) and Eq. (B.8), which accounts for the radial and azimuthal stresses as a function of the displacement ($u$) experienced by a volume element within the capillary due to the application of pressure and its first derivative, $du/dr$. Furthermore, substitution of Eq. (B.7) and Eq. (B.8) in Eq. (B.2) allows attaining a differential equation for the displacements in the pressurized capillary context – Eq. (B.9) –, whose general solution takes the form of Eq. (B.10) – where $A_1$ and $A_2$ are constants to be determined. [B.1]

\[
\sigma_r = \frac{E}{1-\nu^2} \left( \frac{du}{dr} + \nu \frac{u}{r} \right) \quad (B.7)
\]

\[
\sigma_\theta = \frac{E}{1-\nu^2} \left( \frac{u}{r} + \nu \frac{du}{dr} \right) \quad (B.8)
\]

\[
\frac{d^2u}{dr^2} + \frac{1}{r} \frac{du}{dr} - \frac{u}{r^2} = 0 \quad (B.9)
\]

\[
u(r) = A_1 r + \frac{A_2}{r} \quad (B.10)
\]

If Eq. (B.10) is inserted in Eq. (B.7), we can obtain the expression for accounting the radial stress as a function of the radial coordinate, $r$ – Eq. (B.11). This form can be used to find $A_1$ and $A_2$ values by applying the problem boundary conditions: at the outer radius position, $r = r_{out}$, the radial stress must be equal the external pressure level. Besides, at the inner radius position, $r = r_{in}$, the radial stress must recover the internal pressure level. By imposing these conditions, $A_1$ and $A_2$ values can be found as exposed in Eq. (B.12) and Eq. (B.13). [B.1]

\[
\sigma_r = \frac{E}{1-\nu^2} \left[ A_1 (1 + \nu) - A_2 (1 - \nu) \frac{1}{r^2} \right] \quad (B.11)
\]

\[
A_1 = \frac{(1-\nu)}{E} \left[ \frac{p_{in} \left( \frac{r_{in}}{r_{out}} \right)^2 - p_{out}}{1 - \left( \frac{r_{in}}{r_{out}} \right)^2} \right] \quad (B.12)
\]
\[ A_2 = \frac{(1+\nu)}{E} \left[ \frac{(p_{in}-p_{out})r_{in}^2}{1-(\frac{r_{in}}{r_{out}})^2} \right] \]  

(B.13)

Finally, by substituting Eq. (B.12) and Eq. (B.13) in Eq. (B.11) and performing some algebra, we find the radial stress expression as it is exposed in Chapter 2 – Eq. (B.14). Moreover, if we substitute Eq. (B.10) in Eq. (B.8) – with \( A_1 \) and \( A_2 \) expressions as shown in Eq. (B.12) and Eq. (B.13) –, Eq. (B.15) is found, which accounts for the azimuthal stress in a pressurized hollow cylinder.

\[ \sigma_r(r) = \left[ 1 - (\frac{r_{in}}{r_{out}})^2 \right]^{-1} \left[ p_{in} \left( \frac{r_{in}}{r_{out}} \right)^2 - (p_{in} - p_{out}) \left( \frac{r_{in}}{r} \right)^2 - p_{out} \right] \]  

(B.14)

\[ \sigma_\theta(r) = \left[ 1 - (\frac{r_{in}}{r_{out}})^2 \right]^{-1} \left[ p_{in} \left( \frac{r_{in}}{r_{out}} \right)^2 + (p_{in} - p_{out}) \left( \frac{r_{in}}{r} \right)^2 - p_{out} \right] \]  

(B.15)


Appendix C

Surface-core fiber’s refractive index profile

In this appendix, it is described the procedure we used for recovering the refractive index profile of the core region in the surface-core fibers reported in this thesis. As can be read in Chapter 3, the refractive index profile was attained from the germanium concentration in the core measured from an energy-dispersive X-ray spectroscopy (EDS).

Energy-dispersive X-ray spectroscopy consists of a technique which allows the realization of chemical analysis on a sample by analyzing the characteristic X-ray energies which are emitted from the specimen when an electron beam impinges on the same. In an X-ray energy-dispersive spectrometer, a detector can generate voltage pulses whose magnitudes are proportional to the X-ray energy which was emitted by the sample. By the employment of electronic processing techniques, the signal can be allocated in a specific channel in a computer-assisted system and a spectrum for the X-ray counts as a function of the energy is displayed. Figure C.1 shows typical spectra for pure germanium and silica glass samples. [C.1]

![Figure C.1. Typical energy dispersive X-ray spectra for (a) pure germanium and (b) silica glass samples. GeKα, GeKβ and GeL references the characteristics X-ray energies for a germanium atom (to K and L shells) and SiK represents the same for a silicon atom. (Adapted from [C.1])](image)

If a binary system is considered (sample with two chemical elements), Cliff-Lorimer ratio technique can be employed. In this technique, it is assumed that the ratio between the concentrations of the two elements in the system is proportional to the
measured characteristic X-rays intensities (counts). In surface-core fiber characterization, we assumed silicon and germanium as the components of the binary system and, therefore, could write the Cliff-Lorimer equation as in Eq. (C.1) – where \( C_{Ge} \) and \( C_{Si} \) are the germanium and silicon concentration and \( I_{Ge} \) and \( I_{Si} \) are the X-ray intensities (counts) for germanium and silicon respectively. The proportionality constant, \( k_{Ge,Si} \), called Cliff-Lorimer ratio, values 1.92 for a germanium-silicon system. \( \{C.1\} \)

\[
\frac{C_{Ge}}{C_{Si}} = k_{Ge,Si} \frac{I_{Ge}}{I_{Si}}
\]  

\( (C.1) \)

Figure C.2a shows the measured counts in an EDS measurement for germanium and silicon as a function of the position across the core region of a surface core fiber as represented by the yellow arrow in Figure C.2b. By inserting Figure C.2a data in Eq. (C.1), germanium concentration within the core region can be calculated and the profile shown in Figure B.2c can be obtained. Furthermore, by using Eq. (3.1) from Chapter 3, the refractive index profile along the core region can be obtained. Resulting data are shown in Figure C.2d – it can be noted that the germanium doping increases the core refractive index in comparison to pure silica case (blue line in Figure C.2d).

Figure C.2. (a) Measured counts for silicon and germanium along the core region of a surface-core fiber. (b) Image of the analyzed region and representation of the axis under analysis (yellow arrow). (c) Germanium concentration and (d) and refractive index profile along the core region.
Appendix D

Curvature sensitivity of Bragg gratings inscribed in surface-core fibers

When a thick material is bended, tensile and compressive strain can be observed in different regions of the same. In order to characterize it, consider the structure as depicted in Figure D.1a which is bended as represented in Figure D.1b. If the structure (with initial length \( L_0 \)) is bended in such a manner it defines an angle \( \theta \) with respect to the curvature center, we can write the length of the bended region as \( L_{\text{bend}} = (R + y)\theta \), where \( y \) is the distance from the structure neutral axis and \( R \) is the curvature radius. As \( L_0 \) can be expressed as \( L_0 = R\theta \), one can conclude that the length increment at a distance \( y \) from the neutral axis can be written as in Eq. (D.1).

\[
\Delta L = L_{\text{bend}} - L_0 = y\theta
\]  

(D.1)

\( \Delta L \): length variation due to bending; \( R \): curvature radius; \( y \): distance from neutral axis; \( \theta \): angle defined by the curvature.

Figure D.1. (a) Straight and (b) bent structure. \( L_0 \): initial length; \( \Delta L \): length variation due to bending; \( R \): curvature radius; \( y \): distance from neutral axis; \( \theta \): angle defined by the curvature.

Since the strain, \( \varepsilon \), is defined as the length variation divided by the initial length, Eq. (D.2) can be written. It shows that the bend induced strain at a position \( y \) from the neutral axis is proportional to the curvature \( C \) – note we have used the definition of curvature, \( C = 1/R \). As it was discussed in Chapter 3, this linear relationship was explored
in the study of a curvature sensor based on Bragg gratings inscribed in surface-core fibers. \([D.1]\)

\[
\varepsilon = \frac{\Delta L}{L_0} = \frac{y}{R} \Rightarrow \varepsilon = yC
\]

**(D.2)**

**D.1 Bragg wavelength shifting due to strain application**

Fiber Bragg gratings optical response is altered when strain is applied to the fiber. It is manifested as a wavelength shift in Bragg peak spectral position and allows employing Bragg gratings as strain sensors. Particularly, in surface-core fibers, due to the fact that the core is off-center, fiber bending induces compressive or tensile strain levels depending on core and curvature orientation. It turns curvature monitoring possible.

In order to understand the Bragg wavelength shift as strain is applied to the fiber, let us take the differential, considering a length variation \(dL\) caused by a longitudinal force, for the Bragg grating phase matching condition – Eq. (1.1) –, as it is shown in Eq. (D.3) (\(\lambda_B\) is the Bragg wavelength, \(n_{\text{eff}}\) is the fundamental core mode effective refractive index and \(\Lambda\) is the grating pitch). If Eq. (D.3) is divided by \(\lambda_B = 2n_{\text{eff}}\Lambda\), we can rewrite it as Eq. (D.4). \([D.2]\)

\[
d\lambda_B = \frac{\partial \lambda_B}{\partial L} dL \Rightarrow d\lambda_B = \left[2n_{\text{eff}} \frac{\partial \Lambda}{\partial L} + 2\Lambda \frac{\partial n_{\text{eff}}}{\partial L}\right] dL
\]

**(D.3)**

\[
\frac{d\lambda_B}{\lambda_B} = \frac{1}{\lambda_B} \frac{\partial \Lambda}{\partial L} dL + \frac{1}{n_{\text{eff}}} \frac{\partial n_{\text{eff}}}{\partial L} dL
\]

**(D.4)**

In Eq. (D.4), \(\frac{\partial \Lambda}{\partial L} = 1\) since a variation in the fiber length (due to the application of a longitudinal force) is equal to the variation in grating period. Moreover, it allows writing \(dL = d\Lambda\) and recognizing that the first term in Eq. (D.4) is the strain applied to the fiber, \(\varepsilon\). Eq. (D.4) can, therefore, be rewritten as Eq. (D.5) – where, in addition, we rewrote the second term derivative as a function of strain \((dL/L)\). \([D.2]\)

\[
\frac{d\lambda_B}{\lambda_B} = \varepsilon + \frac{1}{n_{\text{eff}}} \frac{\partial n_{\text{eff}}}{\partial \varepsilon} d\varepsilon
\]

**(D.5)**
The second term in Eq. (D.5) refers to the strain-optic effect contribution. To express this contribution as a function of photoelastic coefficient – as it was shown in Eq. (D.4) in Chapter 3 –, we can consider, firstly, Eq. (D.6) and Eq. (D.7) from electromagnetic theory. Eq. (D.6) accounts for the relationship between the electric displacement and the electric field vectors \( \vec{D} \) and \( \vec{E} \) respectively; \( \varepsilon \) is the dielectric tensor and Eq. (D.7) for the energy density, \( U \), carried by a propagating electromagnetic wave. [D.3]

\[
\vec{D} = \varepsilon \vec{E} \tag{D.6}
\]

\[
U = \vec{E} \cdot \vec{D} \tag{D.7}
\]

If we express the components of the electric displacement vector, \( D_k \), \( k = 1, 2, 3 \), as in Eq. (D.8), and substitute it in Eq. (D.7) – also making use of the dielectric tensor symmetry, \( \epsilon_{ij} = \epsilon_{ji} \), \( i \neq j \) –, we can find Eq. (D.9), which can be geometrically interpreted as an equation for an ellipsoid. [D.3]

\[
\begin{pmatrix}
D_1 \\
D_2 \\
D_3
\end{pmatrix} =
\begin{pmatrix}
\epsilon_{11} & \epsilon_{12} & \epsilon_{13} \\
\epsilon_{21} & \epsilon_{22} & \epsilon_{23} \\
\epsilon_{31} & \epsilon_{32} & \epsilon_{33}
\end{pmatrix}
\begin{pmatrix}
E_1 \\
E_2 \\
E_3
\end{pmatrix}
\tag{D.8}
\]

\[
\epsilon_{11}E_1^2 + \epsilon_{22}E_2^2 + \epsilon_{33}E_3^2 + 2(\epsilon_{12}E_1E_2 + \epsilon_{23}E_2E_3 + \epsilon_{13}E_1E_3) = U \tag{D.9}
\]

Since an ellipsoid can always be transformed to its principal axis, there is a coordinate system in which it can be written as Eq. (D.10). As in the principal axis system the relationship between the components of the electric displacement and electric field vectors take the form \( D_i = \epsilon_i E_i \), \( i = 1, 2, 3 \), Eq. (D.11) can be obtained. Moreover, from \( \epsilon_i = n_i^2 \), Eq. (D.12) can be found, where \( n_1, n_2 \) and \( n_3 \) are the material principal axes refractive indexes \( (X_i = \frac{D_i^2}{U}, \ i = 1, 2, 3) \). [D.3]

\[
\epsilon_1E_1^2 + \epsilon_2E_2^2 + \epsilon_3E_3^2 = U \tag{D.10}
\]

\[
\frac{D_1^2}{\epsilon_1} + \frac{D_2^2}{\epsilon_2} + \frac{D_3^2}{\epsilon_3} = U \tag{D.11}
\]
\[ \frac{x_1^2}{n_1^2} + \frac{x_2^2}{n_2^2} + \frac{x_3^2}{n_3^2} = 1 \]  \hspace{1cm} (D.12)

Eq. (D.12) references what is known as the refractive index ellipsoid or the optical indicatrix. The notation can be simplified by writing Eq. (D.12) as a function of a tensor \( B_{ij} = 1/n_{ij}^2 \). It allows obtaining Eq. (D.13) or, more generally, Eq. (D.14). \[ D.3 \]

\[ B_{11}x_1^2 + B_{22}x_2^2 + B_{33}x_3^2 = 1 \]  \hspace{1cm} (D.13)

\[ \sum_{i,j=1}^{3} B_{ij}x_ix_j = 1 \]  \hspace{1cm} (D.14)

The strain-optic effect shows up as a change in the optical indicatrix, which can be expressed as a variation in \( B_{ij} \) tensor, \( \Delta B_{ij} = B_{ij}' - B_{ij} = \Delta(1/n_{ij}^2) \) \[ D.4 \]. In Pockels’ theory of photoelasticity, it is assumed that homogeneous deformations cause the optical indicatrix variation to happen proportionally to the applied strain vector, \( \varepsilon \) (represented by its components \( \varepsilon_j \)). The proportionality is represented by the strain-optic tensor, whose components are expressed by \( p_{ij} \). Thus, strain-optic effect can be expressed by Eq. (D.15). \[ D.5 \]

\[ \Delta B_{ij} = \Delta \left( \frac{1}{n_{ij}^2} \right) = \sum_{j=1}^{6} p_{ij} \varepsilon_j \]  \hspace{1cm} (D.15)

As silica is an isotropic and solid material, its strain-optic tensor assumes the form shown in Eq. (D.16), where \( p_{11} = 0.1, \ p_{12} = 0.28 \) and \( p_{44} = (p_{11} - p_{12})/2 = -0.09 \) \[ D.6 \]. Besides, if the strain, \( \varepsilon \), is considered to be longitudinal (along fiber axis), the strain vector takes the form shown in Eq. (D.16), where \( \nu \) is silica’s Poisson ratio. \[ D.4 \]

\[
\Delta \left( \frac{1}{n_{ij}^2} \right) = \begin{pmatrix}
p_{11} & p_{12} & p_{12} & 0 & 0 & 0 \\
p_{12} & p_{22} & p_{12} & 0 & 0 & 0 \\
p_{12} & p_{12} & p_{33} & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & p_{44} & 0 \\
0 & 0 & 0 & 0 & 0 & p_{44}
\end{pmatrix}
\begin{pmatrix}
\varepsilon \\
-\nu \varepsilon \\
-\nu \varepsilon \\
\varepsilon
\end{pmatrix} =
\begin{pmatrix}
\varepsilon [p_{11} - 2\nu p_{12}] \\
\nu [1 - \nu] p_{12} - \nu p_{11} \\
\nu [1 - \nu] p_{12} - \nu p_{11} \\
0 \\
0 \\
0
\end{pmatrix}
\]  \hspace{1cm} (D.16)
The values found in the second and third lines in $\Delta \left( \frac{1}{n^2} \right)$ matrix expresses the changes in the optical indicatrix on the orthogonal direction to which the strain was applied (changes in the optical indicatrix on the fiber cross section direction, in our case). Their value $\Delta \left( \frac{1}{n^2} \right)$, as written in Eq. (D.17), is what is usually considered to account for the refractive index change due to strain application. [D.4]

$$\Delta \left( \frac{1}{n^2} \right) = \varepsilon \left[ (1 - \nu)p_{12} - \nu p_{11} \right] \quad (D.17)$$

The refractive index variation due to strain application, $\Delta n_{\text{strain}} = n' - n$, is, therefore, obtained by working out Eq. (D.17) and by assuming that the refractive index change is small. Thus, we are able to write $(n' + n) \approx 2n$ and $n'n \approx n^2$. The main steps for this calculation are shown in Eq. (D.18) and the consolidated result is presented in Eq. (D.19), were one defined the photoelastic coefficient, $P_{\varepsilon}$.

$$\Delta \left( \frac{1}{n^2} \right) = \frac{1}{n'^2} - \frac{1}{n^2} = \frac{(n-n')(n+n')}{n'^2n^2} \approx - \frac{2\Delta n_{\text{strain}}}{n^2} \Rightarrow \Delta n_{\text{strain}} \approx - \frac{n^3}{2} \Delta \left( \frac{1}{n^2} \right) \quad (D.18)$$

$$\Delta n_{\text{strain}} \approx - \frac{n^3\varepsilon}{2} \left[ (1 - \nu)p_{12} - \nu p_{11} \right] \equiv -P_{\varepsilon} \quad (D.19)$$

By considering that, in standard optical fibers the fundamental mode effective index value is similar to silica’s one, $\Delta n_{\text{strain}}$ in Eq. (D.18) can be identified as the differential change in the refractive index due to strain application $\left( \frac{\partial n_{\text{eff}}}{\partial \varepsilon} \right)$ as exposed in Eq. (D.5). It allows expressing Eq. (D.5) – the wavelength shift in a Bragg grating spectral response – in the form presented in Eq. (D.20), as it is written in several papers which studied strain sensors.

$$\Delta \lambda_B = (1 - P_{\varepsilon}) \lambda_B \varepsilon \quad (D.20)$$

Finally, by using Eq. (D.2), we can write Eq. (D.20) as Eq. (D.21): the expression for the wavelength shift for Bragg gratings inscribed in surface-core fibers.

$$\Delta \lambda_B = [(1 - P_{\varepsilon}) \lambda_B y] C \quad (D.21)$$
Appendix E

Equation for spectral maxima in antiresonant reflecting waveguide spectrum

In this appendix, we present a derivation for the expression which allows calculating the wavelength that experiences maximum transmission in antiresonant reflecting optical waveguides – Eq. (4.1) in Chapter 4. To do it, we follow the steps described in [E.1].

Consider the ray picture exposed in Figure E.1a for a light ray incident at the point O, defining an angle $\theta$ with respect to the horizontal direction. The wave travels from a medium with refractive index $n_1$ and is directed to a medium with refractive index $n_2$, where $n_1 < n_2$. After impinging at O, the ray refracts (defining an angle $\alpha$ with respect to the horizontal direction) and goes towards the point M. Finally, it reflects back to point Q. As $n_1 < n_2$, reflection at O occurs without any phase inversion and the reflection at M adds an amount $\pi$ rad to phase of the wave. [E.1]

![Figure E.1](image.png)

**Figure E.1.** (a) Ray picture of the antiresonant reflection phenomenon. (b) Enlargement of the triangles $OMQ$ and $APQ$.

For antiresonance effect to happen, the waves represented by (I) and (II) in Figure E.1 should be in phase. As the reflection in M adds $\pi$ rad to phase of the wave, the phase difference due to the different optical paths traveled by the waves, $\Delta \phi$, must be an
odd multiple of π. Therefore, Eq. (E.1) can be written, where \( \lambda_{\text{max}} \) is a wavelength of maximum in the antiresonant spectrum and \( m \) is an integer. [E.1]

\[
\Delta \varphi = (2m + 1) \pi = \frac{2\pi n_2 (\overline{OM} + \overline{MQ})}{\lambda_{\text{max}}} - \frac{2\pi n_1 \overline{OP}}{\lambda_{\text{max}}} \tag{E.1}
\]

By observing the triangle \( OMQ \) (Figure E.1b), one can conclude that \( \overline{OM} = \frac{d}{\sin \alpha} \), where \( d \) is the thickness of the layer with refractive index \( n_2 \). Moreover, Figure E.1b allows recognizing that \( \cos \theta = \frac{\overline{OP}}{\overline{OQ}} \) and that \( \tan \alpha = \frac{2d}{\overline{OQ}} \). Hence, \( \overline{OP} = \frac{2d \cos \theta}{\tan \alpha} \), what allows rewriting Eq. (E.1) as Eq. (E.2). [E.1]

\[
\frac{(2m+1)\lambda_{\text{max}}}{2} = \frac{2dn_2}{\sin \alpha} - \frac{2dn_1 \cos \theta}{\tan \alpha} \tag{E.2}
\]

If Snell’s Law is written at the interface \( \psi \), one concludes that \( \cos \theta = \frac{n_2 \cos \alpha}{n_1} \) and, by substituting it in Eq. (E.2), Eq. (E.3) is found. Additionally, by squaring Snell’s law as in Eq. (E.4), it is possible to obtain the expression for \( \sin \alpha \) presented in Eq. (D.5). Substituting it in Eq. (E.3) allows writing Eq. (E.6). [E.1]

\[
\frac{(2m+1)\lambda_{\text{max}}}{2} = 2dn_2 \left( \frac{1 - \cos^2 \alpha}{\sin \alpha} \right) = 2dn_2 \sin \alpha \tag{E.3}
\]

\[
n_1^2 \cos^2 \theta = n_2^2 \cos^2 \alpha = n_2^2 (1 - \sin^2 \alpha) \tag{E.4}
\]

\[
\sin \alpha = \sqrt{1 - \left( \frac{n_1}{n_2} \right)^2 (1 - \sin^2 \theta)} \tag{E.5}
\]

\[
\frac{(2m+1)\lambda_{\text{max}}}{2} = 2dn_2 \sqrt{1 - \left( \frac{n_1}{n_2} \right)^2 + \left( \frac{n_1}{n_2} \right)^2 \sin^2 \theta} \tag{E.6}
\]

According to [E.2], for the fundamental mode, \( \sin \theta \cong \frac{\lambda_{\text{max}}}{2n_1a} \), where \( a \) is the diameter of the fiber core. By using this result, Eq. (E.7) can be obtained. This is the equation reported by M. A. Duguay et al. in [E.2] which, to our knowledge, is the first demonstration of an antiresonant reflecting optical waveguide.
To obtain Eq. (4.1) as shown in Chapter 4, we have to make an additional approximation, which is to consider the wavelength to be much lower than the dimensions of the fiber core, i.e., $\frac{\lambda_{\text{max}}}{a} \ll 1$. Therefore, we obtain Eq. (E.8), which expresses the wavelengths that experiences maximum transmission in antiresonant reflecting optical waveguides (here, the approximation sign was replaced by an equal sign, as it is usually done in the literature). [E.3]

$$\frac{(2m+1)\lambda_{\text{max}}}{2} \approx 2dn_{2}\sqrt{1 - \left(\frac{n_{1}}{n_{2}}\right)^{2}} + \frac{\lambda_{\text{max}}^{2}}{4n_{2}^{2}a^{2}}$$  \hspace{1cm} (E.7)

$$\lambda_{\text{max}} = \frac{4n_{1}d}{(2m+1)}\sqrt{\left(\frac{n_{2}}{n_{1}}\right)^{2} - 1}$$  \hspace{1cm} (E.8)
Appendix F

Expression for the transmitted power in antiresonant capillaries

Here, it is presented a demonstration for the expression which allows simulating the antiresonant capillaries transmission spectrum – Eq. (4.4) in Chapter 4. The derivation to be exposed herein follow the steps described in [F.1].

As presented in Chapter 4, the model for analytically obtaining the antiresonant capillaries transmission spectrum is based on the consideration which each leaky mode supported by the capillary hollow core can be described as a light ray that impinges on the capillary wall with an angle of incidence $\theta_1$ (Figure F.1). As the wall of an antiresonant capillaries can be seen as a Fabry-Perot etalon, one can use Eq. (F.1), from electromagnetic theory, to account for the reflectivity, $R$, for a light ray which impinges on the capillary wall at an incidence angle $\theta_1$ ($n_2$ is the refractive index of the capillary wall, $\Gamma$ is the Fresnel reflection coefficient, $n_1$ is the capillary hollow core refractive index and $\lambda$ is the wavelength). [F.1]

$$R = 1 - \frac{(1-\Gamma^2)^2}{(1-\Gamma^2)^2 + 4\Gamma^2 \sin^2 \left(\frac{2\pi n_2 d}{\lambda} \sqrt{1 - \frac{n_1^2 \sin^2 \theta_1}{n_2^2}}\right)}$$

(F.1)

Figure F.1. Light ray picture for the propagation along the capillary fiber hollow core.
To obtain the optical power transmitted through the capillary, we assume the power transmitted after the wave traveled a distance $L$, $P_{\text{out}}$, can be obtained from the power of the light launched in the capillary hollow core, $P_{\text{in}}$, by Eq. (F.2), where $\alpha$ is the attenuation constant of the core leaky mode. Additionally, as the transmitted light come from the reflections on the capillary core-cladding interface, $P_{\text{out}}$ can also be equaled to $R^N$, where $N$ is the number of reflections at the core-cladding interface within the distance $L$. \[F.1\]

$$P_{\text{out}} = P_{\text{in}} e^{-\alpha L} = R^N$$ \hspace{1cm} (F.2)

By observing Figure F.1, it is possible to conclude that $x = a \tan \theta_1$, where $a$ is the hollow core diameter. Therefore, as the number of reflections at the core-cladding interface can be written as $N = \frac{L}{x}$, one have that $N = \frac{L}{a \tan \theta_1}$. By inserting this result in Eq. (F.2), Eq. (F.3) can be found. Finally, by substituting Eq. (F.3) in Eq. (F.2), we find the expression for the optical power transmitted through the capillary – Eq. (F.4). \[F.1\]

$$\alpha = - \frac{\ln R}{a \tan \theta_1}$$ \hspace{1cm} (F.3)

$$P_{\text{out}} = P_{\text{in}} \left\{ \left( \frac{L}{a \tan \theta_1} \right) \ln \left[ 1 - \frac{(1-\Gamma)^2}{(1-\Gamma^2)^2 + 4\Gamma^2 \sin^2 \left( \frac{2\pi m_2 d}{\lambda} \sqrt{1 \left( \frac{n_1}{n_2} \right)^2 \sin^2 \theta_1} \right)} \right] \right\}$$ \hspace{1cm} (F.4)
Appendix G

Thermal-induced displacements in metal-filled hollow cylinders

In this appendix, we will provide the derivation of Eq. (5.10) and Eq. (5.11), which accounts for the displacements experienced by the mass elements in metal-filled cylinders composite structures subjected to temperature variations (Figure 5.12 in Chapter 5). To do that, we followed the steps described in [G.1] and applied convenient boundary conditions.

In [G.1], it is assumed that the stresses in the radial, azimuthal and longitudinal directions (σ_r, σ_θ and σ_z), in the metal region, have the form shown in Eq. (G.1). Inside capillary region, in turn, the stresses are assumed to be described by the expressions shown in Eq. (G.2). In Eq. (G.1) and Eq. (G.2), A_1, A_2, B_2, C_1 and C_2 are constants to be determined.

\[
\sigma_{r,1} = A_1 \quad ; \quad \sigma_{\theta,1} = A_1 \quad ; \quad \sigma_{r,1} = C_1 \quad \text{(G.1)}
\]

\[
\sigma_{r,2} = A_2 + \frac{B_2}{r^2} \quad ; \quad \sigma_{\theta,2} = A_2 + \frac{B_2}{r^2} \quad ; \quad \sigma_{r,2} = C_2 \quad \text{(G.2)}
\]

To obtain the constants values, we assume a set of boundary conditions. The first one is that the capillary outer boundary is free. It means that \(\sigma_{r,2}(r_{out}) = 0\), where \(r_{out}\) is the capillary tube outer radius. It allows obtaining Eq. (G.3). The second condition is that the radial stress must be continuous. Therefore, at the inner radius position, \(r_{in}\), we have \(\sigma_{r,1}(r_{in}) = \sigma_{r,2}(r_{in})\). This condition together with Eq. (G.3) allows obtaining Eq. (G.4).

\[
B_2 = -r_{out}^2 A_2 \quad \text{(G.3)}
\]

\[
A_1 = A_2 \left(1 - \frac{r_{out}^2}{r_{in}^2}\right) \quad \text{(G.4)}
\]
The third condition is to consider the plane strain approximation since here the fiber length is assumed to be much greater than the fiber cross-sectional dimensions. Thus, under plane strain approximation, the longitudinal strain, $\varepsilon_z$, is set to zero. By using the Hooke law, Eq. (G.5) can be written to express the longitudinal strain. It is worth emphasizing that, as in the approached problem we are interested in accounting the displacements due to temperature variations, $\Delta T$, the Hooke law must be written with an additional term which accounts for the thermal expansion effect. Thus, by setting $\varepsilon_z = 0$ in both internal and external regions of the composite structure, Eq. (G.6) and Eq. (G.7) can be found. In Eq. (G.5), Eq. (G.6) and Eq. (G.7), $E$ represents Young modulus, $\nu$ the Poisson ratio and $\alpha$ the thermal expansion coefficients. Index 1 stands for the metal properties (inner region) and index 2 stand for the capillary properties (outer region).

$$\varepsilon_z = \frac{\sigma_z}{E} - \frac{\nu}{E} (\sigma_r + \sigma_\theta) + \alpha \Delta T \tag{G.5}$$

$$C_1 = 2\nu_1 A_2 \left(1 - \frac{\rho_{\text{out}}}{r_{\text{in}}^2}\right) - \alpha_1 E_1 \Delta T \tag{G.6}$$

$$C_2 = 2\nu_2 A_2 - \alpha_2 E_2 \Delta T \tag{G.7}$$

The fourth condition is the radial displacement, $u(r)$, continuity. It is written as $u_1(r_{in}) = u_2(r_{in})$, where $u_1(r)$ represents the displacement in the metal region and $u_2(r)$ the displacement in the capillary region. Here, the radial displacement is expressed as a function of the azimuthal strain – as already used in Chapter 2 and explained in Appendix B), $u(r) = r \varepsilon_\theta(r)$. Again, here we write the Hooke law with an additional term for accounting the thermal expansion – Eq. (G.8). Therefore, $u_1(r_{in}) = u_2(r_{in})$ condition allows obtaining Eq. (G.9), which is an expression that allows calculating the $A_2$ constant value from the fundamental parameters of the problem.

$$\varepsilon_\theta = \frac{\sigma_\theta}{E} - \frac{\nu}{E} (\sigma_r + \sigma_z) + \alpha \Delta T \tag{G.8}$$

$$A_2 = \frac{[(1+\nu_2)\alpha_2-(1+\nu_1)\alpha_1]\Delta T}{E_1 \left(\frac{1}{\nu_1-\frac{1}{2}} - \frac{1}{2} - \frac{\rho_{\text{out}}}{r_{\text{in}}^2}\right) + E_2 \left(\frac{1}{\nu_2-\frac{1}{2}} - \frac{1}{2} - \frac{\rho_{\text{out}}}{r_{\text{in}}^2}\right)} \tag{G.9}$$
Finally, we can observe that the expression shown in Eq. (G.9) allows expressing all the other constants $A_1$, $C_1$ and $C_2$ also as a function of the fundamental parameters of the problem by simply substituting Eq. (G.9) in Eq. (G.4), Eq. (G.6) and Eq. (G.7). The knowledge of the values of these constants allows obtaining the expressions for the stresses by substituting them in Eq. (G.1) and Eq. (G.2).

Moreover, as the displacement in each region of the problem is obtained by $u(r) = r \varepsilon_\theta(r)$ and $\varepsilon_\theta(r)$ is calculated by Eq. (G.8) (and, additionally, the expressions for all the stresses are now known), Eq. (G.10) and Eq. (G.11) can be obtained for, respectively, the displacements experienced by the mass elements in the metal and in the capillary tube regions of the composite structure. The parameter $\delta$ seen in Eq. (G.10) and Eq. (G.11) can be calculated as shown in Eq. (G.12).

\[
\begin{align*}
 u_1(r) &= \Delta T \left[ \frac{\delta}{E_1} \left( 1 - \nu_1 \right) \left( \nu_1 + \frac{1}{2} \right) + (1 + \nu_1)\alpha_1 \right] r \quad \text{(G.10)} \\
 u_2(r) &= \Delta T \left[ (1 + \nu_2) \left[ \frac{\delta}{E_2} \left( \nu_2 - \frac{1}{2} \right) + (1 + \nu_2)\alpha_2 \right] r + \frac{\delta r_{\text{out}}^2}{E_2 r} \right] \quad \text{(G.11)} \\
 \delta &= \frac{(1+\nu_2)\alpha_2-(1+\nu_1)\alpha_1}{(1+\nu_1)\left( \nu_1 - \frac{1}{2} \right) \left( 1 - \frac{r_{\text{out}}^2}{r_{\text{in}}^2} \right) + (1+\nu_2) \left( \nu_2 - \frac{1}{2} \right) \frac{r_{\text{out}}^2}{r_{\text{in}}^2}} \quad \text{(G.12)}
\end{align*}
\]
Appendix H

Publications list

In this appendix, a list of the publications and of the research presented in congresses will be presented. My contributions to the journal articles are specified just below their citation (labeled as JHO’s contributions). Journal and Proceedings publications texts are attached to this appendix.

H.1 Journal publications


   JHO’s contribution:
   • Development of the analytical model;
   • Fiber fabrication;
   • Paper text review;
   • Discussion of the results.


   JHO’s contribution:
   • Development of the analytical model;
   • Fiber fabrication;
   • Pressure sensing measurements;
   • Paper writing;
   • Discussion of the results.


   JHO’s contribution:
   • Paper text review;
   • Fiber tapers preparation;
   • Discussion of the results.

JHO’s contribution:
- Proposal of the idea together with CMBC;
- Paper writing;
- Fiber fabrication;
- Sensing experiments;
- Discussion of the results.


JHO’s contribution:
- Proposal of the idea together with CMBC;
- Paper text review;
- Discussion of the results.


JHO’s contribution:
- Proposal of the idea together with CMBC;
- Paper text review;
- Discussion of the results.


JHO’s contribution:
- Paper writing;
- Data analysis;
- Discussion of the results.


JHO’s contribution:
- Paper writing;
- Dual-environment pressure sensing experiments;
- Discussion of the results.
H.2 Conference proceedings publications


H.3 Other research presented in congresses


7. P. E. S. Pellegrini, Jonas H. Osório, C. M. B. Cordeiro, “Photonic crystal fiber long period gratings”. XXXVII Brazilian Condensed Matter Physics Meeting, Costa do Sauípe, Brazil, 2014.
H.4 Award

1. The OFS'24 Best Brazilian Student Paper Award, 24th International Conference on Optical Fibre Sensors, 2015
Metal-filled embedded-core capillary fibers as highly sensitive temperature sensors

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Abstract— We report the fabrication of a metal-filled embedded-core capillary fiber and its employment as a temperature sensor. This simplified structure consists of a germanium-doped elliptical-shaped core placed within the wall of a silica capillary. In a post-process stage the fiber was filled with indium chosen as the sensing element because of its low melting point and reasonable large thermal expansion coefficient compared to silica. The sensor operation is based on the metal thermal expansion that changes the core birefringence due to induced stress variations within the capillary wall. Sensor interrogation was performed by wavelength-scanning and a (14.4 ± 0.7) nm°C⁻¹ sensitivity was measured, which is considerably higher than those usually found in Bragg gratings-based sensors and is amongst the highest ones reported with sophisticated fibers such as metal-filled and index matching fluid-filled photonic-crystal fibers.

Index Terms— optical fiber sensors, capillary fibers, fiber optics, temperature.

I. INTRODUCTION

The intrinsic advantages of optical fiber sensors include immunity to electromagnetic noise, capability of remote sensing, multiplexing, and the possibility of creating highly compact sensors while maintaining their robustness. Recently, several arrangements on temperature sensing were reported using different fibers and interrogation schemes. Fiber Bragg gratings (FBGs) [1] and Long Period gratings (LPGs) [2], side-hole fibers [3,4], Photonic Crystal Fibers (PCFs) [5,6], tapered fibers [7], and waist-enlarged fusion splicers [8] are examples of technologies explored in literature for attaining fiber-based temperature sensors. Interrogation systems are usually based on interferometric schemes, especially Fiber Loop Mirrors (FLMs) [3,5].

The reported complexity and variety of temperature sensors arises from the fact that conventional optical fibers are not very suitable for this purpose, since they respond to bending, are not polarization maintaining, and have low temperature sensitivity [9]. To minimize bending and polarization responses one usually employs a HBr fiber and interrogate it with a FLM scheme. The interference fringes pattern results from the phase difference between the travelling orthogonal modes, and depends on the fiber linear birefringence and length. Since the heat length is inversely proportional to the birefringence, these FLM sensors are usually quite long and may be impractical. Still, sensitivities on the order of 0.94 nm°C⁻¹ were reported [10] showing a great improvement compared to a regular FBG sensitivity (0.01 nm°C⁻¹).

Additionally, microstructured fibers (side-hole fibers and PCFs) can be functionalized in a post-processing stage. This is usually achieved by inserting a temperature sensitive material into some or all of their holes. Metals and liquids can be used to tune the fiber linear birefringence and consequently the sensor length. Sensitivities of -6.3 nm°C⁻¹ [3], -9.0 nm°C⁻¹ [11], and 6.6 nm°C⁻¹ [12] were reported with side-hole indium filled fibers and alcohol-filled PCFs, respectively. An even higher sensitivity of 16.9 nm°C⁻¹ was reported with a PCF filled with an index matching fluid [13].

The advent of PCFs has certainly brought new degrees of freedom by allowing one to adjust the fiber properties through the microstructure design. Nonetheless, some designs may be challenging and time consuming. In this work, we make use of a much simpler design of optical fiber, an embedded-core capillary fiber [14]. Analytical simulations are presented to discuss the role played by the ratio between inner and outer capillary diameter and the core position within the capillary wall on temperature sensitivity. To experimentally demonstrate the sensor operation, the fiber was functionalized by inserting indium into its hole and a sensitivity of (14.4 ± 0.7) nm°C⁻¹ could be measured.

II. TEMPERATURE-INDUCED BIREFRINGENCE IN METAL-FILLED CAPILLARY FIBERS

Material birefringence, \(\Delta n_{\text{mat}}\), can arise from the existence of asymmetric stresses distributions within a structure, which, for example, can be induced from pressure application or be due to bending [15,16]. It can be accounted for by (1), where \(\kappa\) and \(\sigma\) are the stresses on the horizontal and vertical directions, \(\kappa\) is the material birefringence under no stress and \(\kappa_I\) and \(\kappa_2\) are the elasto-optic coefficients (\(C_1 = -0.69 \times 10^{-12}\) Pa⁻¹ and \(C_2 = -4.19 \times 10^{-12}\) Pa⁻¹ for silica) [17,18].

Here, we study a configuration in which a silica capillary is filled with a metal (Fig. 1a). When the structure is heated, displacements are experienced by the mass elements which compose the metal and the capillary region and a birefringence change is expected. However, since the thermal expansion coefficients of metal and silica are different (metal’s one is greater), free expansion is not allowed inside the structure and the displacements of the metal region become restricted.

The displacements for the metal region, $u_i(r)$, and for the silica region, $u_i(r)$, can be accounted from (2) and (3), which are obtained by imposing the following boundary conditions: i) radial displacement and radial stress are continuous; ii) capillary outer surface experiences free expansion. Besides, one has also assumed plane strain approximation since we are considering the structure length is much larger than the cross-section dimensions. To obtain (2), one has followed the steps which are very didactically explained in [19]. In (2) and (3), $\Delta T$ is the temperature variation, $r_{in}$ and $r_{out}$ are respectively the capillary inner and outer radius $r$ is the Poisson ratio, $E$ is the Young modulus and $\alpha$ is the thermal expansion coefficient – index $1$ stands for the filling metal and index $2$ stands for silica. Parameter $\delta$ is accounted by (4).

$$u_i(r) = \Delta T \left[ \frac{\delta}{E_i} \left( 1 + \nu_i \right) \left( \frac{r_i}{r} \right)^2 + \left( 1 + \nu_i \right) \nu_i \right]$$  \hspace{1cm} (2)$$

$$u_i(r) = \Delta T \left[ \frac{\delta}{E_i} \left( 1 + \nu_i \right) \left( \frac{r_i}{r} \right)^2 + \left( 1 + \nu_i \right) \nu_i \right] + \frac{\delta}{E_i} \nu_i$$  \hspace{1cm} (3)$$

$$\delta = \frac{1}{E_i} \left( \frac{1}{\nu_i} - \frac{1}{2} \right) \left( \frac{r_i}{r} \right)^2 + \left( 1 + \nu_i \right) \nu_i$$  \hspace{1cm} (4)$$

Solid red line in Fig. 1b illustrates the displacement of the mass elements, calculated from (2) and (3), within an indium-filled silica capillary with inner radius $20 \mu m$ and outer radius $50 \mu m$ for a $50^\circ C$ temperature variation. Indium is chosen to be the filling metal due to its considerably high thermal expansion compared to silica ($32.1 \times 10^{-6} \degree C^{-1}$ for indium and $0.55 \times 10^{-6} \degree C^{-1}$ for silica [3]) and its low melting point ($150 \degree C$ [5]), which, experimentally, simplifies the accomplishment of the filling process.

In Fig. 1b, one can see that the displacement grows linearly as a function of the radial position for the metal region (up to $20 \mu m$) and then assumes a decaying profile in the silica region. For comparison, one presents as a blue dashed line the displacement which would be observed for an indium solid cylinder with radius $20 \mu m$ experiencing free expansion for the same temperature variation. In the free expansion case, the displacement at $20 \mu m$ is $46.5 \mu m$ while, for the restricted case, the displacement is $30.3 \mu m$. It is seen that the silica capillary constrains the metal thermal expansion lowering the displacement it would be able to experience in free expansion.

In addition, the displacement for a hollow silica capillary (with $20 \mu m$ inner radius and $50 \mu m$ outer radius) is also presented in Fig. 1b (green dotted line). For this situation, at the radial position of $20 \mu m$, the displacement observed for a $50^\circ C$ temperature variation would be $0.6 \mu m$. Hence, it can be visualized that when one considers the capillary is indium-filled, metal expansion pushes silica further it would displace due to its own thermal expansion.

Furthermore, the indium-filled capillary was numerically simulated by using a finite-element-based model in software COMSOL® and the results are presented as blue circles in Fig. 1b. Numerical and analytical results are identical. In the simulations, one used $12.74$ GPa and $72.5$ GPa as indium and silica Young modulus respectively $[20, 21]$. $0.45$ and $0.17$ were the values used for, respectively, indium and silica Poisson ratio $[20, 22]$.

According to [19], the radial ($\sigma_r$) and hoop ($\sigma_\theta$) stresses at a temperature $T$ for a radial position $r$ within the silica region can be expressed as in (5), where $T_s$ is the temperature at which there’s no stress within the composite structure and $\delta$ is obtained by (4). If the radial and hoop stresses are represented in rectangular coordinates for positions along the horizontal axis, materials mechanics theory shows that $\sigma_r = \sigma_{r0}$ and $\sigma_\theta = \sigma_{\theta0}$. [23]. Thus, by using (1) and considering null birefringence under no stress (i.e. $B_0 = 0$), one can
find the material birefringence derivative with respect to temperature for a position $x$ along the horizontal axis as shown in (6).

$$\sigma_1(x) = \Delta(T - T_a) \left(1 - \frac{C_1}{C_2}\right) \cdot \sigma_2(x) = \Delta(T - T_a) \left(1 + \frac{C_1}{C_2}\right)$$

$$\frac{dB_{\text{max}}(x)}{dT} = -2I(C_2 - C_1) \frac{C_1}{C_2} \frac{dx}{x^2}$$

In Fig. 1c, one exposes a plot for the absolute value of the material birefringence with respect to the position within the metal-filled silica capillaries walls. Here, we assumed again capillaries with 20 $\mu$m inner radius and 50 $\mu$m outer radius. For comparison, we assumed the filling metal to be indium, tin or bismuth (once again, these metals were chosen due to their relatively low melting points: 156 °C for indium [3], 231 °C for tin and 271.3 °C for bismuth [17]).

Fig. 1c results show the absolute values of material birefringence derivative as respect to temperature, $dB_{\text{max}}/dT$, are higher for the indium-filled capillary. Although Young modulus and Poisson ratio contributes for accounting these values, one can identify the greater indium thermal expansion coefficient $(32.1 \times 10^{-6} \text{ °C}^{-1}) [3])$ when compared to the other analyzed metals $(23 \times 10^{-6} \text{ °C}^{-1}$ for tin and $13.3 \times 10^{-6} \text{ °C}^{-1}$ for bismuth [21]) as the main parameter which allows obtaining higher $dB_{\text{max}}/dT$ values. Furthermore, by observing Fig. 3, one can visualize that greater $dB_{\text{max}}/dT$ values are obtained for positions closer to the capillary inner radius – a similar behavior of that observed in pressurized embedded-core fibers [14]. In the simulations, 0.36 and 0.33 was used as tin and bismuth Poisson ratios [22] and 42 GPa and 34 GPa as tin and bismuth Young modulus [22,23].

III. EXPERIMENTAL RESULTS AND DISCUSSION

The embedded-core capillary fiber preform was realized by merging a germanium doped silica rod to a silica tube and then drawing it to fiber diameter [14]. The obtained fiber cross section is presented in Fig. 2a. It has a 40 $\mu$m inner diameter and a 100 $\mu$m outer diameter. The core is 41 $\mu$m distant from the center of the fiber and has dimensions of 11 $\mu$m and 3.5 $\mu$m. A 34 cm long fiber was filled with a 17 cm long indium using the molten alloy technique [26].

To characterize the fiber response to temperature the polarimetric scanning wavelength method was used [27]. A broadband optical source was launched into the fiber after passing through a polarizer (P1), as shown in Fig. 2b. This polarizer is used to guarantee that both orthogonal polarization states are equally excited inside the fiber. Light emerging from the fiber was directed to a second polarizer (P2) and recombined to provide an interference fringe pattern. The transmitted signal was observed using an Optical Spectrum Analyzer (OSA). The spectral position of the interference fringes depends on the temperature surrounding the fiber. Temperature variations induce metal expansion or contraction and are optically translated into linear birefringence modifications. These changes shift the interference fringes pattern.

The sensitivity coefficient $C_T$ can then be defined as the wavelength displacement with respect to temperature as shown in equation (7). It can also be expressed as a function of the wavelength, $\lambda$, group birefringence $G$, and phase birefringence derivative with respect to temperature [28].

$$C_T = \frac{\Delta \lambda}{\Delta T} = \frac{\lambda}{G} \frac{dB_{\text{max}}}{dT}$$

Embedded-core capillary fibers were filled with indium at pressures ranging from 2 to 20 bar. Results show that the higher the filling pressure, the lowest the group birefringence [29]. For a 2 bar filling pressure, we measured a group birefringence of $20 \times 10^{-3}$. Fibers with 8 bar and 20 bar filling pressures resulted in group birefringences of $3.4 \times 10^{-4}$ and $1.4 \times 10^{-4}$, respectively. One can easily note that the sensitivity coefficient, as described in eq. (7), is inversely proportional to the group birefringence, which makes higher filling pressures a must-have for higher sensitivities.

To experimentally evaluate the sensitivity coefficient, $C_T$, the indium-filled fiber was placed inside a water bath connected to a heat source (hot plate), as shown in Fig. 2b. The temperature of the water was monitored with a thermocouple and measurements were taken after its stabilization. Fig. 3 shows the wavelength of the dips as a function of temperature. Increasing the temperature redshifts the dips. The inset presents the linear dependence of the wavelength with temperature variations. To determine the sensitivity it is important to note that, due to experimental limitations, not the entire fiber is filled with indium and a small amount of metal is not inside the water bath. To take this into account, one must average these contributions as the ratio of the heated length over total fiber length.

![Fig. 2. (a) Embedded-core capillary fiber filled with indium cross-section. The white bar represents 40 $\mu$m. (b) Experimental setup for temperature sensing. SC: supercontinuum light (SC), P1 and P2: polarizers, O1 and O2: objective lenses. OSA: optical spectrum analyzer.](image)
In this way, we found the temperature sensitivity to be (14.4 ± 0.7) nm°C⁻¹. The sensitivity, as stated in eq. (7), is inversely proportional to the group birefringence. Experimentally, we verified that the group birefringence increases with temperature. For the 8 bar filled-fiber, it is raised from 3.4 to 5.8×10⁻¹⁰ when the temperature goes from 22 to 72°C. This behavior lowers the sensor sensitivity but may be compensated by adjusting the metal filling pressure, as discussed above.

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REFERENCES

Simplifying the design of microstructured optical fibre pressure sensors

Jonas H. Osório1, Giancarlo Chesini2, Valdir A. Serrão2, Marcos A. R. Franco2 & Cristiano M. B. Cordeiro1

In this paper, we propose a way to simplify the design of microstructured optical fibres with high sensitivity to applied pressure. The use of a capillary fibre with an embedded core allows the exploration of the pressure-induced material birefringence due to the capillary wall displacements and the photoelastic effect. An analytical description of pressure-induced material birefringence is provided, and fibre modal characteristics are explored through numerical simulations. Moreover, a capillary fibre with an embedded core is fabricated and used to probe pressure variations. Even though the embedded-core fibre has a non-optimized structure, measurements showed a pressure sensitivity of 3.04 ± 0.01 nm/bar, which compares well with more complex, specially designed fibre geometries reported in the literature. These results demonstrate that this geometry enables a novel route towards the simplification of microstructured fibre-based pressure sensors.

The application of fibre optics in sensing applications has been widely studied in recent years. Hydrostatic pressure, temperature, refractive index, strain and curvature are some examples of the parameters that can be monitored by using optical fibres1. In this context, numerous technologies – such as Bragg and long-period gratings3–5, fibre tapers4, multimode interferometers6, rocking filters8–10, photonic-crystal fibres (PCFs)11–15 or combinations thereof – have been used to explore the potential of optical fibres in performing sensing measurements. Advantages of optical fibre-based sensors include high sensitivity, electromagnetic immunity and the possibility of functioning in harsh environments. Moreover, they are usually very compact, lightweight and provide great liberty with respect to choosing a sensor’s characteristics4.

Due to their inherent design versatility, microstructured optical fibres are a highly suitable platform for realizing pressure sensors16–19. In this approach, they are usually designed in such a manner that the application of hydrostatic pressure generates asymmetric stress distributions within a fibre and, via the photoelastic effect20, birefringence variations. Side-joule PCFs and fibres with sophisticated microstructure geometries (such as the fibre reported by A. A. Kuzin et al.21, which is endowed with a triangular-shaped pattern of air holes), for instance, have already been used to probe pressure variations. The fabrication process of these fibres is, however, complicated and time-consuming and demands much technical effort.

In this paper, we propose the use of a simplified specialty optical fibre structure – the embedded-core capillary fibre – in hydrostatic pressure measurements. The proposed fibre consists of a silica capillary structure with a germanium-doped region (which acts as the fibre core) placed within the capillary wall. Due to the simplicity of the fibre, its fabrication process is straightforward and can be accomplished in a single-step drawing process.

Typical microstructured optical fibres used in pressure sensors are usually endowed with air holes in patterns whose geometric characteristics are chosen so that they can asymmetrically shield the fibre core from the effect of pressure and generate birefringence variations within the core. Here, we avoid the use of a pattern of holes and work with a capillary fibre. The photoelastic effect is explored by simply studying the capillary walls’ displacement due to the application of external pressure and the induced variations in the stress profile.

In the following sections, an investigation of pressure-induced birefringence in capillary fibres is presented. Initially, material birefringence is analytically studied using the Euler solution20 for the stresses within pressurized tubes. In sequence, modal birefringence is studied numerically. Finally, the fabrication of the fibre is described, and experimental pressure-sensing results are reported and compared to simulated data and literature values.

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The results show that pressure-induced birefringence variations attained in embedded-core capillary fibres are similar to those achieved in sophisticated microstructured fibres. An important step towards the simplification of microstructured fibre-based pressure sensors can, therefore, be identified.

**Results**

**Pressure-induced material birefringence in capillary fibres.** The application of hydrostatic pressure to capillary fibres (Fig. 1a) causes displacements on their walls, which implies the induction of stresses into the capillary structure. As material birefringence is a function of the induced stresses, its value is expected to vary if the fibre undergoes pressure. Equation 1 expresses material birefringence, \( B_{\text{mat}} \), dependence on the pressure-induced stresses in the horizontal and vertical directions, i.e., \( \sigma_1 \) and \( \sigma_2 \), respectively [1]. In Equation 1, \( C_1 \) and \( C_2 \) are the elasto-optic coefficients and \( n_0 \) and \( n_\text{re} \) are the material refractive indices under no stress. For silica, the values are \( C_1 = -0.69 \times 10^{-12} \text{ Pa}^{-1} \) and \( C_2 = -4.19 \times 10^{-12} \text{ Pa}^{-1} \).

\[
B_{\text{mat}} = n_{\text{re}} - n_0 + (C_1 - C_2)(\sigma_1 - \sigma_2)
\]  

To study the pressure-induced material birefringence profile inside the wall of capillary fibres, one analysed the Lamé solution for the stresses inside thick-walled tubes subjected to hydrostatic pressure [2]. As already referenced, stresses inside the capillary fibre walls arise from the displacement they experience when hydrostatic pressure is applied. The displacement at a radial position \( r \) inside the capillary wall, \( u(r) \), can be found using Equation 2, where \( r_\text{in} \) and \( r_\text{out} \) are the inner and outer radii of the tube, respectively, \( v \) and \( E \) are the Poisson ratio and Young's modulus of the material the capillary wall is made of (for silica, \( v = 0.165 \) and \( E = 72.5 \text{ GPa} \)), respectively, and \( p_\text{in} \), and \( p_\text{out} \) are the internal and external pressure applied to the fibre, respectively.

\[
u(r) = \frac{E}{2(1-v)} \left[ r - \left( \frac{r_\text{in}}{r_\text{out}} \right)^2 \right] \left( 1 - \frac{r_\text{in}^2 - r_\text{out}^2}{r_\text{out}^2} \right) + \left( 1 + v \right) \left( p_\text{in} - p_\text{out} \right) \frac{r_\text{in}^2}{2E}
\]

Figure 1b shows the displacement profile along the wall of a silica capillary (with the \( r_\text{in}/r_\text{out} \) ratio being equal to 0.5) when it is subjected to an external pressure level of 50 bar (5 MPa) and has an internal pressure level of 1 bar (0.1 MPa). In this simulation, \( r_\text{in} \) is considered to be 40 \( \mu \text{m} \). One can see that for the case shown in Fig. 1b, the displacement at the inner radius position is, in modulus, lower than the one observed at the outer radius position, implying a decrease in wall thickness. This situation is schematized in Fig. 1c, in which the inner and outer wall displacements are represented.

Displacements of the mass elements inside the tube wall allow for defining strains into the fibre structure. According to the Lamé description, the strain along the radial direction is obtained by solving \( \varepsilon_r(r) = \frac{du}{dr} \), whereas the strain along the azimuthal direction is obtained by solving \( \varepsilon_\theta(r) = \frac{du}{r dr} \), where \( u(r) \) is the displacement shown in Equation 2. Considering a situation in which a capillary with inner and outer radii of 40 \( \mu \text{m} \) and 80 \( \mu \text{m} \), respectively, is subjected to an external pressure of 50 bar, the strain results are as shown in Fig. 2a. By observing the behaviour of the strain along the radial direction, it can be observed that it can be either tensile \( (\varepsilon_r(r) > 0) \) or compressive \( (\varepsilon_r(r) < 0) \). There is a point of zero radial strain at the radial position \( r_{\text{zero}} = r_\text{in} \left( 1 + \frac{\sigma_\text{in} - \sigma_\text{out}}{\sigma_\text{in}} \right) \), which, for the situation shown in Fig. 2a (\( r_\text{in} = 40 \mu\text{m}, r_\text{out} = 80 \mu\text{m}, p_\text{in} = 1 \text{ bar}, p_\text{out} = 50 \text{ bar}, v = 0.165 \)), is calculated to be 46.9 \( \mu\text{m} \). Moreover, one can observe that the azimuthal strain is always compressive.
Figure 3. Strain and stresses within capillary fibre wall. (a) Strain and (b) stress as a function of the radial position for a capillary fibre with \( r_i = 40 \mu m \) and \( r_o = 80 \mu m \) under an external pressure of 50 bar and inner pressure level of 1 bar. Green triangles and dark red circles are the results obtained from the COMSOL\textsuperscript{TM} numerical model.

The Lamé description also allows the determination of the radial (\( \sigma_r \)) and hoop (\( \sigma_\theta \)) stresses, which are induced within the tube wall due to the application of hydrostatic pressure. The results are expressed by Equations 3 and 4, where \( r_i \) and \( r_o \) represent the inner and outer radii of the tube, respectively, and \( p_i \) and \( p_o \) represent the internal and external pressure, respectively. Again, due to the problem symmetry, the stresses do not vary azimuthally and are a function of the radial position only:

\[
\sigma_r(r) = \frac{1}{\left(1 - \frac{t_o}{t_{tr}}\right)} \left( \frac{t_o}{t_{tr}} - \frac{r_o - r_i}{r} \right) \left( p_o - p_e \right) \left( \frac{t_o}{r} \right) \]  
\[
\sigma_\theta(r) = \frac{1}{\left(1 - \frac{t_o}{t_{tr}}\right)} \left( \frac{t_o}{t_{tr}} - \frac{r_o - r_i}{r} \right) \left( p_o + p_e \right) \left( \frac{t_o}{r} \right) \]  

Figure 2b shows the radial and hoop stress behaviours along the tube wall (between \( r_i = 40 \mu m \) and \( r_o = 80 \mu m \)) for the situation in which the tube wall is subjected to an external pressure of 50 bar and an internal pressure of 1 bar (according to Equations 3 and 4). Note that the absolute value of the radial stress at the outer radius assumes the external pressure value (\( p_o = 50 \text{ bar} = 5 \text{ MPa} \)), whereas that at the inner radius assumes the internal pressure value (\( p_e = 1 \text{ bar} = 0.1 \text{ MPa} \)), which are the boundary conditions of the problem. Furthermore, numerical data attained from a finite-element-based model built using the COMSOL\textsuperscript{TM} software are also shown in Fig. 2b (green triangles and dark red circles). It is seen that the analytical and numerical results are very similar.

Stresses written in polar coordinates (\( \sigma_r \) and \( \sigma_\theta \)) can be readily expressed in rectangular coordinates (\( \sigma_x \) and \( \sigma_y \)) by employing the transformations presented in Equation 3. To obtain \( \sigma_x \) and \( \sigma_y \) along the horizontal axis, one sets \( \theta = 0 \) and, therefore, concludes that \( \sigma_x = \sigma_r \) and \( \sigma_y = \sigma_\theta \).

\[
\sigma_x = \sigma_r \cos^2 \theta + \sigma_\theta \sin^2 \theta; \quad \sigma_y = \sigma_r \sin^2 \theta + \sigma_\theta \cos^2 \theta \]  

By identifying that along the horizontal axis, \( \sigma_x \) can be expressed by Equation 3 and \( \sigma_y \) by Equation 4, and by substituting these results into Equation 1, one can obtain Equation 6, which expresses the behaviour of the material birefringence at a position \( x \) along the horizontal axis inside the capillary wall. Moreover, for obtaining Equation 6, as shown below, it is assumed that \( n_{tr} \) and \( n_o \) are identical (no birefringence under no stress). Additionally, one defines gauge pressure as \( p_{gap} = p_o - p_e \).

\[
B_{rad}(x) = 2(C_2 - C_1)p_{gap} \left( 1 - \frac{t_o}{t_{tr}} \right) \left( \frac{t_o}{x^2} \right) \]  

If the absolute value of material birefringence is plotted as a function of the position on the horizontal axis for capillaries with different \( r_o/r_i \) ratio values (but with the same inner radius value, i.e., 40 \( \mu m \)) for \( p_{gap} = 50 \text{ bar} \), one obtains the results shown in Fig. 3a. The results show that when external pressure acts on the fibre, induced material birefringence values are higher for capillary fibres with thinner wall thicknesses. Furthermore, greater material birefringence values are attained for positions closer to the inner radius.
Figure 3. Study of pressure-induced material birefringence. (a) Material birefringence along the horizontal axis for capillaries with different $r_{c}/r_{o}$ ratios and (b) for a capillary with $r_{c} = 40 \mu m$ and $r_{o} = 80 \mu m$ under increasing gauge pressure values. (c) Material birefringence as a function of gauge pressure at the positions $r_{c} = 40 \mu m, r_{1} = 60 \mu m, r_{2} = 80 \mu m$ and (d) for a capillary with $r_{c} = 40 \mu m$ and a $r_{c}/r_{o}$ ratio equal to 0.5, 0.6, 0.7 and 0.8.

Figure 3b presents material birefringence modulus as a function of the position along the horizontal axis for a capillary with inner and outer core dimensions of 40 $\mu m$ and 80 $\mu m$, respectively, subjected to four different pressure levels (20, 30, 40 and 50 bar). One can realize that although material birefringence increases for all positions inside the capillary wall, the increment occurs at different rates – they are higher closer to the internal side of the capillary and lower towards the external side. Different slopes of the material birefringence variation due to external pressure application are clearly observed in Fig. 3c, where the material birefringence of a capillary fibre is plotted for the inner radius ($r_{c} = 40 \mu m$), outer radius ($r_{o} = 80 \mu m$), and middle point of the capillary wall ($r_{m} = 60 \mu m$). Slopes varied from $9.3 \times 10^{-12}$ bar$^{-1}$ to $2.3 \times 10^{-10}$ bar$^{-1}$ along the capillary fibre wall. Additionally, as shown in Fig. 3d, material birefringence is plotted as a function of the applied external pressure for capillaries with $r_{c} = 40 \mu m$ but different $r_{c}/r_{o}$ ratios. Based on this graph, one can see that $dB dB$ is higher for higher $r_{m}/r_{o}$ ratio. Therefore, it is observed that material birefringence shows a stronger dependence on pressure variations for positions closer to the inner radius and for capillaries with thinner walls.

Modal birefringence dependence on applied pressure. To explore the birefringence dependence on the applied pressure in practical applications, one studied a configuration in which a high refractive index core is embedded into the capillary wall, as shown in Fig. 1a. The core consists of a germanium-doped region and has an elliptical shape. Although the material birefringence has been analytically studied above, it is necessary to investigate the modal birefringence behaviour. To do this, a capillary fibre with an embedded-core structure was simulated in COMSOL®, and its modal birefringence dependency on applied pressure was obtained.

In the simulations, a capillary fibre with inner and external radii of 40 $\mu m$ and 67.5 $\mu m$, respectively, was used. Moreover, the core was considered to be an ellipse with dimensions of 5.7 $\mu m$ and 11.4 $\mu m$. The effective refractive indices of the $x$- and $y$-polarized core modes were obtained for different pressure conditions, and the birefringence derivative as a function of pressure, $dB_{c}/dP$, was numerically modelled. The calculation of $dB_{c}/dP$
Figure 4. Modal birefringence simulation results. Modal birefringence derivative as a function of the core position in the capillary fibre wall. Blue region represents the capillary wall region, whereas yellow ellipses represent the core area. Insets illustrate the core location within the capillary fibre.

was performed for several core positions inside the capillary wall, as seen in Fig. 4. The blue region represents the capillary wall, and the yellow ellipses represent the core area. Moreover, the insets in Fig. 4 illustrate the core location (dark blue ellipses) within the capillary structure for selected points from the Fig. 4 plot.

As shown in Fig. 4, one can see that when the entire core is located in the capillary wall, the $\frac{dB_{\text{biref}}}{dP}$ behaviour is analogous to that of the material birefringence case – it increases towards the inner capillary wall. As the core approaches the inner or outer wall of the capillary, a section of its area can be outside the capillary structure (see Fig. 4 insets), and decreasing $\frac{dB_{\text{biref}}}{dP}$ values are observed. It is recognized that to obtain a maximized birefringence dependence on pressure variations, it is crucial to completely embed the core area within the capillary structure. As expected from the analytical description, the highest $\frac{dB_{\text{biref}}}{dP}$ values are found for core positions closer to the inner wall.

Pressure-sensing measurements. To provide an experimental realization of the proposed fibre structure, a fibre in which the core was embedded into the capillary structure was fabricated. This structure was named an embedded-core fibre; Fig. 5a shows its cross-section. The capillary diameters are 40 μm and 100 μm, the distance between the centre of the fibre and the core position is 35 μm, and the core dimensions are 11 μm and 3.5 μm. Additionally, aiming to have a second fibre for comparison, the fabrication of a fibre to which the core was placed on the fibre's outer surface was performed; this structure was named a surface-core fibre. In this structure, the capillary inner and outer diameters are 80 μm and 140 μm, respectively, and the core dimensions are 6 μm and 9 μm (Fig. 5b). To fabricate the fibres, macroscopic preforms were prepared by merging a germanium-doped silica rod with a silica tube, and the resulting structure was drawn using a tower facility. Both fibres were fabricated at Unicamp.

The polarimetric wavelength scanning method was used to characterize the sensitivity of the fibres to external pressure variations. In this method, a broadband optical source (supercontinuum from a photonic-crystal fibre – SC) was used to launch light into the optical fibre and a first polarizer (P1) was employed for exciting the two orthogonal modes of the birefringent fibre. A second polarizer (P2) was used to allow recombination and interference between the orthogonal modes that travelled along the fibre, and the transmitted signal was measured using an optical spectrum analyser (OSA). Moreover, a pressure chamber (PC) was used to subject the fibre to different pressure conditions. Figure 5c presents a schematic of this experimental setup.

The interference spectrum measured using the polarimetric wavelength scanning method is characterized by spectral fringes whose spectral positions are dependent on the pressure applied to the fibre (as embedded-core fibre birefringence is altered when pressure is applied). Thus, one defines a sensitivity coefficient: $C_\lambda \equiv \frac{\Delta \lambda}{dP}$, which accounts for the spectral displacement of the interferometric fringes (IF) due to pressure variations. The $C_\lambda$ value can also be expressed as a function of the wavelength, $\lambda$, fibre group birefringence, $G$, and phase birefringence derivative with respect to pressure, $\frac{\partial B_{\text{biref}}}{\partial P}$, as presented in Equation 7. By following the spectral positions of the interferometric fringes as the pressure applied to the fibre is varied, the $C_\lambda$ value can be determined.

$$C_\lambda \equiv \frac{\Delta \lambda}{dP} = \frac{\lambda}{G} \frac{\partial B_{\text{biref}}}{\partial P}$$  \hspace{1cm} (7)

Figure 5d shows the spectral response of the embedded-core fibre when it is subjected to pressure variations. One can see that the fringes blueshift as the pressure is increased. In Fig. 5e, blue squares represent the wavelength shift due to pressure application to the embedded-core fibre – fibre length (36.0 ± 0.1) cm and pressurized fibre.
Figure 5. Embedded-core fibres, surface-core fibres and pressure-sensing results. (a) Embedded-core fibre and enlargement of the core region. (b) Surface-core fibre and enlargement of the core region. (c) Experimental setup for pressure measurements. SC: supercontinuum source; P1 and P2: polarizers; O1 and O2: objective lenses; OSA: optical spectrum analyser; PC: pressure chamber; L: fibre length; Lp: pressurised fibre length. (d) Spectral response of embedded-core fibre for different pressurization conditions. (e) Wavelength shift versus applied pressure for surface-core and embedded-core fibres.

length (12.0 ± 0.1) cm. Red circles in turn are the pressure-sensing results for the surface-core fibre – fibre length (32.0 ± 0.1) cm and pressurized fibre length (12.0 ± 0.1) cm.

By accounting the wavelength shift as a function of the applied pressure one could obtain, after performing an appropriate correction to the fibre pressurized lengths²⁸⁻²⁹, pressure sensitivities of (1.04 ± 0.01) nm/bar and (0.43 ± 0.01) nm/bar for the embedded-core and surface-core fibre, respectively. It is seen that the embedded-core fibre sensitivity is 2.4 times that of the surface-core fibre. This result corroborates the simulation results: a maximized sensitivity could be obtained for a fibre with the core placed within the capillary fibre structure.

Regarding the resolution of the sensors, one can observe that the resolution is dependent on the widths of the spectral dips, whose shifts are followed as pressure is applied. In the measurement presented in Fig. 5d, the dip width at half maximum can be estimated as Δλ/2 = 6 nm. Assuming that one can resolve two spectral dips if they are at least Δλ/50 (≈0.1 nm in this case) apart from each other, the system resolution limit can be estimated to be 0.3 bar. As in the polarimetric scanning method, a longer fibre spectrum will have dips with decreased widths; the system’s resolution can be further improved if longer fibres are employed. It is worth observing, however, that the increase in the number of dips causes them to be spectrally closer, which can reduce the dynamic range of measurements. Additionally, increasing the sensor’s length can limit its applicability.

To determine the dynamic range of the embedded-core fibre sensor, one should analyse the spectral separation of the dips (free spectral range - FSR). This analysis is necessary because, in a practical measurement, if a dip reaches the spectral position of a neighbouring one, misinterpretation of the sensor reading can occur. In the measurement presented in Fig. 5d, the spectral range can be estimated as FSR = 14.2 nm. In terms of pressure, this result means that the sensor’s dynamic range is on the order of 40 bar. In this context, it should be emphasized that although one estimates the system’s dynamic range to be 40 bar for practical applications, data up to 80 bar could be measured because, in our experiments, one has carefully followed the spectral positions of the dips as a function of pressure. Additionally, it is worth noting that the dynamic range of measurements, similar to the sensor’s resolution, can be tuned by adequately choosing the fibre length. If, for example, in a specific application the sensing fibre length was 2 cm, its dynamic range would be on the order of 300 bar, making the sensor suitable, for example, for petroleum exploration. The resolution limit, however, would be approximately 5 bar.

Numerical simulations were also performed to provide a comparison with the experimental results. Simulated sensitivity values for the embedded-core and surface-core fibres were obtained using COMSOL® mechanical and optical analyses by calculating the fibre group birefringence and (dθ/dp)opt using the effective refractive index values. To obtain the most versatile analysis possible, one created realistic models based on fibre microscopility. Simulated sensitivity results were 0.89 nm/bar and 0.50 nm/bar for the embedded-core fibre and
surface-core fibre, respectively. A good agreement can be observed between the simulated and experimental values.

As the proposed fibres have a germanium-doped region that acts as the fibre core, temperature sensitivity can also be expected. This result arises from the fact that undoped and doped silica regions present different thermal expansion coefficients and, therefore, temperature variations can affect fibre birefringence. To measure the temperature sensitivity, the fibres were subjected to temperature variations, and their spectral responses were measured by employing the polarimetric wavelength scanning method. The measurements allowed determination of the following values for the birefringence derivative with respect to temperature: \( \Delta n_{core}/dT = (2.8 \pm 0.1) \times 10^{-7} ^\circ C^{-1} \) for the embedded-core fibre and \( \Delta n_{core}/dT = (4.0 \pm 0.4) \times 10^{-7} ^\circ C^{-1} \) for the surface-core fibre. These values are similar to the ones reported for commercial polarization-maintaining fibres - \( 4.0 \times 10^{-7} ^\circ C^{-1} \) for the PANDA fibre and \( 3.6 \times 10^{-7} ^\circ C^{-1} \) for the Bow-tie fibre. They are, however, higher than the values attained for specially designed microstructured fibres incorporating a germanium-doped core employed in pressure-sensing measurements \( (1.7 \times 10^{-7} ^\circ C^{-1}) \) and for all-silica photonic-crystal fibres \( (1.1 \times 10^{-7} ^\circ C^{-1}) \).

It is worth observing that if a practical application is targeted, a temperature compensation system would be desirable. This could be done, for instance, by performing the fabrication of an embedded-core fibre with two cores (placed at different radial positions within the capillary wall) and by imprinting a Bragg grating in each one of them. As the core of the embedded-core fibre is obtained from standard optical fibre preforms, a Bragg grating temperature sensitivity on the order of 10 pm/°C could be expected for both cores as in standard Bragg grating sensors. Numerical simulations show that by adequately choosing the cores’ positions within the capillary wall, the pressure sensitivities for Bragg gratings in the cores could differ by a factor of 2. By taking into account the Bragg grating temperature and pressure sensitivities for both cores, the pressure measurement from the polarimetric measurement could be temperature-compensated.

Additionally, an off-centre core position makes it necessary to conduct further studies on splicing procedures. Moreover, if a practical application is to be targeted, additional studies on sensor packaging would be necessary. A possible approach could be inserting the fibre into a metallic tube with transversal holes on its side. This would protect the fibre and allow the pressure from the external environment to act on the fibre.

**Discussion**

By observing the embedded-core fibre sensitivity, it can be seen that this fibre structure is an interesting platform for the performance of pressure-sensing measurements. The experimentally measured sensitivity – \( (1.04 \pm 0.01) \) nm/bar – is found to be higher than that of other fibre sensors that also focus on polarimetric measurements. For instance, H. Y. Fu et al. reported 0.362 nm/bar for a commercial all-silica photonic-crystal fibre, and T. Martyniuk et al. measured 0.59 nm/bar for a commercially available microstructured fibre.

Additionally, the birefringence derivative with respect to pressure \( \left( \Delta B/\Delta P \right) \) can be estimated to be \( (2.33 \pm 0.02) \times 10^{-5} \) bar\(^{-1} \) using Equation 7 for the embedded-core fibre. This value is on the same order of magnitude as those achieved for sophisticated microstructured fibres, such as the photonic-crystal fibre reported by G. Stakiewicz-Barabuch et al. \( \left( \Delta B/\Delta P \approx 2.52 \times 10^{-5} \right) \) and the specially designed fibre endowed with a triangular pattern of air holes described by A. Annäkiewicz et al. \( \left( \Delta B/\Delta P \approx 8.89 \times 10^{-5} \right) \), whose designs were optimized for pressure sensing. The fabrication process of these fibres, however, is much more complex than the one used for obtaining the embedded-core fibres, which requires only a relatively simple fibre drawing process.

Furthermore, one can visualize that there is still room for enhancing the pressure sensitivity of this non-optimized fibre reported herein. Analytical simulations of an embedded-core capillary fibre with, respectively, 70 μm and 100 μm inner and outer diameters and with the core placed 42.5 μm away from the fibre centre (at the middle point of the capillary wall) – all very realistic geometric parameters – were realized. The obtained material birefringence derivative with respect to pressure was 3.4 times the value expected for an embedded-core fibre with the same dimensions as the one we fabricated.

Additional numerical simulations showed that the core asymmetry has little influence on the \( \Delta B/\Delta P \) values. The sensitivity coefficient \( C_\Delta \), however, can be boosted for fibres with more symmetric cores because the guided mode will present lower group birefringence levels. The \( C_\Delta \) value for a core with dimensions of 4 μm × 5 μm, for example, is simulated to be approximately 6 times higher than the \( C_\Delta \) value for a core with dimensions of 4 μm × 12 μm (these data were found for an embedded-core fibre with an inner radius of 40 μm and outer radius of 67.5 μm, with the core placed at the middle point within the capillary wall).

In conclusion, one can emphasize that in this paper, we provided a new route for the simplification of microstructured optical fibre sensors by exploring the photelastic effect in capillary fibres. Initially, an analytical description of the pressure-induced material birefringence within a capillary structure was explored. The results demonstrated that an enhanced material birefringence dependence on pressure could be attained for thinner capillaries and at positions closer to their inner walls.

To explore the fibre modal characteristics, numerical simulations were performed, and the results confirmed the analytical simulation predictions. Additionally, it could be noted that the birefringence dependence on pressure variations drops for situations in which part of the core region area is outside the capillary.

Finally, we reported the fabrication of an embedded-core fibre and its use in pressure-monitoring experiments. Measurements revealed a sensitivity of \( (1.04 \pm 0.01) \) nm/bar and allowed the estimation of the birefringence derivative with respect to pressure to be \( (2.33 \pm 0.02) \times 10^{-5} \) bar\(^{-1} \). Both the values are very similar to the ones reported for more complicated, specially designed fibre structures. We can visualize, therefore, embedded-core fibres as a very interesting platform with the potential to considerably simplify microstructured optical fibre hydrostatic pressure sensors.
Methods

Correction of sensitivity values regarding the pressurised fibre lengths. Cn values denote a situation in which the whole fibre length is pressurized. Because in the experiments only a fraction of the fibre is pressurised (pressurized length, Lp), a correction to the experimentally measured sensitivities must be made. It is performed by simply multiplying the measured sensitivities by a factor Lp/L (where L is the fibre length) (11,12).

Embedded-core fibre fabrication procedure. The embedded-core fibre fabrication process is very similar to that of the surface-core fibre, which was recently reported by the authors (13). The only difference is that in the embedded-core fibre fabrication method, an additional jacketing procedure is performed.

Initially, a surface-core preform is prepared by merging a germanium-doped silica rod with the external surface of a silica tube (10). In sequence, the surface-core preform is inserted into another silica tube, which acts as a jacket. Therefore, the core region is located in between the inner tube and the jacketing one. To obtain the fibre whose cross-section is shown in Fig. 5a, one employed an inner tube with dimensions of 9.5 mm × 11.5 mm and an outer tube with dimensions of 18 mm × 20 mm.

During fibre drawing, a vacuum is applied in the space between the tubes, allowing the tubes to merge. In the merging process, the core is compressed and acquires an elliptical shape. The choice of the germanium-doped rod and tube dimensions for preparing the preform allows planning regarding the core size and its position within the capillary wall.

References


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Author Contributions

I.H.O. worked on the analytical simulations, performed fibre fabrication and sensing measurements, and wrote the paper. G.C. assisted I.H.O. during fibre fabrication and discussion. V.A.S. and M.A.R.F. worked on the numerical simulations, discussion and fibre fabrication proposal. C.M.B.C. coordinated the research project and revised the paper with I.H.O.

Additional Information

Competing Interests: The authors declare that they have no competing interests.

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Integration of bow-tie plasmonic nano-antennas on tapered fibers

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Abstract: In this article, a new and flexible approach to control the electric field enhancement of bow-tie nano-antennas by integrating them on the lateral of a tapered optical fiber is proposed. The device is driven by a Q-switched laser and the performance of a fabricated nano-antenna in a quartz slide is tested by a Surface Enhanced Raman Scattering (SERS) experiment. A refractive index sensing experiment is also performed and a sensitivity of (240 ± 30) nm/RIU is found in the 1.33-1.35 index range.

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1. Introduction

Nano-antennas are the optical equivalent of antennas [1] that are used to transmit and receive information at radio and microwave frequencies: these antennas are being used for imaging of living cells, manipulation of nano-particles, sensing and enhancement of the efficiency in solar cells [2]. Many of these applications are possible because nano-antennas can enhance photo-physical phenomena such as the local electric field [2].

In addition to dipole antennas, other antenna configurations [2] are possible such as multiple element Yagi-Uda antennas [3], spiral nano-antennas [4], plasmonic nanowire [5], honeycomb-like antenna structure [6] and bow-tie antennas [7]—such devices expand the characteristics of conventional dipole antennas as improved far-field directivity. Dipole and bow-tie antennas, on the other hand, can confine the fields in very small regions, depending on the device gap dimensions [8, 9]. An electric field enhancement factor (EF) of about 10 was achieved by Li and co-authors when the gap size was between 20 and 50 nm [9] and the wavelength of 980 nm. Besides, Liu and associates have shown a maximum electric field EF of more than 10 with the hot spot confined in a 20 nm gap (2 = 680 nm) [10]. Furthermore, a bow-tie plasmonic quantum cascade laser antenna has been reported by Yu and associates [7] where a sub-wavelength air gap between two metallic regions can enhance the electric field by more than 50 times—however, the device operated at 0.7 μm, considerably reducing the challenges of fabricating such device and its practical interest [7].

Single-element dipole or bow-tie antennas generally produce a non-directional radiation pattern: fields are localized in a small footprint to collect external light coming from a laser.
with much larger spot-size diameter. A desirable direction is to integrate the nano-antennas with other optical components to increase their functionalities. A nano-antenna can, for example, be directly fabricated on the optical fiber tip [11]. In this setup, however, all power guided by the fiber is solely used to drive the antennas and it can also be damaged at high fluences [12]. Moreover, an array of antennas at the end of an optical fiber can reflect light back to the laser and produce instabilities in its operation.

In this article, we show, for the first time according to the best of our knowledge, the possibility to integrate the nano-antennas array on the lateral side of a tapered optical fiber. Our approach allows a flexible control of the electric field enhancement by adjusting the fiber diameter and, in consequence, the overlap between the guided field and the metallic structure. It should be noted that the optical field travelling along the fiber can, apart from driving the nano-antennas, be also used for other functions. As a demonstration of the flexibility of our method, we fabricate an array of bow-tie nano-antennas on a 9.5 µm diameter tapered fiber which is connected to a Q-switched fiber laser. The performance of the nano-antenna device is measured experimentally and the current array of nano-antennas is used as a refractive index sensor.

2. Device principle, structure and theoretical analysis

Nano-antennas enhance the incident electric field of the optical mode that travels along the taper. Light propagating in a standard optical fiber is well confined in the core, however, when light reaches the micro-taper, it leaks away from the core and reaches the boundary between the air and cladding regions. The micro-taper allows light to strongly interact with the antenna. More specifically, when field is oriented along the antenna gap (z-direction in our case), a highly intense electric field is generated in the air gap due to the excitation of localized surface plasmons [2, 7]: a nano-antenna efficiently converts free-space propagating light into localized energy [2]. By controlling the diameter of the micro-taper, we can control the ratio of the electric field in the micro-taper with respect to the electric field at the center of a standard fiber. The net result is that, by controlling the diameter of the nano-taper, we can control the overall electric field enhancement of the combined micro-taper and nano-antenna device.

![Fig. 1. Schematic diagram of (a) single bow-tie nano-antenna (b) tapered fiber including dimensions with nano-antennas array position. Fiber axis aligned with the x-direction, electric field is in the z-direction.](image)
In addition, the use of micro-tapers also allows us to control the amount of energy density (fluence) that reaches the antenna, which can cause its obliteration if it is too high. In summary, we aimed to provide a flexible way to integrate nano-antennas with fiber lasers, by allowing the control of the fluence reaching the antenna and, at the same time, producing controllable gain of the combined micro-taper and nano-antenna structure.

The schematic of a single nano-antenna is shown in Fig. 1(a): the bow-tie nano-antenna is made by gold, being designed to operate around the free-space wavelength of 1090 nm and has a thickness ($h$) of 100 nm, a width ($w$) of 270 nm, a gap ($l_{gap}$) of 50 nm and a $h_{row}$ distance of $w/2$. In both simulation and experiment, the bow tie structure sits on silica. In order to create a nano-antenna array, the distance between two bow-tie nano-antennas are chosen as 2 μm and the typical position of the nano-antennas array can be seen in Fig. 1(b).

The Corning HI 1060 singlemode optical fiber (at the designed wavelength) is used. It has a typical 125 μm cladding diameter and mode field diameter of about 6 μm in a 5.3 μm core diameter. The tapering process is based on the “flame brushing technique” [13] where an oscillating flame heats a specific region of the optical fiber reducing the glass viscosity while both fiber tips are simultaneously stretched. Pulling the fiber as it is heated causes its length to increase and, by mass conservation, its diameter to decrease [13]. The core and cladding diameters are reduced by the same ratio meaning that a 9-10 μm taper will have a sub-wavelength core diameter of 380–420 nm.

The optical properties of a single bow-tie nano-antenna is analyzed by using commercial Synopsis Fullwave [14] 3D Finite Difference Time Domain (3D FDTD) software. The structure is designed to operate with TE modes with the main electric field along the $+z$ direction and directed across the gap. The computational area is terminated by perfectly matched absorbing boundary layers. The grid sizes are non-uniform and chosen as $Δx = Δz = 10$ nm in the plane of nano-antenna with the vertical grid size of $Δy = 20$ nm. The grid sizes are further refined to 5 nm at the edges of the metallic layers. The time step is chosen as $Δt = 4.66 \times 10^{-18}$ s, which is well below the stability limit. The refractive index of silica and air are considered as 1.45 and 1.0, respectively. The material properties of gold are considered from the material library of the software [14]: the relative permittivity model of gold is modeled as,

$$ε_{gold}(ω_{FW}) = 1 + \sum_{n=1}^{N} \frac{Δɛ_n}{\omega_{FW}^{2} - \lambda_n^{2} + \iota \omega \gamma_n}$$

where $λ_n$, $ɛ_n$, $c_n$ and $Δɛ_n$ are coefficients that are built-in in software material library [14] and their values are shown in the RSOFT Fullwave manual [14]. In addition, $ω_{FW} = 2π/λ_0$ is the Fullwave computational frequency where $λ_0$ is the free-space wavelength in μm.

Fig. 2. Electric field enhancement factor (EF) as function of (a) wavelength (b) gap ($l_{gap}$) for single bow-tie nano-antenna (c) Normalized electric field ($E_z$) profile.

In the simulations, the light source is considered to be the main $LP_{01}$ mode with a spot size diameter of around 6 μm. Besides, the propagation direction is assumed to be along $+x$ direction. The electric field enhancement factor of a nano-antenna is defined as (EF),
EF = \frac{|E_{\text{out}}|}{|E_{\text{inc}}|} \tag{2}

where $|E_{\text{out}}|$ and $|E_{\text{inc}}|$ are the magnitude of the electric field in the middle of the nano-antenna gap and incident light to the nano-antenna respectively.

Figure 2(a) shows the electric field enhancement factor (EF) as a function of the wavelength for a single bow-tie nano-antenna with $l_{\text{gap}}$, $h$, $w$ and $h_{\text{con}}$ equals 50 nm, 100 nm, 270 nm and 135 nm, respectively: it is shown that the structure resonates at 1090 nm, with a maximum electric field enhancement of EF = 8.3. In the wavelength range from 1025 nm to 1125 nm, the EF is close to 8. Moreover, the effect of changing bow-tie antenna gap dimension ($l_{\text{gap}}$) is shown in Fig. 2(b): the EF varies from 13 to 6.5 as the gap width increases from 30 to 70 nm. In order to see the field confinement in a bow-tie nano-antenna, the electric field ($E_z$) profile in the x-z plane is shown in Fig. 2(c). The electric field enhancement for TM polarization is close to 1 meaning that there is no electric field enhancement for TM modes because electric field is not oriented across the antenna gap. To be more precise, in case of TE and TM modes, the electric field is parallel ($z$-direction) and perpendicular ($\gamma$-direction) to the metal/dielectric interface, respectively. As a result, the electric field perpendicular to the metal/dielectric interface ($\gamma$-direction) is not enhanced while the electric field parallel to this interface ($z$-direction) is enhanced approximately 8 times.

Three dimensional (3D) simulations of an array of five bow tie nano-antennas is also studied for TE polarization in order to analyze the interaction between nano-antennas in the array. The electric field enhancement factor of 6, 5.5, 6.8, 8.4 and 11 are observed at the wavelength of 1090 nm for the 1st, 2nd, 3rd, 4th and 5th bow-tie nano-antenna in the array, respectively. The variable electric field enhancement in different antennas can be explained by the interference of the reflected optical fields from different antennas and, to a lesser extent, to coupling of light between different elements (the antennas are 2 μm apart from each other in the array, so coupling is not strong).

Although it might be possible to produce a directional array with the antennas, the array that we fabricated is small (5 antennas) and the distance between adjacent antennas (of about 2 μm) was randomly chosen. Finally, we might say that the electric field scattered through air is expected to be lower than the electric field scattered into the fiber taper region due to the higher refractive index contrast between silica and air.

Fig. 3. (a) Relative electric field with respect to the input field intensity, in the tapered fiber (b) output electric field, as a function of radial distance of the tapered fiber.

The relative electric field intensity with respect to the input field intensity (the launched field intensity at the taper edge is considered to be 1.0) for a tapered fiber diameter of 9.5 μm
as a function of the radial distance is shown in Fig. 3(a): the relative electric field is higher at the core center (radial distance = 0 μm) of the tapered fiber and then decreases gradually with the radial distance.

In order to analyze how different taper diameters affect the performance of the nano-antenna array, the electric field enhancement (logarithmic scale in the vertical axis) as a function of taper diameter is shown in Fig. 3(b). It can be observed in Fig. 3(b) that it is possible to produce a high electric field enhancement of 173 (inset) with a 1 μm diameter taper. It should be noted that it would be hard to fabricate the nano-antennas in such thin fiber and they could also be damaged by the high power—nearly all the power in the fiber leaks through the taper. An electric field enhancement of 4.02 is obtained from the nano-antenna placed on the taper with a diameter of 9.5 μm. Fabrication of nano-antennas on different diameter of the tapers provides flexibility in adjusting the fluence and the electric field enhancement in the antennas.

3. Fabrication and experimental results

Figure 4 shows the SEM image of the fabricated bow-tie antenna on the 9–10 μm optical fiber taper. In order to prepare the nanoantennas, a 100 nm thick gold layer is deposited on the tapered fiber by using Temescal BJD-2000 electron beam evaporator system. Since gold does not bond very well to silica (due to lattice constants mismatch), a 5 nm thick titanium adhesion layer is predeposited on the tapered fiber prior to gold deposition.

Bow-tie nano-antennas are fabricated on the tapered fiber by performing a milling process with a focused ion beam (FIB) (FEI Helios 600). To prepare the bow-tie geometry, gold from antenna’s surrounding areas is carefully removed. As an example, five bow-tie nano-antennas are fabricated on the 9.5 μm diameter optical fiber taper in order to create the array: the distance between consecutive nano-antennas is 2 μm—a SEM image is shown in Fig. 4(a). Figure 4(b) shows the measured dimensions of a single fabricated nano-antenna: \( w = 265.6 \) nm, \( l_{pp} = 49.99 \) nm and \( h_{min} = 134.3 \) nm. These dimensions are very close to the dimensions considered in simulations (\( w = 270 \) nm, \( l_{pp} = 50 \) nm and \( h_{min} = 135 \) nm).

Nano-antennas are passive device which needs to be driven by a light source. Here, we are driving the nano-antennas with a Q-switched laser. It is worthy to mention that the tapered fibers with nano-antennas can be connected to different laser systems. The combination of tapered fibers with nano-antennas provides a powerful platform to integrate nano-antennas with optical fiber systems, allowing the generation of different values of electric field enhancement. Also, it allows the creation of distributed imaging and sensing systems which could be used in a plethora of applications for chemical, physical and biological analyses.

![Fig. 4. Scanning Electron Microscope (SEM) image of the fabricated (a) bow-tie antenna arrays (b) single bow-tie, on the tapered optical fiber.](image-url)
In principle, any fiber laser system working at 1090 nm could be used to drive the combined micro-taper and nano-antennas. However, in order to better control the fluence (energy per unit area) that reached the antennas, we have used a Q-switched laser. In fact, as demonstrated by Mironov and co-authors [15], a high fluence reaching the antenna can obliterate the antennas and a Q-switch laser can produce pulses with controlled fluence and, at the same time, allows the nano-antennas to cool down in the interval between consecutive pulses. In addition, the Q-switched laser has an emission spectrum broad enough to allow us to conduct the refractive index sensing measurements.

![Schematic of the Q-switched ring fiber laser setup](image)

Fig. 5. Schematic of the Q-switched ring fiber laser setup (a) Average power ($P_{\text{avg}}$) as a function of pump power of Q-switched fiber laser while MoS$_2$ is used as SA (inset shows generated single pulse).

An optical pulsed fiber laser is constructed and used to drive the tapered fiber with the nano-antennas as shown in the schematic in Fig. 5(a). The fiber laser consists of a 980 nm pump laser, 6 m Yb doped fiber, MoS$_2$ as a saturable absorber (SA) [16, 17], an optical isolator, and a 90:10 coupler. Initially, a 980 nm continuous wave (CW) laser, which has a maximum peak power of 1.5 W and can be externally modulated at a maximum repetition rate of 3 kHz, is used to pump the ring laser as shown in Fig. 5(a). A WDM coupler is then used to couple the pump light into the ytterbium (Yb) doped (YB 1200-6/125 DC) fiber, and prevents a reflected beam at 1090 nm to return to the pump laser. After passing through 6 m of the Yb doped fiber, light passes firstly through the SA and then through the optical isolator. A small portion (10%) of the emitted light goes to a polarizing fiber and then to the fiber taper with the nano-antenna array. The fiber taper is about 15 cm long: taper waist (~5 cm) plus transition regions (~10 cm each) is then spliced with the polarizer.

Figure 5(b) shows the average output power as a function of pump power of the laser for a duty cycle of 50% (initially reducing the output power by half) and $P_{\text{pump}}$ refers to the peak pump power while inset shows a generated single pulse for a repetition of 1 kHz: the pulse duration (FWHM) at a peak pump power of 590 mW is about 12 μs. We can reach up to around 25 mW of average power ($P_{\text{avg}}$) based on our constructed laser as shown in Fig. 5(b).

### 3.1 Measured performance of the fabricated nano-antenna

The performance of the fabricated nano-antenna is indirectly measured through a Raman experiment. Unfortunately, it was not possible to test the fabricated combined micro-taper with the nano-antennas with the existing Raman system. Firstly, the combined micro-taper with nano-antennas would not fit into the Raman setup which allowed only small samples in the system. Secondly, the whole system would need to be re-aligned and potentially damaged with the introduction of the fiber laser setup. Thirdly, the driving laser had a collimation...
system that operated at 785 nm, meaning that the nano-antennas had to be re-designed to operate at this wavelength with a similar electric field enhancement factor. Fourthly, issues of laser safety would arise with the change of the existing driving laser since the fiber pump laser is a Class 4 laser.

Although the SERS experiment produced limited results, it allowed a comparison of the electric field enhancement of individual antennas with our calculations of electric field enhancement of the antennas. Also, the Raman signal would be lower at 1090 nm and the detectors are generally less sensitive at this wavelength. The commercial Raman system had a system of lenses which allowed the excitation of a single antenna in the fabricated antenna array in the glass slide. As described in different textbooks [18], the enhancement of the signal produced by metallic structures is proportional to the fourth power of the electric field, i.e., SERS signal $\propto |EF|^4$. In the experiment, we have used 100% ethanol with a concentration of 17 mol/l, and we have measured Raman spectra with a glass slide and glass slide with nano-antenna by using a Renishaw inVia 2 Raman spectrometer.

![Diagram of Raman system](image)

Fig. 6. (a) Schematic diagram of the Raman system for SERS measurement (b) Raman spectra of bow-tie nano-antenna fabricated on a tapered fiber and the quartz substrate used as a reference.

The schematic diagram of the Raman system for SERS measurement is shown in Fig. 6(a). The Raman spectrometer is driven by a laser source (laser in Raman system not Q-switched laser) with incident power of 13 mW with the help of dicroic mirrors and lens. The light is then focused on the sample by using another mirror and a 50x objective lens as shown in Fig. 6(a) which is only capable of illuminating one bow-tie antenna of the array due to its spot size limitation. The sample structure includes an array of five bow-tie nano-antennas on a glass plate with rescaled dimensions as $l_{bow}$, $h$, $w$ and $h_{bow}$ equals 50 nm, 100 nm, 170 nm and 85 nm, respectively, at the wavelength of 785 nm. An extra optical filter (notch filter) and a computer-controlled system is used to ensure the laser signal is not reaching the detector and visualize the spectrum as well as control the system, respectively. A glass plate is placed under the sample to bind the sample with ethanol solution: ethanol is dropped from top by using a pipette. We ensured that the layer of ethanol has a uniform thickness by observing the sample with a microscope. In a similar way, ethanol is placed on top of a quartz surface which is used as a reference. Figure 6(b) shows the Raman intensity of the proposed device (solid curve) compared with the quartz surface (dotted curve) under the same condition. The intensity is averaged with 25 static scans with an acquisition time of 32 seconds. The main Raman signal for ethanol [19] is present as can be seen by strong and sharp line at 880 cm$^{-1}$ in Fig. 6(b) (solid green line).

The experimentally measured SERS EF can be calculated by [20-24]
\[ EF_{\text{SERS}} = \frac{I_{\text{SERS}}}{I_{\text{ref}} / N_{\text{ref}}} \]

where \( I_{\text{SERS}} \) and \( I_{\text{ref}} \) are the SERS intensities for the bow-tie device and from the reference quartz surface, respectively. In addition, \( N_s \) and \( N_{\text{bulk}} \) are the number of molecules within the excitation volume of the laser spot for the analyte in the reference region, respectively, and can be calculated as [22, 23]

\[ N_s = \mu_s A_p \]

\[ N_{\text{bulk}} = C_v N_s / h A_{\text{beam}} \]

where \( \mu_s \), \( A_p \), \( C_v \), \( N_s \), \( h \), and \( A_{\text{beam}} \) are the surface packing density of ethanol on gold, surface area of the patterned device, concentration of the solution used for non-SERS measurement, Avogadro’s number, the effective height of the focused beam, and the spot size area of the excitation laser, respectively. Table 1 shows typical values of all the parameters used in the above equations.

The above equations allow us to calculate the SERS enhancement factor for the device at the Raman shift of 880 cm\(^{-1}\) (typical Raman shift for ethanol solutions). The measured SERS EF of \( 4.8 \times 10^4 \) is obtained for single bow-tie nano-antenna, which is higher than the theoretical SERS EF of \( 4.8 \times 10^3 \) (assuming a fourth order dependence of the SERS enhancement on the local electric field enhancement EF). The measured enhancement of SERS is about ten times higher than the theoretical value because the SERS chemical factor can vary by a factor of \( \sim 10-10^6 \) [21, 23].

**Table 1. Typical parameters [22].**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Quantity</th>
<th>Typical value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \mu_s )</td>
<td>Surface packing density of ethanol on gold</td>
<td>( 9.88 \times 10^{-5} ) m(^2)</td>
</tr>
<tr>
<td>( A_p )</td>
<td>Surface area of the patterned device</td>
<td>( 1.44 \times 10^{-15} ) m(^2)</td>
</tr>
<tr>
<td>( C_v )</td>
<td>Concentration of the solution used for non-SERS measurement</td>
<td>( 1.71 \times 10^2 ) mol m(^{-3})</td>
</tr>
<tr>
<td>( N_s )</td>
<td>Avogadro’s number</td>
<td>( 6.02 \times 10^{23} ) mol(^{-1})</td>
</tr>
<tr>
<td>( h )</td>
<td>A parameter defined by confocal volume of the spectrometer</td>
<td>( 4.04 \times 10^{-6} ) m</td>
</tr>
<tr>
<td>( A_{\text{beam}} )</td>
<td>The spot size area of the excitation laser</td>
<td>( 1.33 \times 10^{-12} ) m(^2)</td>
</tr>
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</table>

### 3.2 Sensing application of the proposed integrated device

The proposed integrated device can also work as a refractive index sensor. The idea is to measure the plasmonic resonance wavelength (\( \lambda_r \)) change when the external refractive index varies (\( \Delta n \)). The measurements are carried out with the presence of different concentration of ethanol (from 0% to 100%) in pure water. The direct transmission can be measured by an optical spectral analyzer (OSA) for different concentration of ethanol: the peak of the transmission spectrum is changed due to the change of ethanol concentration.

In terms of sensing experiment procedure, the aforementioned Q-switched fiber laser (Fig. 5(a)) is used at the wavelength of 1090 nm. The tapered fiber with fabricated nano-antennas is initially immersed in a small container with distilled water and the transmission spectrum is measured with an optical spectrum analyzer (OSA); a transmission peak is observed at the wavelength of 1096.11 nm as can be seen in inset of Fig. 7(a). Later on, a solution with an appropriate ratio of ethanol and water (e.g., 25%, 50%, 75% or 100% ethanol concentration by volume) replaces the distilled water solution and we conduct the measurement of the spectrum again. It should be mentioned that there is an interval of at least two hours between different experiments, allowing the evaporation of any residual solution left on the antennas after they are removed from the container. The resultant shift of the transmission peak (\( \Delta \lambda \)) for different ethanol concentration is calculated by...
\[ \Delta \lambda = \lambda_{\text{ethanol(mixed)}} - \lambda_{\text{ethanol(100\%)}} \]  \hspace{1cm} (6)

where \( \lambda_{\text{ethanol(mixed)}} \) and \( \lambda_{\text{ethanol(100\%)}} \) represents the transmission peak wavelength for the ethanol concentration with mixed water and pure ethanol, respectively.

Fig. 7. (a) Resonance wavelength shift with respect to different concentration of ethanol (b) Peak wavelength as a function of corresponding refractive index of ethanol/water mixture.

The fabricated device (tapered fiber region with nano-antennas array) is immersed in different solutions and the transmission spectrum is measured as shown in inset of Fig. 7(a): the resonance peak blue shifts when the solution refractive index increases. The change in ethanol concentration leads to variations in the refractive index of ethanol solution affecting the transmission through the tapered fiber with nano-antennas array. Sellmeier equations for pure water [25] and pure ethanol [26], allows obtaining their refractive indexes at 1090 nm as 1.3235 and 1.3535, respectively. By using Eq. (7), it is possible to attain the refractive index, \( n \), for a mixture of two liquids (pure ethanol and pure water in this case) with refractive indexes \( n_1 \) and \( n_2 \), respectively, as [27]:

\[ n = \frac{2g + 1}{\sqrt{1 - g}} \]  \hspace{1cm} (7)

where

\[ g = \left( \frac{n_1^2 - 1}{n_1^2 + 2} \right) \phi + \left( \frac{n_2^2 - 1}{n_2^2 + 2} \right) (1 - \phi) \] \hspace{1cm} (8)

and \( \phi \) stands for the volume concentration of the liquid with refractive index of pure ethanol (\( n_1 \)).

Therefore, one can replot wavelength shift data as a function of the mixture refractive index as shown in Fig. 7(b) and estimate system sensitivity as (240 ± 30) nm/RIU. The obtained value is similar to other highly sensitivity refractive index fiber sensors such as the ones based in long-period gratings interferometers [28] and multimode interference configurations [29], whose sensitivities are also around 200 nm/RIU. Other setups based on, for instance, birefringent microfibers [30] can provide higher sensitivity values. However, results found in [30] were obtained for thinner fiber tapers which needed a polishing procedure, making the system less robust.

It is true that the refractometric sensor has not produced a very high sensitivity when compared with long period gratings and interferometers. One of the reasons of a lower sensitivity is that the device was not optimized for sensing: the article reports the RI sensing...
measurement to demonstrate an application for the nano-antenna array on the tapered fiber. Besides that, it would be possible to measure sensitivities experimentally on the magnitude order predicted by Calderon and colleagues [31] and our device is more compact compared to long periodic gratings based sensitivity devices [32]. Moreover, it would also be possible to improve the sensitivity figure by placing a circular hole within the bowtie nano-antenna triangular element as demonstrated by Nien et al. [33].

4. Conclusions

In summary, a flexible approach to integrate nano-antennas in an optical device is studied. The method is based on using tapered optical fibers to control the electric field enhancement from nano-antennas array when comparing to the electric field in the fiber core. It is shown that the amount of electric field enhancement that can be reached to the nano-antennas is ~4 and this factor can be increased up to 170 by using, for example, a 1 μm tapered fiber. The current device (tapered fiber with nano-antennas) shows the flexibility of our approach. The fabricated nano-antenna performance is measured with a Raman experiment, showing a SERS enhancement of about $4.8 \times 10^4$ for the 880 cm$^{-1}$ line of ethanol. As an example of the application of the setup as a sensor, a refractive index probing experiment is carried out and a sensitivity value of (240 ± 30) nm/RIU is found. The integration of nano-antenna array on tapered fiber may find applications in bio-sensing, imaging, nano-particles manipulation, beam steering [34] and far-field emission collimation of semiconductor lasers.

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Bragg gratings in surface-core fibers: Refractive index and directional curvature sensing

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ABSTRACT

In this paper, we report, to our knowledge, the first extended study of the inscription of Bragg gratings in surface-core fibers and their application in refractive index and directional curvature sensing. The research ranges from fiber fabrication and grating inscription in untapered and tapered fibers to the performance of simulations and sensing measurements. Maximum sensitivities of 40 nm/RIU and 202.7 pm/m° were attained in refractive index and curvature measurements respectively. The obtained results compare well to other fiber Bragg grating based devices. Ease of fabrication, robustness and versatility makes surface-core fibers an interesting platform when exploring fiber sensing devices.

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1. Introduction

Optical fibers are a very important platform for building up sensors. Temperature, pressure, strain, refractive index and curvature are examples of parameters which can be monitored by the employment of optical fiber-based systems. The importance of developing fiber sensors has recently grown due to the advantages they can provide over other sorts of sensors, such as high sensitivity, electromagnetic immunity and increased robustness. Moreover, fiber-based devices are usually very compact and lightweight [1,2].

Numerous technologies can be employed for turning the fiber sensitive to the parameter whose variation is desired to be measured. Fiber gratings, for example, can be used to sense many parameters, such as refractive index, strain, curvature and temperature variations [3,4]. Furthermore, tailoring fiber geometry is another possibility for achieving the desired sensitivity. It is often done when dealing with photonic crystal fibers [5].

Specifically for refractive index monitoring, long-period gratings [6,7], multimode interferometers devices (MMI) [8,9] and birefringent microfibrhes [10,11] are some of the fiber based devices that are usually employed for obtaining this sort of measurement.

For these technologies, sensitivities values can range from hundreds to thousands of nanometers per refractive index unit. Concerning curvature measurements, again long-period gratings and MMI based setups are often employed [12,13]. Moreover, Bragg gratings inscribed in multicore fibers have also been studied as an alternative for obtaining directional curvature determination [14–16].

In this paper, we report, to our knowledge, the first extended study of Bragg gratings inscribed in surface-core fibers and their application in refractive index and curvature probing. Surface-core fibers have firstly been reported by C. Guan et al. in [17], where theoretical studies of refractive index sensitivity can be found. Besides, an experimental study of refractive index sensing based on interferometry has also been published [18]. Recently, we have reported the fabrication and the possibility of inscribing long and short-period gratings in surface-core fibers [19]. Moreover, we studied the use of surface-core fibers for hydrostatic pressure sensing [20].

The research reported herein comprehends an investigation that ranges from fiber fabrication and inscription to its application in refractive index and directional curvature probing. When studying refractive index variations, a maximum sensitivity of 40 nm/RIU could be measured for refractive index variations around 1.42 RIU. Other fiber Bragg gratings devices reported in literature show sensitivity values ranging between 15 nm/RIU and 30 nm/RIU.

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RIU [21–23]. Regarding curvature probing, a directional behavior was demonstrated and a sensitivity of 202.7 pm/m could be attained. This value is two times higher than the values found in literature for similar FBG based sensors [14–16]. It’s worth emphasizing that is not our intention reporting record high sensitivities values, but present the study of a specially fiber structure obtained from a very simple fabrication process and its application in sensing measurements.

2. Fiber fabrication

Surface-core fibers are designed so that the core region is placed at fiber external boundary. In order to obtain the fiber, a four-step process is carried out. Firstly, a multimode germanium doped rod is drawn from its initial diameter of 21.0 mm (Fig. 1a). In the second step, the rod is inserted in a HF bath for etching. During this process, the diameter is decreased form 0.8 mm to 0.65 mm. By performing this procedure, the silica layer (Fig. 1a) is removed. This step is important for reflective index tests, since it allows a more pronounced interaction between the core mode evanescent field and the external medium.

In the third step, the thinned rod is merged to a silica tube (with inner and outer diameter of 5 mm and 10 mm, respectively) by the employment of a blowtorch in order to obtain the fiber preform (Fig. 1b). Finally, the preform is directly drawn to its final diameter (130 µm). The fiber cross-section is shown in Fig. 1c and a zoom of the core region is presented in Fig. 1d. As the core’s reflective index is higher than the surrounding medium’s one, light is guided through the surface-core fiber by total internal reflection.

It is worth underlining that all the steps for surface-core fiber fabrication are straightforward, what makes it much simpler than the fabrication of other specialty optical fibers such as photonic-crystal fibers. For obtaining photonic-crystal fibers, for instance, usually stack-and-draw procedure is employed [24]. In this method, numerous silica tubes and rods are drawn and manually assembled in a preform stack. In sequence, jacketing processes allows obtaining the desired proportion between core, cladding and outer fiber sizes. This process is very time consuming and demands much effort from a technical point of view.

3. Bragg gratings imprinting

Fiber Bragg gratings consist of short-period longitudinal modulation of optical fibers core refractive index. It allows coupling between forward and backward propagating core modes. The coupling occurs at a specific wavelength $\lambda_g$ as shown in Eq. (1), where $n_{eff}$ is the effective refractive index of the fundamental core mode and $A$ is the grating period.

\[ \lambda_g = 2n_{eff}A \]  

The grating inscription was performed by employing the phase mask technique. A Quantel Q-Smart 450 UV laser together with a phase mask were used to create an FBG in the infrared region. A cylindrical lens was used for focusing the UV laser beam on the fiber during gratings’ inscription process and the resulting FBGs have their length in the order of millimeters. For monitoring the FBG spectrum in real-time during grating inscription, a SMF pigtail was butt coupled to the surface core fiber. A small amount of index matching oil was used in the coupling for reducing Fresnel reflections at fiber ends and for lowering the background noise. A CCD camera was placed at the end of the fiber in order to provide an image of the core illumination conditions. By observing the CCD camera image, one could find the core position and optimize the coupling of light to the fiber. The FBGs were inscribed with enough reflectivity to be seen in reflection. Fig. 2a shows the spectrum (collected from a FS2300 Industrial BraggMETER from FiberSensing) of a FBG which was imprinted in a surface-core fiber by using a phase mask with period 1062.65 nm (spectra are normalized for better visualization). The tested fibers were maintained under tension during the gratings spectra acquisition.

4. Refractive index sensing

As in the studied fibers the core region is placed on fiber external surface, the evanescent field associated to the guided mode permeates the surrounding medium. It causes the core effective refractive index to be dependent on external refractive index variations. As the Bragg peak spectral location is determined, besides grating period, by the mode effective refractive index value (Eq. (1)), variations in external refractive index imply on Bragg peak shifting. Therefore, by monitoring the Bragg peak shift, a refractive index sensor can be obtained.

In the refractive index measurements, the surface-core fibers were immersed into solutions of water and glycerin and the reflection Bragg peak was monitored. Results showed, however, a very low sensitivity to external refractive index variations (0.07 mm RIU). It can be identified by the minimum wavelength shift which was observed in Bragg peak spectral position as the external refractive index, $n_{ext}$, was varied (Fig. 2a). Thus, in order to enhance fiber sensitivity, tapers from surface-core fibers were produced prior to Bragg grating inscription. The tapers were prepared by using flame-brushing technique [25] and the grating imprinting was done by using the same phase-mask technique. In the flame-brushing technique, the resulting fiber taper presents two transition zones and a uniform region with constant diameter (taper waist). The gratings were imprinted in the uniform waist of the fiber tapers (prepared with 10 mm in length).

The diameter reduction causes the mode effective refractive index to be more sensitive to the surrounding refractive index variations. Tapers 80 µm and 20 µm thick were tested and the resulting spectra are shown in Fig. 2b and c (the spectra were normalized for better visualization). It is worth observing that the grating in the 80 µm taper was imprinted by using a phase mask with pitch 1075.34 nm and the one in the 20 µm with1071.2 nm, implying in different spectral positions for the Bragg peaks. Moreover, since the core mode in the 20 µm taper has a greater fraction of its evanescent field in the external med-

![Fig. 1. (a) Germanium-doped silica preform employed for obtaining the fiber core. (b) Diagram for germanium doped silica rod and silica tube merging procedure using blowtorch. (c) Surface-core fiber cross-section. (d) Inset of the core region.](image-url)
ium when compared to the 80 μm taper, the effective refractive index of the mode in the 20 μm taper is lower than the one in the 80 μm [22]. By observing Eq. (1), one can see that a lower effective refractive index causes the Bragg peak to appear at a lower wavelength.

Fig. 2d shows the wavelength shift as a function of the external refractive index for the untapered fiber (black circles) and for the 80 μm (red triangles) and 20 μm thick (blue squares) fiber tapers. It is seen that a greater wavelength shift is observed for the tapered fibers due to the more effective interaction between the core mode evanescent field and the surrounding medium. The sensitivity for refractive indexes around 1.42 RIU could be measured as 8 nm/RIU and 40 nm/RIU for the 80 μm and 20 μm thick fiber tapers respectively (Fig. 2d). Moreover, one can estimate, if an optical spectrum analyzer with 10 pm spectral resolution is used, the maximum sensor resolution as 2.5 × 10⁻⁴ RIU.

The maximum sensitivity value achieved for the surface-core fiber reported herein (40 nm/RIU, for a taper 20 μm thick) compares well with results from other authors who analyzed the shift of FBG fundamental mode. Ref. [21], for instance, reports a sensitivity of approximately 15 nm/RIU for a 6 μm taper in the refractive index range between 1.326 and 1.378 RIU. Besides, in Ref. [22], authors have found a value of 30 nm/RIU for a 8.5 μm taper in the same refractive index range. It can be observed that the results reported herein were obtained for thicker fiber tapers, which means an enhancement in sensor robustness.

Higher sensitivities values (in the order of hundreds or thousands of nm/RIU) are found in literature for setups based in other technologies such as fiber interferometers [26,27] and plasmonic devices [28]. Moreover, other approaches also using Bragg gratings in microfibers can be found in literature. For example, in Refs. [29] and [30], authors have monitored the FBG higher-order modes for achieving, respectively, maximum sensitivities of 92 nm/RIU and 102 nm/RIU around 1.388 RIU. In [29], a 7 μm taper was used and, in [30], a 6 μm thick one was employed. Moreover, a higher sensitivity can be found in [31] - 660 nm/RIU around 1.39 RIU – where the authors studied a filled-milled Bragg grating induced on a 0.9 μm taper. These values were found, however, for very thin tapers, again reducing sensor robustness.

5. Fiber simulation

Numerical simulations were performed in order to corroborate experimental results. The fiber cross-section was initially drawn in a vector graphics editor (Corel Draw) in order to obtain a better reproduction of fiber geometry. In sequence, the drawing was imported into Comsol for mode analysis.

The core region of the surface-core fibers is germanium doped and has a graded-index profile. Energy-dispersive X-ray spectroscopy technique (EDS) was employed for recovering the germanium concentration along the core region (Fig. 1e, right axis). By employing Eq. (2), where n is the refractive index of a germanium-doped silica glass at a concentration X and at a wavelength λ, it is possible to attain the refractive index of germanium-doped silica glass [32]. SA, SB, and SC are the Sellmeier coefficients for silica (SiO₂) and GA, GB, and GC are the ones for germanium dioxide (GeO₂). Their values can be found in [32].

\[ n^2 = 1 + \sum \frac{SA}{\lambda^2 - (SB - \lambda - SC)^2} \]  

By using Eq. (2) and taking into account the germanium concentration distribution along the core, one obtained the core refractive index profile (Fig. 2e, left axis). A Gaussian function was fitted to the experimental data and the resulting curve (red line in Fig. 2e) was used for defining core refractive index in simulations, whose results are shown as dashed lines in Fig. 2d. As can be seen in Fig. 3d, good agreement is observed between simulated and experimental data.

6. Directional curvature sensing

In surface-core fibers, the core region is out of the center of symmetry. It makes the fiber able to probe directional curvature variations, since, depending on curvature direction, the fiber core experiences compression or expansion (Fig. 3a). In order to monitor curvature variations, a setup as depicted in Fig. 3b was used.

Initially, the fiber containing the FBG was fixed between two rotator fiber holders (under straight condition). One of the stages on
which the fiber was fixed to a motorized stage whose linear movement towards the fixed stage implied on curvature increments.

In curvature sensing measurements, the curvature bending, $C$, is calculated as the inverse of the curvature radius ($r$ in Fig. 3b) and is related to the displacement from the straight condition $h$ by Eq. (3) -- where $2l$ is the length of the bent fiber section [31].

$$C = \frac{2h}{R^2 + l^2}.$$  \hspace{1cm} (3)

For measuring directional curvature variations, care was taken in order of being sure that the curvature was being made on the right direction. Firstly, the fiber movement was limited to follow a single axis by keeping it between parallel plastic boards, following reference [31] authors’ description. The second important point was being sure that the fiber had the right core orientation. To do that, a 50× magnification lens together with a beam profiler were used to monitor the core end face orientation at the region close to the fiber holder. Thus, by rotating the two fiber holders by the same angle, we could adjust the desired core orientation (see Fig. 3b).

For characterizing the response of the surface-core FBG to curvature variations, four configurations -- different core orientation and bending direction -- were tested. The investigated arrangements and the obtained results are summarized in Fig. 4. Green squares stands for grating under expansion and blue triangles for grating under compression. Red circles and pink rhombus are the results found for the situation in which the fiber was rotated 90° from the initial position (see Fig. 4).

In Fig. 4, one can observe that grating extension causes, as expected, the Bragg peak to redshift (positive wavelength shift). In contrast, grating compression causes the Bragg peak to blueshift (negative wavelength shift). Different wavelength shifting behavior shows the feasibility of using surface-core fiber for directional curvature probing. The results obtained for the situation in which the fiber was rotated (red circles and pink rhombus in Fig. 4) also followed the expected behavior (no curvature sensitivity is expected as the core is on the curvature neutral axis [33]). The observed small wavelength variations (within 0.35 nm) are due to possible misalignment between the grating axis and the bending plane.

The attained curvature sensitivities, 188.6 pm/m⁻¹ and 202.7 pm/m⁻¹, are high when compared to other FBG bending sensors reported in literature (whose values range from 50 pm/m⁻¹ to 100 pm/m⁻¹) [14–16]. They are also higher than the one found for FBG inscribed in eccentric core polymer fiber (63.3 pm/m⁻¹) [33]). Other fiber configurations (not based in FBGs), can, however, provide increased curvature sensitivities. Two and three core optical fibers interrogated in interferometric setups are reported to attain sensitivities values as high as hundreds of nanometers per inverse meter [34,35].

7. Conclusion

To our knowledge, this paper is the first extended description of the study of FBGs inscribed in surface-core fibers and their application on refractive index and directional curvature sensing.
measurements. The research reported herein studied surface-core fibers from their fabrication to the performance of simulations and measurements of refractive index and curvature variations. It does not aim to report recorded signal sensitivities values but exposing the study of a new fiber structure which can be prepared by means of a very simple fabrication process and that can be applied in sensing measurements.

In the refractive index sensing experiments, a maximum sensitivity of 40 nm/RU could be measured around 1.42 RLU. The obtained value compares well to other setups that monitor the spectral position of the FBG fundamental mode peak. Furthermore, the sensor reported herein has increased robustness when compared to other FBG-based refractive index sensors since a thicker fiber’s neck is employed (20 µm outer diameter).

In curvature probing, a directional behavior of the optical response could be observed due to the fiber geometry. A maximum sensitivity of 202.7 pm/° was attained. This is also a good remark when compared to other FBG based curvature sensors reported in literature.

In conclusion, the results demonstrated the feasibility of the application of surface-core fibers on refractive index and directional curvature probing. Simple design, ease of fabrication, robustness and versatility makes this kind of fiber an interesting platform for the development of fiber-based devices for sensing purposes.

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References

Intensity liquid level sensor based on multimode interference and fiber Bragg grating

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Abstract
In this paper an intensity liquid level sensor based on a single-mode—no-core—single-mode (SMS) fiber structure together with a Bragg grating inscribed in the later single mode fiber is proposed. As the no-core fiber is sensitive to the external refractive index, the SMS spectral response will be shifted related to the length of no-core fiber that is immersed in a liquid. By positioning the FBG central wavelength at the spectral region of the SMS edge filter, it is possible to measure the liquid level using the reflected FBG peak power through an intensity-based approach. The sensor is also self-referenced using the peak power of another FBG that is placed before and far from the sensing part. The temperature error analysis was also studied revealing that the sensor can operate in environments where the temperature changes are minimal. The possibility to use a second setup that makes the whole device temperature insensitive is also discussed.

Keywords: fiber Bragg grating (FBG), no-core fiber (NCF), liquid level sensor, multimode interference (MMI)

(Some figures may appear in colour only in the online journal)

1. Introduction

Liquid-level sensing is a requirement in many applications such as fuel storage, liquids quantitative and qualitative monitoring and chemical processing. Nowadays, liquid level can be detected with various traditional mechanical or electrical methods. Among them are the float, ultrasonic [1], magnetostrictive [2], differential pressure [3], and capacitive methods [4], etc. However, they present several disadvantages such as high maintenance cost, susceptibility to electromagnetic interference, structure complexity and low resolution. Nevertheless, their application can be compromised if the liquid to be measured is conductive, potentially explosive or erosive. Optical fiber sensors appear as a promising technology to solve many of these problems, since they are made of dielectric and therefore they are non-conductive and cannot be eroded by most of the liquids. Additionally, these sensors can offer multiplexing capabilities, compact size, high resolution and immunity to electromagnetic interference.

To date, several optical fiber liquid level sensors have been reported on literature, where the key concept relies on the interaction of the evanescent field of the optical signal with the liquid refractive index (RI). This has been done by using long period gratings [5], etched fibers [6], D-shape fibers [7], and also multimode fiber devices (MMI) based on unclad multimode fibers [8–11]. In fact, some of these sensors are
based on complex fabricating procedures or elaborate device structures. Additionally, the measurement concept on most of the fiber optic liquid level sensors relies on the wavelength dependency, which therefore, needs an expensive optical detection system to recover the liquid level.

Regarding MMI fiber based sensors, apart from measuring liquid level based on the change of the resonance wavelength, they have been used in special arrangements to detect individually or simultaneously a variety of parameters, such as: temperature, refractive index [12–14], strain [15, 16], vibration [17], bending [16], magnetic field [18], and displacement [19]. For the refractive index detection, as it occurs for the liquid level detection, it is necessary to expose the fiber core to the external environment. This can be done with a multimode fiber (MMF) composed of a single material commonly known as no-core fiber (NCF), or by simply etching the cladding of a MMF [14]. In fact, fiber based MMI are a simple device that comprises a single-mode—multimode—single-mode structure (SMS), which allows easy and compact implementation. On the other hand fiber Bragg gratings (FBGs) are a common sensing device widely used in sensing applications [20]. The potential of combining these fiber structures has already been subject of study in literature [11–16, 18, 21]. Although, none of these studies has reported the capability to measure liquid level based on the peak power of an FBG.

In this work, we propose the combination of a SMS structure based on a NCF together with a single mode FBG to measure liquid level. The measurement principle is based on the detection of the FBG reflected peak power offering, thus, an easy characterization method. The dependence of temperature on the FBG peak power was also subject of study in this work.

2. Principle of operation

The experimental setup and schematic of the sensor are shown on figure 1. The sensor shown on the inset of figure 1 is composed of a NCF which is a pure silica rod with 125 µm diameter, sandwiched between two single-mode fibers (SMF), where the later SMF has an FBG inscribed on it. Considering the SMS structure in air, multiple modes will be excited when the fundamental mode of the leading SMF is injected on the NCF. As these modes have different propagation constants, they will interfere as they propagate along the NCF. This will allow the formation of multiple images of the input field, which are an exact replica of both phase and amplitude. The length in which these images are formed can be obtained from the restricted symmetric interference condition [22], which is given by:

\[ L = \frac{pL_g}{4}, \quad p = 0, 1, 2, 3 \]

with \( L_g \) defining the beat length [22], expressed as:

\[ L_g \approx \frac{4\pi\text{ncf}D_{\text{ncf}}^2}{3\lambda_0} \]

where \( \lambda_0 \) is the free space wavelength, with \( \text{ncf} \) and \( D_{\text{ncf}} \), respectively the effective refractive index and diameter of the fundamental mode of the NCF considering air as external medium. If the NCF is precisely cleaved where one of the images is being formed, a bandpass filter centered at \( \lambda_0 \) will be formed. The combination of (1) and (2) provides the wavelength at which this filter will be centered:

\[ \lambda_0 \approx p\frac{\text{ncf}D_{\text{ncf}}}{L} \quad (3) \]

When the SMS structure is fully immersed in a liquid the refractive index difference between the two media (silica/liquid) is lower when compared with the case where the fiber is in air. Thus, due to the Gouy–Häckel effect, the lateral penetration of the field into the liquid will be higher [22]. Consequently, the effective diameter \( D_{\text{ncf}} \) will increase, increasing also the effective refractive index \( \text{ncf} \), because the evanescent filed penetrates more into the liquid. Consequently, the center wavelength of the bandpass filter expressed in equation (3) will be redshifted [8].

On the other hand, when the NCF is surrounded by two different media (e.g., one part immersed in a liquid and another part in air), the sensor passes to act as the combination of two NCFs, and the center wavelength of the band pass filter will be estimated from equation (4), [8]:

\[ \lambda_0 = 4\frac{\text{ncf}_{\text{air}}D_{\text{ncf}}^{\text{air}}}{L} \left( \frac{L_{\text{in}}}{L} \right) + 4\frac{\text{ncf}_{\text{air}}D_{\text{ncf}}^{\text{air}}}{L} \left( \frac{L_{\text{out}}}{L} \right) \quad (4) \]

where the first part of the equation refers to the NCF in liquid and the second part refers to the NCF in air. The variables \( L_{\text{in}} \) and \( L_{\text{out}} \) are respectively the length of the NCF with and without the liquid; \( \text{ncf}_{\text{air}} \) and \( \text{ncf}_{\text{air}} \) express the effective
refractive index and diameter of the fundamental mode of the NCF section in liquid.

At this stage and without using the FBG it is possible to use the shift of the center wavelength produced by the MMI bandpass filter to measure liquid level [8, 9, 11]. However, one of the drawbacks of this measurement concept is the large width of a typical MMI spectra that imposes uncertainty on the estimation of the peak wavelength.

Nevertheless, the MMI spectral response can act as a bandpass filter. Therefore, if an FBG is introduced after the NCF and at a specific wavelength region, it is possible to linearly measure the FBG peak power with the external refractive index [13, 14]. This happens, because the SMS structure and FBG are sensitive and insensitive to the external refractive index, respectively. This will be translated as a relative movement of the MMI spectrum related to the FBG spectrum, imposing power variation on the FBG spectra due to the filtering of the MMI spectra.

It is known that standard FBGs are wavelength insensitive to changes on the external refractive index medium and, so, to the liquid level. On other hand, looking to equation (4), the center wavelength of the bandpass filter of the SMS structure is liquid level dependent. Therefore, using the SMS structure followed by an FBG, one can find that this fiber device allows one to monitor the liquid level by measuring the reflection peak power of the FBG.

3. Experimental setup

The NCF used in this work was produced in our facilities and it has a diameter of 125 μm and a refractive index of 1.444 at 1550 nm. Equation (3) was used to calculate the NCF length needed to get a peak centered at λ₀ = 1550 nm. In order to have enough length for the manipulation and for the splicing process, it was chosen the 4th self-image (ρ = 4), giving a length of 58.2 mm. The NCF was then measured with a digital caliper and cleaved with a fiber optic cleaver machine. Each end of the NCF was then fusion spliced to a single-mode fiber creating the SMS structure.

3.1 Preliminary tests

In order to define the center wavelength where the grating should be written, it is necessary to find the wavelength regions where the FBG peak power can experience maxima variations on the liquid level detection. Therefore, the SMS structure was subjected to the two opposite conditions, respectively fully in air and fully immersed in liquid (i.e. water). The correspondent spectral responses were acquired with an interrogator system (FS2200—Industrial BraggMETER, FiberSensing) and are depicted on figure 2(a). The correspondent power difference between the two spectra is shown on figure 2(b). As predicted, the MMI spectrum is redshifted when it is immersed in water. The power difference between the spectrum in air and fully immersed in water produces negative and positive power values that can be seen on figure 2(b). Results show that greater power variations are observed around 1535 and 1561 nm.

![Figure 2](image.png)

**Figure 2.** (a) Spectra collected for the SMS structure in air and water; (b) power difference between the spectra in air and water, shown in (a).

Nevertheless, the shape of the MMI spectra acts as a bandpass filter and to get a straight evolution of the FBG peak power with the liquid level, the MMI spectra need to have a straight tendency on the region where the FBG will be written.

3.2. Liquid level detection optimization

Regarding the above observations, we decide to evaluate the wavelength region that maximizes de liquid level detection performance. Thus, the response of the SMS structure was characterized with increments of liquid level, allowing to know the correspondent power values at specific wavelength regions (i.e. 1535 and 1561 nm). To do that, both ends of the fiber sensor where fixed onto a support in a straight position, in order to avoid undesired strain and bend effects on the NCF that may affect the transmission spectrum. The support was therefore attached to a motorized linear stage (LTS300 from Thorlabs), which was used to precisely move the sensor inside a liquid container in a 3 mm step. The container is filled with water and it was placed on top of a hot source (IKA®C-MAG HS7), which kept the temperature constant at 25 °C. This experimental setup can be seen on figure 1. In order to avoid the zones where the fusion splices were made, the characterization was performed at the central part of the SMS structure, covering a range of 51 mm from the total 58.2 mm. The correspondent transmission spectra can be seen on figure 3(a).
From the spectra depicted on figure 3(a), it was possible to determine the optical power for the two wavelength regions that satisfy the best sensitivity range, respectively at 1535 and 1561 nm (figure 3(b)). Considering the obtained results, one can find that the optical powers obtained at 1561 nm have produced a staighter dependency in a broader range when compared to the values at 1535 nm. For that reason, we decide to inscribe an FBG centered at a region nearby 1561 nm.

3.3. Grating inscription

The Bragg grating was inscribed through the phase mask technique, using a 266 nm UV radiation from a Quantel Q-Smart 450 laser. The laser repetition rate was set to 10 Hz, with pulse energy of 5 mJ, during 15 min exposure time. The long inscription time is related to the lower photosensitivity of the fiber, which can be reduced by hydrogen load the fiber prior to the inscription process. The grating was inscribed at 1561.2 nm with 3 nm in length and at 60 nm after the NCF (see the inset of figure 1). Thanks to the multiplexing capabilities offered by the FBG technology, another FBG was written before the NCF and far from the sensing part—FBG0 in figure 1. This FBG was centered at 1541 nm and will be used for power calibration during the acquisitions since it does not interact with the sensor part.

4. Results and discussions

4.1. Sensor characterization

The sensor characterization was done following the same procedures described before at section 3.2, for the SMS structure. In order to evaluate the hysteresis of the system, two different situations were tested: descending and ascending the sensor on the liquid container.

The correspondent FBG reflection spectra collected when the sensor is being immersed in water (3 mm steps) are shown in figure 4(a).

From figure 4(a), it can be seen that as the liquid level increases there is an increase of the reflection FBG peak power, in accordance with the results depicted on figure 3(b). This FBG peak power is then calibrated with the peak power reference of the FBG0. The correspondent evolution of the calibrated peak power on the immersion and emersion of the sensor in water, were plotted on figure 4(b). As can be seen, the calibrated FBG peak power evolution follows a linear regression model \( R^2 = 0.998 \). The obtained sensitivity was 0.25 dB mm\(^{-1} \) with a total optical power variation of 12 dB for an operational range of 51 mm. Considering a detection system with a resolution of 0.02 dB, one can find that the system resolution is 0.08 mm.

Another pertinent issue about this liquid level sensor is the total loss induced by the SMF-NCF-SMF splices. The
relevance of that is due to the different core diameters and refractive index, which can compromise the system performance. Thus, we estimate that the splicing losses are essentially the loss of the MMI peak power when it is measured in transmission. Since the interrogator has an output power source with 4 dBm and based on the peak power reading of the SMS spectra when it is in air, shown in figure 2(a) (-0.96 dBm), we estimate -3 dB loss for the two fiber splices (in transmission). Since the sensor operates in reflection (needs to pass twice times on the NCF), we estimate a total system loss of ~6 dB.

The NCF length calculated from equation (3), has been chosen to operate the SMS structure at the 4th self-image. Thus, by using an exact multiple of this image, it is possible to use a longer section of the NCF. Therefore, the 12 dB sensing range can be used with a longer NCF fiber, allowing the use of the sensor in a wider range of lengths, with restrictions only in the sensor resolution.

Additionally, the sensor employed on this paper can be constructed in a cost effective way, by just using low cost components as LED and photodetectors, together with a 2 × 2 fiber coupler for power calibration and signal detection.

4.2. Temperature error analysis

It is known that both FBG and MMI spectral responses are temperature dependent [11–13, 15, 18]. Consequently, this effect may compromise the accuracy of the proposed liquid level sensor under different temperature conditions. Therefore, a temperature test was performed in order to evaluate the measurement uncertainty due to temperature variations. To do that, the fiber based sensor composed by the SMS structure and FBG at 1561 nm was placed on a thermal chamber, where the temperature was raised from 20 to 55 °C, in steps of 5 °C. The correspondent calibrated FBG peak power variations for the different temperatures were determined and they can be seen in figure 5.

Results show that the FBG peak power was linearly blue shifted with increasing temperature. A linear regression model was applied to the experimental data points, obtaining a sensitivity of ~-0.049 dB °C⁻¹. The observed power shift at the different temperatures corresponds to the active filtering produced by the MMI spectra over the FBG spectra, when both parts (SMS structure and FBG) are being affected. The low temperature dependence is thus the result of the different spectra wavelength shifts produced by each part of the sensor (SMS structure and FBG), which have revealed opposite sensitivity contributions (10.7 and ~-42.4 pm °C⁻¹ for the FBG and SMS structure respectively), (see figure 6).

To find the uncertainty on the liquid level detection when temperature is considered (\(\delta_T\)), the sensitivity found for the temperature characterization (i.e. figure 5) and the one found for the liquid level characterization were used:

\[
\begin{align*}
\delta_T &= \frac{0.049\text{ dB °C}^{-1}}{0.25\text{ dB} \text{ nm}^{-1}} = 0.2\text{ mm °C}^{-1} \\
\end{align*}
\]

(5)

The estimated value can therefore, compromise the accuracy of the proposed sensor at high temperature changes. However, this may be solved by calibrating the signal using a parallel sensor based on the same configuration studied on this paper where the NCF is replaced by a step index MMF. In that way, the parallel sensor will be independent to the liquid level, since the MMF has an outer cladding that avoids the interaction of the light with the external environment. On the other hand, the parallel sensor will be temperature dependent. By using both sensors simultaneously and in real time it is possible to recover the liquid level independent of temperature.

5. Conclusions

We have proposed and demonstrated a simple and reliable liquid level sensor based on the use of a SMS structure and FBG. The detection relies on a self-referenced method that is based on the acquisition of the FBG peak power. The developed sensor can be deployed in a low cost solution based on an optical source centered at the FBG together with a photodetector a fiber coupler.
The sensitivity reported with the proposed sensor was 0.25 dB mm$^{-1}$. The temperature tests used to verify the temperature influence on the liquid level measurement showed an uncertainty of 0.2 mm °C$^{-1}$, revealing that the sensor can operate in environments where the temperature changes are minimal. Additionally, the sensor can be simply operated in reflection avoiding too much instrumentation.

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Simultaneous measurement of strain, temperature and refractive index based on multimode interference, fiber tapering and fiber Bragg gratings

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Abstract
We report the development of an optical fiber sensor capable of simultaneously measuring strain, temperature and refractive index. The sensor is based on the combination of two fiber Bragg gratings written in a standard single-mode fiber, one in an untapered region and another in a tapered region, spliced to a no-core fiber. The possibility of simultaneously measuring three parameters relies on the different sensitivity responses of each part of the sensor. The results have shown the possibility of measuring three parameters simultaneously with a resolution of 3.77 με, 1.36 °C and 5 × 10⁻⁶, respectively for strain, temperature and refractive index. On top of the multiparameter ability, the simple production and combination of all the parts involved in this optical-fiber-based sensor is an attractive feature for several sensing applications.

Keywords: MMI, multimode interference, fiber sensor, fiber Bragg grating

(Some figures may appear in colour only in the online journal)

1. Introduction

Nowadays, optical fiber sensors are widely used to detect physical, chemical and biological parameters. Among the key features of these sensors are their immunity to electromagnetic interference, the capability to resist harsh environments and the ability to multiplex signals.

An interesting optical fiber sensor which has been receiving attention in recent years is the fiber modal interferometer, commonly known as MMI (multimode interference). This device comprises a single-mode–multimode–single-mode (SMS) fiber structure and presents advantages like simplicity of production, high sensitivity [1, 2] and compactness. Therefore, a variety of parameters such as temperature [1, 3], strain [4], refractive index [1, 3], liquid level [5], displacement [6] and vibration [7], have been measured by this fiber-based device. In addition, the combination of different detection schemes has also been reported to discriminate the parameters being measured [8].

On the other hand, fiber Bragg gratings (FBGs) are a common device widely used in sensing applications [9]. However, they suffer from the same multiparameter discrimination problem reported for MMI-fiber-based devices. Therefore, many schemes have also been adopted to discriminate each parameter individually [10, 11].

Due to the inherent advantages of both MMIs and FBGs, the scientific community has recently proposed the combination of both fiber devices to discriminate different parameters. This will allow the simultaneous measurement of strain and temperature [12–14], strain and curvature [4],

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refractive index and temperature [15, 16, 17], and also magnetic field and temperature [18]. However, none of these works have shown the capability to measure three parameters simultaneously.

Nevertheless, simultaneous measurement of strain, temperature and refractive index has been reported using either tilted FBGs [11], long period gratings connected to polarization-maintaining FBGs [19] or etched-core FBGs [10]. However, the refractive index measurement principle adopted for the first case is based on a change of the envelope area of the cladding mode resonances, which may lead to difficulties on the fitting approximation of the lower and upper envelope curves. In the second case, the FBG wavelength shift and reflection power were used to simultaneously detect the three parameters, yet the results concerning the reflection power have revealed both low sensitivity and repeatability. Regarding the last case, the thin etched-fiber diameter (7 μm) can compromise the manipulation of the sensor head in practical applications.

In this work we present a novel optical fiber sensor capable of simultaneously measuring and discriminating three parameters: strain, temperature and refractive index. A singular combination of two FBGs and a no-core fiber (NCF, an all-silica fiber) was used. The FBGs were inscribed in the same fiber (SMF-28), but in two different parts: one in a tapered region and another in an untapered region. A section of an NCF was then spliced between the fiber containing the FBGs and another single-mode fiber (SMF). As each part of the sensor presents different sensitivity responses to the different physical stimuli, it was possible to simultaneously discriminate the three parameters under study.

2. Principle of operation

In order to produce the fiber sensor, a section of an SMF-28 was tapered down with the flame-brushing technique. In this technique the flame is swept along the fiber while it is being stretched, producing a fiber taper that contains a reduction in its cross section. The taper produced is composed of two adiabatic transitions with a uniform waist in the middle with the following dimensions: 50 μm in diameter and 10 mm in length. The taper diameter was chosen in order to provide enough fiber robustness for easy manipulation during the grating inscription and during measurement. After the tapering process, 266 nm UV radiation from a Quantel Q-Smart 450 was used to inscribe Bragg gratings in the waist of the tapered (50 μm) and untapered fiber (125 μm), through the phase-mask technique. The laser beam has a circular shape with a 6.5 mm diameter and a pulse duration of 5 ns. The phase mask pitch was selected to produce FBGs in the infrared region with enough separation between them, allowing easy discrimination. The laser beam was guided by mirrors and passed through a cylindrical lens (f = 20 cm) which was followed by a slit 3 mm in width, used to shape the beam onto the fibers. The FBGs were written under a repetition rate of 10 Hz, with pulse energy of 5 mJ, during a 15 min exposure time. The long inscription time is related to the lower photosensitivity of the fibers, that can be reduced by hydrogen loading prior to the inscription process. The FBGs were produced to be 3 mm in length and with a high enough peak-to-noise level to be detected in reflection.

The second part of the sensor is composed of the SMS structure containing the NCF, which is a pure silica rod with a diameter of 125 μm and with a refractive index of 1.444 at 1550 nm. The complete fiber sensor can be seen in the inset of figure 1. To allow the phenomenon of self-imaging for a specific wavelength in the SMS structure, it is necessary to know the distance at which the input field is replicated, in both amplitude and phase [1]. This length can, therefore, be calculated through

\[
L_{NCF} = \frac{4D_{NCF}^2n_{NCF}}{\lambda},
\]

where \(n_{NCF}\) and \(D_{NCF}\) are the effective refractive index and diameter of the fundamental mode, respectively; \(L\) corresponds to the length of the NCF and \(\lambda\) is related to the peak wavelength.

The calculated length, estimated to have a peak centered at 1550 nm, was thus 58.2 mm. A digital caliper together with a fiber optic cleaver machine were used to cut the NCF at the desired length. The two ends of the NCF were fusion-spliced to an SMF-28 and to the SMF containing the FBGs. To do this, the fibers were inserted in a fiber fusion machine and aligned through the cladding. The NCF was then fusion-spliced to the SMFs and the sensor was ready for the characterization tests.

When changes in strain (\(\Delta C\)), temperature (\(\Delta T\)) or refractive index (\(\Delta n\)) are applied simultaneously, both parts of the sensor (FBGs and MMI) will react by changing their resonance wavelength. The correspondent wavelength shifts can be expressed by the following matrix:

\[
\begin{bmatrix}
\Delta \lambda_{FBG1} \\
\Delta \lambda_{FBG2} \\
\Delta \lambda_{NCF}
\end{bmatrix} =
\begin{bmatrix}
K_{C,FBG1} & K_{T,FBG1} & K_{n,FBG1} \\
K_{C,FBG2} & K_{T,FBG2} & K_{n,FBG2} \\
K_{C,NCF} & K_{T,NCF} & K_{n,NCF}
\end{bmatrix}
\times
\begin{bmatrix}
\Delta C \\
\Delta T \\
\Delta n
\end{bmatrix},
\]

Figure 1. Setup used for the characterization of strain temperature and refractive index. The inset figure shows the sensor structure composed of the combination of two FBGs in untapered and tapered regions of an SMF-28, and an SMS structure containing an NCF.
where, $\Delta \lambda_{\text{FBG}_i}$ and $\Delta \lambda_{\text{FBG}_2}$ represent the wavelength shifts of the FBG in tapered and untapered fiber, respectively; $\Delta \lambda_{\text{NCF}}$ denotes the wavelength shift of the NCF; and $K_I$ and $K_e$ are the sensitivity coefficients, corresponding to the changes of strain, temperature and refractive index, respectively.

Subscripts FBG$_1$, FBG$_2$ and NCF refer to the individual contribution of the FBGs in the untapered/tapered fiber and SMS structure. The three parameters under study can, therefore, be calculated through the equivalent matrix as

$$
\begin{bmatrix}
\frac{\Delta \varepsilon}{\Delta T}
\frac{\Delta T}{\Delta \rho}
\end{bmatrix} = \begin{bmatrix}
M^{-1}
\end{bmatrix} \times
\begin{bmatrix}
\Delta \lambda_{\text{FBG}_1}
\Delta \lambda_{\text{FBG}_2}
\Delta \lambda_{\text{NCF}}
\end{bmatrix},
$$

where $M^{-1}$ is the inverse coefficient matrix.

The wavelength measurement resolution (i.e., $\delta(\Delta \lambda_{\text{FBG}})$, $\delta(\Delta \lambda_{\text{FBG}_1})$ and $\delta(\Delta \lambda_{\text{NCF}})$), given by the resolution of the acquisition system, will determine the uncertainty on the measured strain, temperature and refractive index. The correspondent values can be calculated through

$$
\begin{bmatrix}
\delta(\Delta \varepsilon)
\delta(\Delta T)
\delta(\Delta \rho)
\end{bmatrix} = \begin{bmatrix}
\frac{\delta(\lambda_{\text{FBG}})}{\lambda_{\text{FBG}}}
\frac{\delta(\lambda_{\text{FBG}_1})}{\lambda_{\text{FBG}_1}}
\frac{\delta(\lambda_{\text{NCF}})}{\lambda_{\text{NCF}}}
\end{bmatrix},
$$

3. Experimental setup

The experimental setup used to characterize the fiber sensor is shown in figure 1. Both fiber tips were glued to a fixed stage and another to a motorized linear stage (GTB 150/3). The distance between the stages where the glue was inserted was 27 cm. On the central region of the setup, a liquid container was placed above a hot plate (IKA®C MAG HST). The liquid container is used to surround the fiber sensor with a specific refractive index. The hot plate is, therefore, used to control the temperature of the solutions. In order to observe the FBG and SMS spectral responses, an interrogator system (FS2200—Industrial BraggMETER, FiberSensing) was used to measure the reflection signal from the FBGs as well as the transmission signal from the SMS structure. The fiber sensor configuration used to measure the reflection signal from the FBGs is presented in figure 1, where the FBG precedes the SMS structure. On other hand, if the opposite configuration is chosen (SMS followed by the FBGs), the FBG reflectivity will be modified by the envelope of the SMS spectra, that is dependent on the external conditions [4,16]. Therefore, the uncertainty present on the peak wavelength detection with such a configuration could be higher, leading us to exclude this scheme.

The sensor characterization was performed, getting the sensitivity coefficients of each parameter individually: one parameter changes while two others remain constant. For the strain test, the fiber sensor was kept in water, at a constant temperature of 22°C. The strain was imposed in steps of 92.6 με in a range of 1389.0 με. In order to characterize the sensor to temperature, the liquid container was left with water in it. The temperature was swept from 22–85 °C and no strain was imposed during the tests. For the refractive index tests, the liquid container was filled with six different solutions of water/isopropyl alcohol whose refractive index was previously measured. For each solution, the temperature of the bath was maintained at a constant 22 °C and no strain was imposed on the sensor. The refractive index of the different solutions was measured at 22 °C using a Nippon Abbe® handheld refractometer with a resolution of $1 \times 10^{-4}$ and a 590 nm wavelength radiation.

4. Results and discussion

Regarding the results obtained for the FBGs strain test (figures 2(a) and (c)), it can be observed that both FBGs presented a red shift with increasing strain, with values of 5.77 and 0.92 pm με$^{-1}$, respectively for the FBG in tapered and untapered fiber. The red shift was expected since the FBGs grating pitch increases with increasing strain.

On other hand, the sensitivities obtained for the untapered and tapered FBGs were decreased and increased respectively, when compared with the value of 1.2 pm με$^{-1}$ found for the standard characterization of an FBG written in the same SMF-28. This result is due to the unequal strain distributions along the fiber sensor. The relation between the strain applied in each part of the sensor and the correspondent cross-sectional area can be written as

$$
\frac{\varepsilon_{\text{fiber}}}{\varepsilon_{\text{taper}}} = \frac{A_{\text{taper}}}{A_{\text{fiber}}},
$$

where $\varepsilon_{\text{fiber}}$ and $\varepsilon_{\text{taper}}$ refer to the strain on the fiber and taper, respectively; $A_{\text{taper}}$ and $A_{\text{fiber}}$ refer to the cross-sectional area of the fiber and taper respectively. Thus, the applied strain will be higher in the tapered region than in the untapered region, since its area is smaller [20]. This leads to a decrease in the sensitivity on the untapered FBG, and to an increase in the tapered FBG [20].

Using the definition of strain and following the deductions given at [20], we can theoretically estimate the sensitivity for the FBG written on the untapered section of the fiber as

$$
K_{1(\text{taper})} = K_{0(\text{FBG})} \times \frac{L_{\text{FBG}} + L_{\text{FBG}_1} + L_{\text{taper}} + L_{\text{fiber}}}{L_{\text{fiber}} \left( \frac{d_{\text{FBG}}}{d_{\text{taper}}} \right)^2 + L_{\text{FBG}} \left( \frac{d_{\text{FBG}}}{d_{\text{fiber}}} \right)^2 + L_{\text{taper}} + L_{\text{FBG}}},
$$

and for the FBG written on the tapered section as

$$
K_{2(\text{taper})} = K_{0(\text{FBG})} \times \frac{L_{\text{FBG}} + L_{\text{FBG}_1} + L_{\text{fiber}} + L_{\text{fiber}}}{L_{\text{FBG}} \left( \frac{d_{\text{FBG}}}{d_{\text{FBG}_1}} \right)^2 + L_{\text{taper}} + L_{\text{FBG}}},
$$

where $K_{0(\text{FBG})}$ refers to the strain coefficient of a common FBG written in an SMF28 fiber (1.2 pm με$^{-1}$); $L_{\text{FBG}}$, $L_{\text{FBG}_1}$, $L_{\text{taper}}$ and $L_{\text{fiber}}$ are the lengths of each sensor section; $d_{\text{FBG}}$, $d_{\text{FBG}_1}$, $d_{\text{taper}}$ and $d_{\text{fiber}}$ refer to the diameters of
each fiber section. In order to verify the theoretical behavior of both sensitivities presented in equations (6) and (7) for different pulling fiber lengths, we have plotted the two curves on figure 3.

The theoretical values found for the experimental pulling fiber length (27 cm), were 6.33 and 1.01 pm με⁻¹ for the tapered and untapered fiber, respectively. These theoretical values reveal a close match to the experimental ones, considering that the fiber dimensions used for the theoretical calculation are based on approximated values of the fiber structures and grating dimensions. Additionally, it can be seen from the same figure, that the length of the pulled fiber sensor is also determinant for the FBGs sensitivity, since for longer lengths the effect of the taper section becomes negligible [30].

For the NCF, it can be seen from figures 2(b) and (c), that there was a blue shift with increasing strain, corresponding to a sensitivity of −1.29 pm με⁻¹. This result is mainly explained by equation (1), since L NCF increases and D NCF decreases with increasing strain.

Moreover, the unequal strain distribution that occurs on the tapered and untapered section of the SMF-28 will also occur on the NCF fiber, leading to a smaller sensitivity than the theoretical value.

In order to estimate the maximum strain supported by the fiber sensor, we have performed rupture tests for 20 samples with dimensions similar to the ones used in the strain sensitivity measurements. The results show that the tapered region can support maximum strain values that range from half to two times that of the correspondent measured value for the untapered fiber, (10 ± 2) με. Moreover, the observed values are comparable to the ones found for a standard single-mode optical fiber, 5.5 με, as reported in [21].

Regarding the experimental characterization of the refractive index, the resonant Bragg wavelength for the FBGs does not change with the different solutions (see the data points collected for the Bragg wavelength shifts on figure 4(b)). This result was expected because the fundamental mode on the tapered/untapered regions of the fiber is strongly coupled to the fiber core and, therefore, its evanescent field does not interact with the surrounding medium. On other hand, the NCF presents strong interaction with the surrounding environment (see the spectra change in figure 4(a)). Since the fiber does not present an outer cladding layer, the guided modes can strongly
interact with the external refractive index solutions. From the different NCF spectra collected, the peak wavelength change was calculated as the center wavelength at 30% of the maximum peak. This was done in order to minimize the uncertainty on the peak wavelength position due to the power transfer that appears between peaks (mainly on the last two spectra of figure 4(a)). The corresponding wavelength shifts were calculated and can be seen in figure 4(b). Additionally, it can be observed that the wavelength shift increases with increasing refractive index and, as expected, the behavior is not linear under the range studied [1, 22]. In order to obtain a linear tendency for the resonant wavelength shifts, a narrow refractive index range (~1.33–1.37) is considered. This range is still valid for several areas of engineering such as environmental sensing; therefore, one can obtain a sensitivity of 116.5 nm RIU−1.

For the temperature characterization, the correspondent spectra change for FBGs and NCF were obtained and can be seen in figures 5(a) and (b), respectively. From figure 5(c), it can be noticed that the resonance wavelength shifts for the FBGs are similar and positive with increasing temperature. This red shift is mainly due to the thermo-optic coefficient (i.e. change of the refractive index of silica material with temperature). Regarding the results obtained for the NCF (spectra in figure 5(b) and asterisk points on figure 5(c)), it can be seen that there is a red shift of the peak wavelength with increasing temperature. However, this test was done with the fiber sensor immersed in water; therefore, the temperature changes imposed on the characterization test will indirectly induce a change in the refractive index of water [23]. This is not the case with the FBGs since they are wavelength-independent of the external refractive index (figure 4(b)).

Therefore, the NCF wavelength shifts due to the temperature changes alone (ΔλT) can be calculated as

$$Δλ_T = Δλ_{T,A} - K_{NCF} \times Δn_{water} \times ΔT,$$

where Δλ_{T,A} is the overall shift due to the direct and indirect contribution of temperature and water refractive index change, respectively; K_{NCF} is the calculated refractive index sensitivity of the NCF (116.5 nm RIU−1); and Δn_{water} is the water thermo-optic coefficient, calculated from the data points given in [24] as ~2 × 10−4 °C−1. The correspondent ΔλT found after the correction can be seen on figure 5(c) as the square points. The correspondent NCF temperature sensitivity was then calculated from the corrected wavelength shifts, giving a value almost four times higher than the ones found for the FBGs. This higher value is probably due to the higher thermo-optic coefficient of the NCF when compared to the SMF-28 [13].

Using the above tests and linear fits, the correspondent Δε, ΔT and Δn can be simultaneously calculated through

$$\begin{bmatrix} Δε \\ ΔT \\ Δn \end{bmatrix} = \begin{bmatrix} 0.92 & 5.77 & -1.29 \\ 9.89 & 8.62 & 34.82 \\ 0 & 0 & 116.500 \end{bmatrix} \begin{bmatrix} Δλ_{T,BG} \\ Δλ_{T,BG} \\ Δλ_{T,NCF} \end{bmatrix}.$$

The sensor was experimentally tested, giving maximum relative errors of 0.4%, 11% and 8 × 10−3 RIU, respectively, for strain, temperature and refractive index. The differences in the maximum relative errors can be attributed to inaccuracy and uncertainty during the calibration process and also on the peak wavelength detection, especially for the NCF spectra that has a broadened shape. Considering a detection system with a wavelength resolution of 10 pm and using equation (4), the resolution of strain, temperature and refractive index can be calculated respectively as 3.77 με, 1.36 °C and 5 × 10−4.

In order to compare the proposed sensor with the ones found in literature, capable of simultaneously detecting strain, temperature and refractive index (i.e. [10, 11, 19]), we have constructed a table where we can compare the system resolutions. The values were calculated using equation (4), considering a detection system with a resolution of 10 pm in wavelength and 0.02 dB in amplitude (for sensors based on power (i.e. [11, 19]). The values obtained for sensor 1, presented at [19], were calculated considering a silica fiber Young’s modulus of 70 GPa. Additionally, the refractive index value calculated for sensor 3 [11] was calculated individually since this parameter is taken independently from the temperature and strain parameters. The correspondent system resolutions can be seen in table 1.

The values presented in table 1 show that the proposed sensor is well positioned among the different sensors found.

<table>
<thead>
<tr>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>ε (με)</td>
<td>3.77</td>
<td>7.11</td>
<td>1.96</td>
</tr>
<tr>
<td>T (°C)</td>
<td>1.36</td>
<td>4.02</td>
<td>0.60</td>
</tr>
<tr>
<td>N</td>
<td>5.0 × 10−4</td>
<td>0.25</td>
<td>9.0 × 10−4</td>
</tr>
</tbody>
</table>

Figure 5. (a) Reflection spectra collected for both FBGs at different temperatures; (b) normalized transmission spectra collected for the NCF with different temperatures, and considering the inherent refractive index change of water; (c) wavelength shifts collected from the wavelength peak power for all the parts involved in the sensor at different temperatures.
in literature, achieving values very close to the ones presented for sensor 2 (i.e. [10]).

The proposed fiber-optic sensor is simply produced due to the easy concatenation of all the parts involved. However, the NCF cleaning process needed to achieve a peak power wavelength centered at the wavelength range of the measurement system needs to be done with special care. This can be easily solved using a learning process.

The capability to simultaneously discriminate strain, temperature and refractive index can be a useful tool; for instance, in the control of the cure processes of materials, where the knowledge of these three parameters is important.

5. Conclusions

We have proposed and demonstrated a simple and effective all-fiber sensor to simultaneously measure strain, temperature and refractive index. The ability to measure different variables without stabilization of the ambient conditions is useful in different areas. The concatenation of the different fiber technologies allows the possibility of simultaneously measuring three parameters with a resolution of 3.77 με, 1.36 °C and $5 \times 10^{-4}$, respectively, for the strain, temperature and refractive index. The simple design and measurement scheme is a highly promising feature for multiparameter sensing applications.

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References

Determination of Young’s modulus using optical fiber long-period gratings

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Abstract
Curvature sensitive CO2 laser induced long-period fiber gratings (LPGs) were employed to measure the Young’s modulus of materials. Two techniques, ‘bar resonance’ and ‘through transmission’, were used. In the first case, flexural vibrations of bars made of various industrial materials arranged in a cantilever configuration were probed by the LPG. The measured response allowed us to obtain the bar’s vertical movement as a function of time, its frequency components and the bar material’s Young’s modulus. In the second case, the optical response of LPFGs was used to determine the propagation velocities of perturbations along a bar, which allowed the straightforward calculation of the Young’s modulus. The values obtained show good agreement with the ones reported in the literature. The results obtained in this paper demonstrate the feasibility of using LPFGs to dynamically characterize a material’s elastic properties. To the best of our knowledge, this is the first demonstration of the use of long-period fiber gratings for dynamically determining Young’s modulus values.

Keywords: optical fiber sensor, vibration sensor, Young’s modulus, long-period fiber grating

(Some figures may appear in colour only in the online journal)

1. Introduction

Predicting a material’s behavior under deformation is a very important task in engineering. Thus, measuring a material’s Young’s modulus, which is a fundamental parameter allowing us to determine the stiffness of a given material, is essential for the development of engineering projects [1].

Young’s modulus can be obtained from static and dynamic measurements. When the Young’s modulus is studied from a static point of view, a setup in which a uniaxial stress is applied on the sample is usually employed. By taking into account the slope of the stress-strain curve at the origin, the elastic modulus is then calculated. Dynamic measurements, in turn, are more precise than the static ones because they employ very low strain levels. Moreover, they are nondestructive and repeatable tests [1]. These measurements are generally performed using the ‘through transmission’ [2] or the ‘bar resonance’ technique [1, 3].

Although Young’s modulus can be dynamically measured using electrical sensors [1], there are a number of advantages to building up fiber optics-based devices. Among these advantages are the small size of the devices, their ease of fabrication, their high sensitivity and their immunity to electromagnetic interference. Besides, they are very robust and make it possible to act in harsh environments and can be inserted into the structure to be tested. It is particularly important, for instance, in civil engineering applications, since the fiber can be inserted into walls, beams and floorings [4, 5].

In this paper, we show the feasibility of using CO2 laser induced long-period gratings (LPFGs) for determining the Young’s modulus of materials. To do this, two methods were studied. In the first method, we characterized the dynamic response of bars made of different materials put in oscillation. By recovering the bars’ flexural oscillations from the LPFG time response and by taking the fast Fourier transform (FFT) of it, the movement vibration frequencies could be obtained. Knowledge of these vibration frequencies for the oscillation lengths of different bars allowed us to calculate the materials’ Young’s moduli. In the second method, the Young’s modulus was determined by measuring the propagation velocities of
longitudinal and transversal perturbations along a bar also via the observation of the LPG’s optical responses.

2. Young’s modulus determination

The first setup to be presented for measuring a material’s Young’s modulus employs the ‘bar resonance’ method [1, 3]. In this technique, a bar of the material of interest is arranged in a cantilever configuration and put in oscillation. The resulting movement is studied in order to obtain the bar material’s Young’s modulus value. In contrast to reference [1], where the authors employed a force sensor to register the displacement of the bar as a function of time, here we use a curvature sensitive long-period fiber grating to obtain this measurement.

The Young’s modulus of optical fibers was previously measured [6, 7]. However, we emphasize that our interest is in measuring the Young’s moduli of materials other than the one that the fiber is made from. Thus, to our knowledge, this is the first paper to report the use of long-period fiber gratings for determining the Young’s moduli of materials of interest.

Consider a horizontal bar set in a configuration in which it is fixed at one of its ends. If the bar is vertically deflected from its equilibrium state and then released, the resulting movement is oscillatory and its amplitude decays as a function of time. The formal treatment of this movement, via the Euler–Bernoulli equation, indicates that the general solution has a series form with infinite frequency components, which are given by equation (1), where $\rho$ and $Y$ are, respectively, the material density and Young’s modulus; $A$ and $L$ are, respectively, the cross-sectional area and the vibrating length of the bar; $f_s$ is the second moment of the cross-section, which for a rectangular bar of width $d$ and depth $t$, can be calculated as $d t^2/12$. Moreover, in equation (1) one can find the parameter $\lambda_0$, known as modal eigenvalue, which is determined by the boundary conditions of the problem [1]

$$ f_s = \frac{\lambda_0 (Y/d) \frac{Yr^2}{\rho A}}{L^2}, $$

(1)

As we focus on the determination of the Young’s modulus, one can see, from equation (1), that the knowledge of only one frequency component is enough to attain our goal. In this investigation, we determined the first frequency component, $f_s$, and then found the Young’s moduli of the materials of interest.

The second method reported here for obtaining the Young’s modulus employs the ‘through transmission’ technique of acoustic waves [8]. The experiment is carried out by exciting longitudinal and transversal mechanical perturbations on a long bar and then by measuring the propagation velocities of these perturbations. Knowledge of the longitudinal and transversal velocities of the induced mechanical perturbation ($v_x$ and $v_y$, respectively) allows us to calculate the Young’s modulus of the material from equation (2) (where $\rho$ is material density) [8]

$$ Y = \frac{3 \rho v_i^2}{\frac{2}{v_L^2} \left( v_L^2 - \frac{4}{3} v_T^2 \right)}, $$

(2)

3. Long-period gratings and their curvature sensitivity

Long-period fiber gratings (LPGs) consist of a longitudinal periodic perturbation of the refractive index of an optical fiber which is able to provide coupling between core and cladding modes at certain wavelengths. Equation (3) describes the wavelengths $\lambda_n^{(m)}$ where the coupling between the referenced modes happen—$n_{cl}$ is the effective refractive index of the core mode, $n_{cl}^{(m)}$ is the effective refractive index of the $m$th order cladding mode and $A$ is the period of the refractive index perturbation. Experimentally, the wavelengths at which coupling is attained are seen as dips in the LPG transmission spectrum (one example can be seen in the inset of figure 2) [9]

$$ \lambda_n^{(m)} = (n_{cl} - n_{cl}^{(m)}) A. $$

(3)

The refractive index modulation for inducing long period gratings can be obtained, for instance, by applying an electrical arc or by pressurizing a corrugated board against the fiber [9]. Also, exposing the fiber to a femtosecond, UV or CO2 laser is a means to achieve the refractive index longitudinal pattern [10].

In this research, CO2 laser-induced LPGs imprinted on standard telecom optical fibers were employed. The gratings obtained in this way have the property of being sensitive to the curvature conditions to which the fiber is subjected (the curvature itself and its orientation). This sensitivity arises from the fact that the fabrication method provides a nonuniform refractive index change on the cross-section of the fiber, causing the cladding modes field distribution to be asymmetric. Thus, according to the direction that the fiber is bent, the overlap integral value between the coupled modes can increase or decrease and, therefore, a variation in the coupling coefficient between the modes is observed [11, 12].

This variation on the coupling coefficient can be experimentally realized when observing the depth of the LPG spectral resonances: the deeper the resonance, the higher the coupling coefficient between the modes. As it is associated with the bending conditions, the fiber curvature state can be probed if this feature is characterized.

In order to perform a characterization measurement of the LPG response to curvature variations, a 500 µm pitch and 2.5 mm long LPG was set in a configuration as shown in figure 1. In the experimental setup, a super-luminescent LED (SLED) is used as the light source. An optical spectrum analyzer (OSA) and a photodetector (PDT) coupled to an oscilloscope (OSC) are used for taking measurements. The LPG is glued (using Loctite® Super Bond) on a bar made of a material of interest, which has one fixed end and the other one is let free. The deflection of the bar (accounted as a vertical displacement $\Delta y$ of the free bar end), causes the LPG to bend and, thus, its curvature response can be monitored. It’s worthwhile emphasizing that, during characterization, the free bar end is deflected by using a micrometric screw.

Figure 2 shows how the optical response of the LPG, whose transmission spectrum is presented in the inset, varies according to the bar end vertical displacement $\Delta y$. The situation in which the bar is straight is defined as $\Delta y = 0$. Positive
variations in $\Delta y$ indicate upward displacements and negative variations downward displacements.

The vertical axis in the figure 2 plot follows the same logic. The voltage measured in the photodetector is assumed to be zero when the bar is straight. If there is an increment in the transmitted light power, the voltage variation is positive; if, in contrast, there is a light power decrement, the voltage variation is negative.

By observing the figure 2 inset, one can see that when $\Delta y$ is positive, the LPG resonance is shallower than when $\Delta y$ is negative. Ergo, when detecting light using the photodetector, its voltage response is proportional to the overall optical power from the broadband light source, negative voltage variations are related to negative $\Delta y$ values and positive voltage variations identify positive $\Delta y$ values. It happens due to the fact that, for a shallower resonance, a higher overall light power level sensitizes the photodetector and, for a deeper one, a lower light power level is detected.

The dependence of voltage on bar vertical displacement is seen to be linear. The angular coefficient of the fitted line, $(42 \pm 2) \text{ mV mm}^{-1}$, acts as a calibration factor for recovering the vertical displacement of the bar from optical data. It’s worth emphasizing, however, that the linear behavior is observed since the measurements were performed in a small curvature range. For macrobending conditions, a nonlinear behavior is expected [13].

Figure 2. System calibration. The vertical displacement of the bar implies a depth variation of the LPG resonance. It can be accounted for as a voltage variation in the photodetector. Inset shows the spectral characteristics of the LPG resonance.

Figure 3. Photodetector (left axis) time response and its conversion to vertical displacement (right axis). Inset shows the fast Fourier transform (FFT) amplitude as a function of frequency.

4. ‘Bar resonance’ method results

The ‘bar resonance’ method allows us to obtain the Young’s modulus of a material by probing the flexural movements of bars put in oscillation in a cantilever setup. In order to probe the oscillatory movement of the bar, we again use the configuration shown in figure 1 with the photodetector as the measurement system.

Initially, the bar is deflected ($\Delta y < 2 \text{mm}$) and then released. The subsequent movement around the equilibrium position causes the LPG to bend upwards and downwards. The signal measured in the oscilloscope takes a sinusoidal form whose amplitude decays as a function of time (figure 3).

The left axis of the plot in figure 3 shows the photodetector signal measured by the oscilloscope when a 21 cm long steel bar is put in oscillation—the LPG was glued at a distance $L = (13.00 \pm 0.05) \text{ cm}$ from the fixed end of the bar. Dividing this data by the calibration constant, $(42 \pm 2) \text{ mV mm}^{-1}$, one can calculate the vertical displacement $\Delta y$ of the bar—right axis in figure 3. Furthermore, it is worth observing that the movement acceleration can be obtained by simply taking the second derivative of the signal shown in figure 3. Experimental
Figure 4. Fundamental frequency versus vibrating bar length plot for tested materials. Dots represent the measured data and solid lines the fitted curves.

Table 1. Characteristics of the bars employed in the experiments.

<table>
<thead>
<tr>
<th>Material</th>
<th>Density, ρ (kg m⁻³)</th>
<th>Cross-section area, A (mm²)</th>
<th>Cross-section second moment, J (mm⁴)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel</td>
<td>7935 [14]</td>
<td>24.774 ± 0.003</td>
<td>1.9827 ± 0.0006</td>
</tr>
<tr>
<td>Aluminum</td>
<td>2700 [15]</td>
<td>73.204 ± 0.005</td>
<td>13.543 ± 0.003</td>
</tr>
<tr>
<td>Copper</td>
<td>8960 [15]</td>
<td>34.197 ± 0.004</td>
<td>2.5181 ± 0.0008</td>
</tr>
<tr>
<td>Polystyrene</td>
<td>1072 [16]</td>
<td>112.775 ± 0.003</td>
<td>99.265 ± 0.009</td>
</tr>
</tbody>
</table>

Table 2. Measured and literature Young’s moduli values.

<table>
<thead>
<tr>
<th>Material</th>
<th>Yield strength (GPa) (this paper)</th>
<th>Yield strength (GPa) (literature)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel</td>
<td>200 ± 3</td>
<td>190–213 [17, 18]</td>
</tr>
<tr>
<td>Aluminum</td>
<td>70.9 ± 0.8</td>
<td>70–72 [1]</td>
</tr>
<tr>
<td>Copper</td>
<td>108 ± 2</td>
<td>110–120 [1]</td>
</tr>
<tr>
<td>Polystyrene</td>
<td>3.03 ± 0.06</td>
<td>2–4 [19]</td>
</tr>
</tbody>
</table>

results show that the movement acceleration reaches values in the order of 20 m s⁻².

By taking the Fourier transform of the measured signal, one can identify the frequency components of the oscillating bar movement. The inset in figure 3 shows the amplitude of the fast Fourier transform (FFT), calculated from figure 3 data, as a function of the frequency. The fundamental frequency, identified as the highest peak in the figure 3 inset plot, is found to be (10.10 ± 0.02) Hz.

Figure 4 shows the fundamental frequency data measured for different bar vibration lengths and for different bar materials (steel, aluminum, copper and polystyrene). This plot allowed us to obtain each of the tested materials’ Young’s modulus by fitting the experimental data using equation (1). It is worth observing that the variation in the bar vibrating length is done by simply changing the point where the bar is fixed.

As can be seen in equation (1), if one wants to obtain the Young’s modulus from fitting a fundamental frequency versus vibrating length plot, it is necessary to know the material density, bar cross-sectional area and its second moment values. These values are shown in table 1. Also, one needs to know the modal eigenvalue for the fundamental mode, λ₁. This value, calculated to be 1.875 for the studied configuration, is obtained from an eigenvalue equation that arises when considering the problem boundary conditions in the Euler–Bernoulli equation (nonzero vertical displacement and zero initial velocity). The graphical method for obtaining this value is explained in [1].

Table 2, in turn, shows the measured Young’s moduli values and the expected ones from the literature. From data shown in table 2, one can analyze that the Young’s moduli values obtained herein show a good resemblance to the ones found in the literature. It makes the optical method proposed in this paper a good alternative for performing a fast, efficient and nondestructive measurement of a material’s Young’s modulus.

5. ‘Through transmission’ technique results

The ‘through transmission’ method for determining a material’s Young’s modulus is based on the measurement of the propagation velocities of longitudinal and transversal acoustic perturbations along a bar of the material of interest. Here, we used the setup shown in figure 5, where two LPGs were glued on the tested bar (made of aluminum) at a distance ΔL apart from each other.

When longitudinal and transversal acoustic perturbations are induced on a bar end, they propagate along the bar with different velocities, vL and vT, respectively. These perturbations can be induced on the bar by simply hitting it longitudinally or transversally, as indicated in figure 5.

The propagation of the acoustic waves along the bar causes the LPGs’ optical responses to alter when the pulses reach the position where they are glued. As the LPGs are a distance ΔL = (2.55 ± 0.01) m apart from each other, the pulse reaches the second LPG position after the time interval Δt that it reached the first LPG one. By taking into account this time interval and the distance between the LPGs, one can calculate the pulse velocity.

Figure 6 shows how the time interval Δt is measured. The optical responses of the LPGs are measured as a function of time by using two photodetectors connected to an oscilloscope (figure 5). The voltage measured while there is no perturbation on the bar is assumed to be zero. When the perturbation reaches the LPG’s position, a voltage variation is observed.
To account for the time interval $\Delta t$ that the perturbation pulse took to cover the distance $\Delta L$ between the gratings, the first peak in the voltage variation versus time plot was considered. A threshold was defined for a local maximum to be considered a peak that had arisen due to pulse passage. One considered a peak a local maximum with greater amplitude than three times the standard deviation of the voltage variation points between zero and 2 ms (which is the voltage fluctuation level without any external perturbation).

The measurement of the time interval $\Delta t$ was performed ten times for longitudinal and transversal perturbations separately. For longitudinal perturbations, $\Delta t$ was found to be $(4.7 \pm 0.5)$ ms and, for transversal perturbations, it was found to be $(8 \pm 1)$ ms. By dividing the distance between the gratings by the time interval just presented, longitudinal and transversal perturbation velocities were calculated to be $(5400 \pm 500)$ m s$^{-1}$ and $(3200 \pm 400)$ m s$^{-1}$ respectively.

The knowledge of these velocities allowed us to obtain the Young’s modulus of the bar material (aluminium) via equation (2). The attained value was $(70 \pm 10)$ GPa when using $2700$ kg m$^{-3}$ as the material density.

Concerning the frequency response of the system, one can say that we were able to measure signals that ranged from a few hertz up to 5 kHz. A specific study, however, is still needed to explore the frequency limits of the sensor.

The Young’s modulus value obtained by the ‘through transmission’ method, $(70 \pm 10)$ GPa, is comparable to the ones obtained using ‘bar resonance’ technique and found in the literature, $(70.9 \pm 0.8)$ GPa and $70.72$ GPa, respectively (see table 2), although it is less accurate. We believe that this lack of accuracy arises from the difficulty in defining the moment in time when the perturbations sensitize the LPGs. The measurement of the time interval between the moments when the perturbations reach the first and second LPGs provides a value in the order of milliseconds and an error in the same order of magnitude. Thus, we believe if the measurement could be performed using a longer bar and greater spacing between the LPGs, the percentage error could be reduced. Furthermore, our future research will include a more thorough study of how to attach the LPGs to the bars more efficiently. We believe that improvements to the gluing process will contribute to the optimization of the optical response.

6. Conclusions

This paper has reported the application of fiber long-period gratings to vibration monitoring and Young’s modulus determination. To the best of our knowledge, this is the first article to deal with the determination of a material’s Young’s modulus using long-period fiber gratings.

Steel, aluminum, copper and polystyrene samples were tested and the experimental results for Young’s modulus values, obtained by ‘bar resonance’ and ‘through transmission’ techniques, are in good agreement with the ones reported in the literature. Besides, the ‘bar resonance’ measurement method reported herein allows us to obtain the acceleration of the studied movement—which was in the order of $20$ m s$^{-2}$.

Therefore, the presented results indicate that long-period fiber gratings can be straightforwardly employed in the dynamic characterization of a material’s elastic properties.

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Photonic-crystal fiber-based pressure sensor for dual environment monitoring

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In this paper the development of a side-hole photonic-crystal fiber (SH-PCF) pressure sensor for dual environment monitoring is reported. SH-PCF properties (phase and group birefringence, sensitivity to pressure variations) are measured and compared to simulated data. In order to probe two environments, two sections of the SH-PCF with different lengths are spliced and set in a Solex fiber-like configuration. This setup allows obtaining the individual responses of the first and second fiber independently, which is useful for a space-multiplexed measurement. As the employed fiber is sensitive to pressure variations, we report the use of this configuration for dual environment pressure sensing. © 2014 Optical Society of America

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1. Introduction

Photonic crystal fibers (PCF) are an excellent platform for sensing applications due to their inherent design versatility [1]. By adequately choosing the microstructure, fiber characteristics can be tailored in order to optimize the physical properties of interest. This versatility permits the development of a great variety of PCF-based sensors for the monitoring of different physical quantities (e.g., hydrostatic pressure [2], strain [3], and curvature [4]).

The properties of PCFs can be chosen in such a way that their optical response is dependent on hydrostatic pressure variations. This dependence is mediated by the geometrical and photoelastic effects and is highly dependent on PCF microstructure geometry [5]. Birefringent PCFs are often used to build up hydrostatic pressure sensors, as reported in previous papers [2,5,6,7]. In these papers authors perform pressure sensing measurements by two means: either exploring the phase birefringence dependence on pressure variations or studying the spectral behavior of a fiber subjected to different pressure conditions in an interferometric configuration.

In the first case, the physical quantity to be analyzed is the phase birefringence derivative with respect to pressure ($\partial B/\partial P$) and the measurement is performed by using a laser as the light source and a photodetector for taking information about the transmitted power. $\partial B/\partial P$ value depends on the wavelength ($\lambda$), the length of the fiber submitted to external pressure ($L_e$) and on the pressure $P$ needed to rotate the fiber output light polarization $\pi$ rad (one polarization cycle). This dependence is expressed by Eq. (4) [2].
\[
\frac{\partial B}{\partial P} = \frac{\lambda}{T \mu P}, \tag{1}
\]

The second type of measurement is based on the employment of a broadband light source and on the measurement of the spectral response of an interferometric configuration. This response is characterized by the existence of interferometric fringes whose spectral position shifts as the pressure is varied. In order to characterize this dependence, a sensitivity coefficient \( C_s \) is defined and its value can be accounted for by Eq. (2) [6],

\[
\frac{\Delta \lambda}{\Delta P} = C_s \approx \frac{\lambda}{G} \frac{\partial B}{\partial P}, \tag{2}
\]

where \( \lambda \) is the central wavelength of a local minimum in the spectra (destructive interference), \( \Delta \lambda \) is the central wavelength shift caused by the application of external hydrostatic pressure, \( \Delta P \) is the pressure variation, \( G \) is the group modal birefringence, and \( \partial B/\partial P \) is the phase birefringence derivative with respect to pressure, as described before.

In this paper, we theoretically and experimentally studied the sensitivity of a side-hole PCF (SH-PCF), a fiber with longitudinal holes beside the microstructured region [8] to hydrostatic pressure variations and employed the same in a dual environment pressure sensing measurement. We focused on studying fiber properties and on obtaining the dual environment sensor. It is not our goal to report record pressure sensitivity value.

In order to build the sensor, we make use of a simple technique developed in our group at UNICAMP, which employs two birefringent fibers set in an in-series configuration. This technique, reported in [9], employs an input and an output polarizer whose angles are chosen in such a manner that the first or second fiber-individual responses can be independently obtained. By separately measuring the first and second fiber responses, we demonstrate the performance of a hydrostatic pressure sensor with two probing regions for dual environment monitoring.

2. Fiber Characterization

A side-hole SH-PCF [8,10] was chosen to act as the platform for the hydrostatic pressure sensing experiment due to its high sensitivity to pressure variations. Fiber cross-section is shown in Fig. 1(a). The inset presents an image of the microstructured region. Hole diameter (\( d = 1.7 \mu m \)) and separation (\( \Lambda = 2.8 \mu m \)) are also represented.

The experimental setup for performing the initial characterization measurements is represented in Fig. 1(b). The SH-PCF was previously spliced to standard single mode fibers and placed into a pressure chamber. The light source is polarized by the first polarizer (\( P_1 \)) and launched into the SH-PCF in such a manner that both orthogonal modes of the birefringent fiber are excited. The output polarizer (\( P_2 \)) allows the light from the orthogonal modes to interfere and the optical response is measured by a photo-detector (PDT) or an optical spectrum analyzer (OSA).

In order to measure \( \partial B/\partial P \), one uses the setup represented in Fig. 1(b) with a laser at 633 or 1550 nm as the light source and a photodetector connected to an oscilloscope as the measurement system. Due to the orthogonal mode’s different phase velocities (effective refractive indices are different), they reach the end of the fiber with a phase difference (\( \Delta \phi \)), which is dependent on phase birefringence (\( B \)), fiber length (\( L \)), and wavelength of the light source as shown in Eq. (3).

\[
\Delta \phi = \frac{2\pi B L \Lambda}{\lambda}. \tag{3}
\]

For a fixed fiber length, phase difference \( \Delta \phi \) defines the output light polarization, which can be linear, circular—if \( \Delta \phi = \pi n \) or \( \Delta \phi = \pi(n + 1/2) \), respectively (\( n \) is an integer)—or elliptical. When external pressure is applied on an SH-PCF, the anisotropic stress propagation in the microstructure changes the effective refractive index of both propagation axes of the fiber differently. Consequently, there is a variation in \( B \), which generates a change in \( \Delta \phi \). Thus, the polarization state of the light that leaves the fiber is altered.

Figure 2(a) shows the optical response at 633 nm when 108 cm of SH-PCF is subjected to a pressure variation of 0.69 MPa (approximately 6.9 bar) during 1.7 s. The voltage signal from the photodetector (measured in an oscilloscope) oscillates as the pressure varies in time. The maximum and minimum occur when the output fiber light aligns with the passing and blocking polarizer axes, respectively. A complete signal oscillation (i.e., a polarization cycle, which corresponds to the interval between two
the OSA. A typical spectrum is shown in Fig. 3(a). Curvatures in standard fiber sections are minimal. It avoids degrading the polarization state of the light to be launched in the SH-PCF.

The spectrum presented in Fig. 3(a) allows calculating fiber group birefringence (G) by Eq. (4), where S is the wavelength difference between two consecutive dips in the spectrum and L is the length of the fiber [2]. Phase birefringence (B) can be calculated by Eq. (5), where γ is a fitting parameter related to the empirical relation expressed by Eq. (6) and obtained by a self-consistent method (A is another fitting constant) [15]. Figures 3(b) and 3(c) show the experimental results (points) for group and phase birefringence versus wavelength:

\[ G(\lambda) = \frac{\lambda^2}{SL}. \]  
\[ B(\lambda) = \frac{\lambda}{2L} \left[ \left(1 + \frac{S}{\lambda}\right)^{\gamma-1} - 1 \right]^{-1} \]  
\[ B(\lambda) = A\gamma. \]

To experimentally account for C_S, Eq. (2), spectra are taken for situations in which different pressure values were applied on the fiber. A particular fringe is chosen and its wavelength shift is divided by the pressure variation. Experimentally measured C_S values are presented in Fig. 3(d). Due to the decrease (in modulus) of group birefringence, as expected from Eq. (2), C_S is higher for lower wavelengths. Theoretical values for B, G, and C_S were also calculated by employing a commercial finite-element method based software. Lines in Figs. 3(b)–3(d) presents simulated data for G, B, and C_S as a function of \( \lambda \). Note that B and G have opposite sign for this fiber.

Moreover, Fig. 3(d) exposes a simulation for a commercial PCF usually employed in pressure sensing measurements (PM-1550-01 by NKT Photonics). SH-PCF proposed in this paper has a higher sensitivity coefficient than the commercial PCF. At \( \lambda = 1550 \) nm, for instance, the sensitivity coefficient for the SH-PCF is about 2.8 times higher than the one for the commercial PCF. We calculated the C_S value for the fiber reported in [31] and found it is 1.34-fold higher than the one of the fiber reported herein (at \( \lambda = 1550 \) nm). Anuszkiennicz et al. [14], in turn, by using a different technique (rocking filter inscribed in a PCF), could experimentally demonstrate an extremely high sensitivity value ~177 nm/MPa.

3. Dual Environment Hydrostatic Pressure Sensing

After characterizing the SH-PCF, the fiber was used to build up an all-fiber sensor able to probe two different environments. To do this, one employs the technique recently reported in [9] where two birefringent
fibers are spliced in such a way that their principal axes are rotated in relation to each other and placed in an experimental setup as schematized in Fig. 4.

Although fibers are spliced, it is possible to obtain single fiber responses by conveniently adjusting the input and output polarizers, i.e., one can measure the first or the second fiber responses separately by simply tuning the polarizer’s angles. As reported in [9], for obtaining the first fiber response, the second polarizer must be aligned to one of the principal axes of the second fiber. Similarly, the condition for obtaining the second fiber response is launching light in the system with the input polarization along one of the principal axes of the first fiber.

In the experiment reported herein, two sections of the SH-PCF [with total lengths \( L_1 = (22.5 \pm 0.02) \) cm and \( L_2 = (55.5 \pm 0.02) \) cm] were spliced and put into two different pressure chambers (Fig. 4). After the first fiber response was obtained (Fig. 5(a) top), this fiber was subjected to different pressure conditions and spectra were recorded for every situation. Analogously, for the case in which the second fiber response was attained (Fig. 5(a) bottom), spectra were taken for different hydrostatic pressure values applied on the fiber. Figure 5(b) shows the wavelength shift of a particular dip as a function of the pressure applied on the fiber for the two situations just described. \( C_S \) values of \( (1.69 \pm 0.04) \) nm/MPa and \( (2.22 \pm 0.04) \) nm/MPa were obtained for the first and second fiber, respectively. This difference is justified by the fact that different fractions of the lengths of the fibers were pressurized (pressurized lengths: \( L_{p1} = 2 \) cm and \( L_{p2} = 8 \) cm). The predicted value for the relation between the \( C_S \) values to be measured \( (R) \) is given by Eq. (7). This equation follows from the development reported in [9] for the case in which the pressurized lengths of the fibers are different:

\[
R \equiv \frac{C_{S1}}{C_{S2}} = \frac{L_{p2}}{L_{p1}} \frac{L_2}{L_1}.
\]  

(7)

According to Eq. (7), the predicted value for \( R_{\text{predicted}} \) is \( (0.65 \pm 0.08) \). Experimental values from Fig. 5(b) provide \( R_{\text{experimental}} = (0.76 \pm 0.03) \). Thus, one can observe that the predicted and experimentally verified values for \( R \) are consistent.

Using the setup schematized in Fig. 4, for the situations in which the first and second fibers responses were obtained separately, \( dB/dP \) values at \( \lambda = 1550 \) nm were measured in the same way that it was measured using the single-fiber configuration (by substituting the broadband light source by a one that is a laser). \( dB/dP \) values obtained were \((2.5 \pm 0.2) \times 10^{-6} \) MPa\(^{-1}\) for the first fiber and \((2.9 \pm 0.3) \times 10^{-6} \) MPa\(^{-1}\) for the second one. The results are consistent with the one obtained in the
single-fiber configuration, $(2.70 \pm 0.06) \times 10^{-6} \text{ MPa}^{-1}$, as expected.

4. Conclusions

In this paper, the development of a pressure sensor with two sensitive regions for dual environment monitoring was presented. To do this, two sections of a SH-PCF were spliced in a series configuration and placed in a setup where input and output polarizers angles could be tuned in order to obtain separate fiber responses.

First, the fiber was characterized. Phase and group birefringence and the sensitivity parameter $C_{s}$ were measured and compared to simulated values showing good agreement. Also, pressure sensitivity of the SH-PCF was compared to the one presented by the commercial fiber PM-1550-01 (NKT Photonics), usually employed in pressure measurements. SH-PCF sensitivity was found to be about 2.8-fold the PM-1550-01 respective value.

Finally, the dual environment pressure-sensor performance was demonstrated. The proposed configuration allows performing independent pressure measurements in two disconnected environments. Hence, the sensor was shown to have two sensing regions, which can be placed in the environments of interest for pressure variations probing.

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Nano-antennas on tapered fiber: a new and flexible approach

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Abstract—This paper proposes a new and flexible approach to control the electric field enhancement of bow-tie nano-antennas by integrating them on the lateral of a ~9 µm tapered optical fiber. The device may find applications in bio-sensing and imaging.

Keywords—integrated optics, plasmonics; nano-antennas array

I. INTRODUCTION

Nano-antennas, the optical equivalent of antennas [1], are being used for imaging of living cells, manipulation of nanoparticles, sensing and enhancement of the efficiency in solar cells due to the photo-physical phenomena such as the local electric field [2]. Compared to the other nano-antenna structures, dipole and bow-tie antennas can confine the fields in very small regions, depending on the device gap dimensions [3]. For example, a maximum electric field enhancement factor (EF) of more than 10 can be achieved with the hot spot confined in a 20 nm gap (λ~680 nm) as described by Liu et al [4].

Single-element dipole or bow-tie nano-antennas generally produce a non-directional radiation pattern. Thus, a desirable route is to integrate the nano-antennas with other optical components to increase their functionalities. We show, for the first time according to the best of our knowledge, the possibility to integrate the nano-antennas array on the lateral side of a tapered optical fiber showing the flexibility of controlling the nano-antennas electric field EF.

II. DESCRIPTION OF THE DEVICE

Fig. 1a shows the schematic of a single bow-tie nano-antenna. It sits on silica and is made of gold, being designed to operate around the free-space wavelength of 1090 nm. Besides, it has a thickness (h) of 100 nm, a width (w) of 270 nm, a gap (lgap) of 50 nm and a nanowire distance of w/2. To increase their functionalities, a nano-antenna array can be created on the top of a fiber taper by setting single nano-antennas in sequence. A typical configuration is represented in Fig. 1(b).

The Corning H1 1060 singlemode optical fiber (with cladding and core diameters of 125 µm and 5.3 µm, respectively) is used to make a 9–10 µm taper by employing so-called “flame brushing technique” [5]. In this method, oscillating flame heats a specific region of the optical fiber while its ends are simultaneously stretched. It causes fiber length to increase and, by mass conservation, its diameter to decrease [5]. The core and cladding diameters are reduced by the same ratio. It means that a 9-10 µm taper will have a sub-wavelength core diameter between 380 and 420 nm.

Fig. 1: Schematic diagram of (a) single bow-tie nano-antenna and (b) a tapered optical fiber showing the nano-antennas array position (fiber axis is aligned along the z-direction with electric field is in the z-direction).

A bow-tie nano-antenna is modeled and analyzed by using commercial Synopsys Fullwave [6] software. The structure is optimized for TE modes: the main electric field along the z-direction (see fig.1) and directed across the gap. The perfectly matched layer (PML) boundary is used and the non-uniform grid sizes are chosen as Δx=Δz=10 nm in the plane of nano-antenna with the vertical grid size of Δy=20 nm. The grid sizes are further refined to 5 nm at the edges of the metallic layers and the chosen time step is Δt=4.66×10⁻¹⁵ s (well below the stability limit). The refractive index of silica and air are considered as 1.45 and 1.0, respectively and the properties of gold are considered from the material library of the software [6]; the relative permittivity of gold model can be found in [7].
In this calculation, one considers the main LP01 mode with a spot size diameter of around 6 μm as the light source. Propagation direction is assumed along +z direction which is also the fiber axis. The electric field enhancement factor (EF) of a nano-antenna can be defined as the ratio of magnitude of the electric field in the middle of the nano-antenna gap to the incident light to the nano-antenna [8].

III. RESULTS AND DISCUSSIONS

Figure 2 (a) shows the EF as a function of the wavelength for a bow-tie nano-antenna for gap of 50 nm. It is shown that the structure resonates at 1090 nm, with a maximum electric field enhancement of EF=8.3. The electric field is confined in the gap of the bow-tie nano-antenna as can be seen in 2(b).

![Electric field enhancement](image)

Fig. 2: (a) The spectra of electric field enhancement factor (EF), and (b) the normalized electric field (EF) profile for a bow-tie nano-antenna

For a tapered fiber of 9.5 μm diameter, the relative electric field intensity with respect to the input field intensity as a function of the radial distance is shown in Fig. 3 (a): the launched field intensity at the taper edge is considered to be 1.0 in this case. It is seen from Fig. 3(a) that the relative electric field is higher at the core center (radial distance = 0 μm) of the tapered fiber and then decreases gradually with the radial distance.

![Electric field intensity](image)

Fig. 3: (a) Relative electric field with respect to the input field intensity and (b) Electric field enhancement as a function of the taper diameter

Fig. 3(b) depicts how different taper diameters affect the performance of the nano-antenna array by showing the electric field enhancement (logarithmic scale in the vertical axis) as a function of taper diameter. The highest electric field enhancement one could obtain in the simulations is 173, which is calculated for a 1 μm diameter taper – Fig. 3(b). An electric field enhancement of ~3.5 is obtained for a nano-antenna placed on a 9.5 μm thick taper. In order to adjust the fluence and the electric field enhancement in the antennas, they can be fabricated on different tapers diameters. It demonstrates the flexibility of the proposed integrated device.

In summary, a flexible approach to integrate nano-antennas in an optical device is studied and proposed: its principle is based on using tapered optical fibers to control the electric field enhancement from nano-antennas array when comparing to the electric field in the fiber core. Our proposed flexible device (nano-antennas on a 9.5 μm tapered fiber) can be straightforwardly driven by a Q-switched pulsed fiber laser for example. It is shown that the amount of electric field enhancement that can be reached to the nano-antennas is ~ 4 and that this factor can be increased up to 170 by using, for example, a 1 μm tapered fiber—such great control shows the flexibility of our approach.

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Optical sensing with antiresonant capillary fibers

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ABSTRACT

Herein, we present a study of the use of polymer capillary optical fibers in sensing measurements. In particular, we approach the application of these fibers for temperature sensing. To do this, an analytical model for describing the spectral characteristics of the light transmitted through the capillaries was employed. Thermal expansion and thermo-optic effect influences on the transmitted spectrum were evaluated. Moreover, a $140 \pm 6$ pm/°C temperature sensitivity was measured, which is in good resemblance to simulated data and is around 14 times higher than the sensitivity attained in conventional Bragg gratings sensors.

Keywords: Capillary fiber, polymer fiber, antiresonant reflecting optical waveguide, temperature sensor

1. INTRODUCTION

The publication of the study of negative-curvature fibers by Pyramíkov et al. in 2011 [1] reelected the field of research towards the development of antiresonant reflecting optical waveguides (ARROW) [2]. Since then, numerous investigations have been published, in which authors have identified a great number of properties – such as low dispersion, low nonlinear response, high damage threshold – and studied their transmission characteristics and potential applications [3]. Besides, due to its simpler structure when compared to usual hollow core microstructured fibers which guides light by photonic bandgap effect [4], negative-curvature fibers can be obtained by a much simpler fabrication process.

An even simpler fiber structure that can also provide the possibility of guiding light by antiresonant reflection and that shows opportunities when performing sensing measurements are capillaries fibers [5]. When light is launched in the hollow core of capillary fibers, reflection occurs at the capillary fiber walls and leaky modes propagation is possible. The capillary walls can be thought as Fabry-Perot interferometers whose resonances imply in transmission minima in the capillary fibers spectrum. The wavelengths that experiences high loss when propagating through the capillaries, $\lambda_0$, can be found by Eq. (1), where $n_2$ and $n_1$ are respectively the refractive indexes of the hollow core and of the capillary wall, $d$ is the wall thickness and $m$ is the minimum order. [2]

$$\lambda_0 = \frac{2n_2d}{m} \left( \frac{n_2}{n_1} \right)^2 - 1$$

By observing Eq. (1) it is possible to understand that if the physical properties of the capillary (refractive index and thickness) are altered, the transmission minimum will be attained at a different wavelength. It allows recognizing the possibility of using the capillary fibers for sensing measurements.

In this paper, we report the study of polymer capillary fibers in temperature sensing. An analytical method was explored for obtaining the spectral transmission characteristics of the capillaries and for understanding the influence of thermal expansion and thermo-optic effect in the configuration under investigation. Moreover, one reports an experimental realization of the proposed sensor by using a compact all-fiber setup. We attained a sensitivity of $140 \pm 6$ pm/°C, which is around 14 times higher than conventional Bragg gratings-based temperature sensors [6].
2. ANALYTICAL SIMULATIONS

In order to study capillary fibers spectral characteristics, one employed the model described in [7], which provides an analytical description of the power transmitted through the capillary fibers. The capillary structure is represented in Fig. 1a, where core and capillary refractive indexes are represented \( n_1 \) and \( n_2 \), respectively as well as the inner and outer capillary diameters, \( D_{in} \) and \( D_{out} \). The model is based on the consideration that each leaky mode of the hollow core can be described as a light ray that impinges on the capillary wall with an angle of incidence \( \theta_i \), given by Eq. 2, where \( n_{eq} \) is the effective refractive index of the hollow core leaky modes (Fig. 1b). The effective refractive index of a specific leaky mode can be calculated by Eq. (3), where \( i \) is the wavelength and \( u_{eq} \) is a root of the equation \( J_{eq}(u_{eq}) = 0 \) [5, 7].

\[
\theta_i = \sin^{-1}\left(\frac{n_{eq}}{n_1}\right)
\]  
(2)

\[
n_{eq} = 1 - \frac{1}{2}\left(\frac{n_2}{n_1}\right)^2
\]  
(3)

The determination of the angle of incidence allows obtaining the transmitted power through the capillary fiber as expressed in Eq. (4) – where \( P_{in} \) is the power of the light launched in the hollow core and \( P_{out} \) is the transmitted power after the wave have traveled a distance \( L \) through the capillary, \( d \) is the core wall thickness and \( \Gamma \) is the Fresnel reflection coefficient, as expressed in Eq. (5), written for a TE polarized wave [7]. Fig. 1c shows the simulated transmission spectrum for a 2 cm long PMMA capillary fiber with inner diameter 160 \( \mu m \) and outer diameter 240 \( \mu m \). Fig. 1d shows the transmission spectrum between 1558.5 nm and 1552 nm for a better visualization of the 56th order transmission minimum \( -56 \) in Eq. (1). At this minimum, one can calculate \( n_{eq} = 0.99997 \) and \( \theta_i = 89.6^\circ \). PMMA dispersion was taken into account by using the Sellmeier coefficients available in [8].

\[
P_{out} = P_{in} \exp\left[\frac{L}{2\Gamma \tan \theta_i}\right] \ln\left[1 - \left(1 - \Gamma^2\right)\frac{4\Gamma^2}{\lambda} \left(1 - \frac{n_2}{n_1}\right)^2 \sin^2 \theta_i\right]
\]  
(4)

\[
\Gamma = \left[\sqrt{1 - \sin^2 \theta_i - \frac{n_2}{n_1}} \sqrt{\frac{n_2}{n_1} \sin^2 \theta_i}\right] \left[\sqrt{1 - \sin^2 \theta_i} + \frac{n_2}{n_1} \sqrt{\frac{n_2}{n_1} \sin^2 \theta_i}\right]
\]  
(5)

![Figure 1](image)

Figure 1. (a) Capillary fiber structure; \( n_1 \) and \( n_2 \): core and capillary refractive indexes; \( D_{in} \) and \( D_{out} \): inner and outer diameter of the capillary fiber. (b) Light rays picture of the propagating wave along the core. White arrows represent refracted light through the capillary wall. (c) Simulated transmission spectrum for a PMMA capillary with \( D_{in} = 160 \mu m \), \( D_{out} = 240 \mu m \), length \( L = 2 \) cm. (d) Transmission spectrum between 1558.5 nm and 1552 nm (56th order minimum; \( n_{eq} = 0.99997 \) and \( \theta_i = 89.6^\circ \).

As said before, Eq. (1) allows understanding that variations on the capillary wall thickness and on its refractive index imply in shifting of the minimum spectral position. As temperature variations cause both these parameters to vary, it is straightforward thinking the capillary fibers as a platform for temperature sensing measurements. In order to study...
temperature influence on capillary transmission spectrum, one has initially evaluated capillary thermal expansion and thermo-optic effect separately and, in sequence, their combined effects. It was done by including, in Eq. (4), a variation in capillary wall thickness due to thermal expansion \( \Delta d = d \Delta T \); \( d \): wall thickness; \( \Delta T \): temperature variation) and a variation in its refractive index due to thermo-optic effect (using \(-1.3 \times 10^{-4} ^\circ \text{C}^{-1}\) as PMMA thermo-optic coefficient \([9]\)).

Fig. 2a shows the behavior of a transmission minimum of a 2 cm long PMMA capillary fiber with inner diameter 160 \( \mu \)m and outer diameter 240 \( \mu \)m when one only considers thermal expansion effect (thermo-optic effect neglected). It is seen that the spectral position of the transmission minima redshifts as the temperature is increased. On the other hand, Fig. 2b shows the spectral shifting of the transmission minimum when only the thermo-optic effect is considered (thermal expansion neglected). In this case, the minimum spectral position blueshifts when the temperature is raised. Moreover, Fig. 2c shows the capillary transmission minimum when both effects are taken into account. Blueshift of the minimum spectral position is observed once again, what allows recognizing that the thermo-optic effect has a greater contribution than thermal expansion in the studied configuration (which is due to high PMMA thermo-optic coefficient, 15 times higher than silica’s one \([9]\)). Finally, Fig. 2d presents a plot of the minimum wavelength shift as a function of temperature variation when only thermal expansion is considered (red line), when only thermo-optic effect is considered (blue line) and when both the effects are considered (purple line). By Fig. 2d data, it is possible to estimate \(-141.8 \text{ pm/} ^\circ \text{C}\) as the temperature sensitivity of the configuration.

![Figure 2](image2.png)

**Figure 2.** Transmission minimum shifting when considering (a) thermal expansion only, (b) thermo-optic effect only, (c) both thermal expansion and thermo-optic effects. (d) Wavelength shift as a function of the temperature variation.

### 3. EXPERIMENTAL RESULTS

To provide an experimental realization of the sensor studied herein, one have assembled an experimental setup as presented in Fig. 3a, where one use a broadband light source (BLS) coupled to a multimode fiber (MMF) which launches light into the capillary fiber. Another multimode fiber is placed at the end of the capillary in order to collect the transmitted light. The transmission power is measured in an optical spectrum analyzer (OSA).

![Figure 3](image3.png)

**Figure 3.** (a) Experimental setup. BLS: broadband light source; MMF: multimode fiber; SMF: single-mode fiber; OSA: optical spectrum analyzer. (b) Experimental transmission spectrum for a capillary with inner diameter 160 \( \mu \)m, outer diameter 240 \( \mu \)m and length 13 cm. (c) Zoom in the spectral region between 1500 nm and 1600 nm. (d) Wavelength shift as a function of temperature variation.
The transmitted power spectrum for a PMMA capillary with inner diameter 160 \( \mu m \), outer diameter 240 \( \mu m \) and length 13 cm is shown in Fig. 3b, where transmission minima can be observed. Fig. 3c shows the experimental (red line) and simulated (blue line) transmission spectra between 1500 nm and 1600 nm for comparison. One can observe that in the simulations, the minima are much narrower that in the experimental results. We believe that this broadening may be due to the multimode characteristics of the capillary fiber hollow core. We are implementing improvements in our model in order to obtain a better resemblance between experimental and simulated data.

To measure system temperature sensitivity, the capillary fiber was placed over a hotplate and the temperature was varied while spectrum shifting was monitored. Fig. 3d shows the wavelength shift as a function of the temperature variation. By fitting Fig. 3d data, one can obtain a sensitivity of \((-140 \pm 6) \text{ pm/}^\circ\text{C}\). This value is in close proximity to the simulated sensitivity shown in Fig. 2d \((-141.8 \pm 0.2) \text{ pm/}^\circ\text{C}\) and is around 14 times higher than the conventional Bragg gratings temperature sensors [6].

CONCLUSION

In this paper, one discussed the study of polymer capillary optical fibers for temperature probing. An analytical model was explored for simulating the characteristics of the antiresonant reflecting optical waveguide. Due to our intention of investigating temperature influences in the optical response of the capillary structure, thermal expansion on the capillary walls and thermo-optic effect was added to the model in order to recover the shifting of the transmission minima as a function of temperature variations.

By performing this study, one could identify that spectral shifts mediated by thermal expansion and thermo-optic effect happened towards different directions and that the thermo-optic effect contribution is greater so that transmission minima blueshift when temperature is increased. This analysis allowed predicting a temperature sensitivity of \(-141.8 \text{ pm/}^\circ\text{C}\).

Moreover, temperature sensitivity was experimentally measured as \((-140 \pm 6) \text{ pm/}^\circ\text{C}\). The obtained value compares well to the simulated one and is around 14 times higher than standard Bragg gratings-based temperature sensors.

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In-series fiber Bragg gratings and multimode interferometers for sensing applications

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Abstract: Bragg gratings and multimode interferometers are employed for monitoring strain, refractive index, temperature and liquid level variations. Resolutions of 4.3 με, 1.6 °C, and 4 x 10⁻⁶ RIU were obtained for strain, temperature and refractive index respectively. Liquid level measurements revealed a sensitivity of 0.25 dB/mm.

OCIS codes: (060.2370) Fiber optics sensors; (060.3735) Fiber Bragg gratings; (280.4788) Optical sensing and sensors.

1. Introduction

Optical fibers are a very suitable platform for probing physical parameters variations. Due to its compact size, robustness and electromagnetic immunity, fiber optics based sensors have been widely explored. Moreover, fiber sensors can be optimized for the performance of high sensitivity and high resolution measurements and have its properties tailored for providing an adequate dynamic range of operation. [1]

Fiber Bragg gratings (FBGs) are a widely used technology for obtaining fiber optics sensors. They consist of a periodic refractive index modulation (with a period of hundreds of nanometers) along the fiber length. This refractive index modulation provides coupling between the fundamental core mode to a counter-propagating core mode at a specific wavelength λg given by Eq. 1 – where ng ef is the effective refractive index of the core mode and A is the grating period. This coupling is seen, in a spectral reflection measurement, as a peak located at λ0. Thus, if an external parameter (such as temperature and strain) influences ng ef or A values, one see that the coupling will take place at another λg value. Experimentally, it is seen, in a reflection measurement, as a shift in Bragg peak spectral position. [1]

\[ λ_0 = 2 n_{ef} A \]  

Besides FBGs, fiber based multimode interferometers (MMI) appear as another interesting platform for the design of optical sensors. A commonly used configuration is called SMS (single mode-multimode-single mode) structure, where a multimode fiber section is spliced between two single mode fibers. In this configuration, light is launched into the multimode fiber section by the single mode fiber (SMF). Numerous modes are then excited and interference among them is observed. For a multimode fiber section with length L_{MMF}, a transmission peak at a wavelength λ_{SMS} can be observed, which is given by Eq. 2, where D_{MMF} and L_{MMF} is the multimode fiber diameter and length respectively; n_{MMF} is the core refractive index of the multimode fiber. By monitoring the peak spectral position, a variety of different parameters can be sensed. [2]

\[ λ_{SMS} = 4 D_{MMF}^2 n_{MMF} / L_{MMF} \]

In this paper, we report two demonstrations of the employment of FBGs and a SMS structure set in an in-series configuration for sensing purposes. In the first application, it is demonstrated the possibility of simultaneously measure strain, temperature and refractive index variations by the use of FBGs inserted in conventional and tapered fibers in combination with a no-core fiber (NCF), which is simply a silica rod. In the second approach, a FBG intensity-based measurement is studied for determining liquid level variations. The reported sensors show the feasibility of the employment of fiber Bragg gratings and fiber multimode interferometers for multi-parameter monitoring and for intensity-based schemes.

2. Simultaneous measurement of strain, temperature and refractive index variations

For simultaneously monitoring strain, temperature and refractive index variations, two FBGs and a SMS structure were set in an in-series arrangement as shown in Fig. 1a. As can be seen in Fig. 1a, FBG1 was inserted in a standard telecom optical fiber and FBG2 was inserted in a 50 μm thick fiber taper (which was previously obtained by flame-brushing technique). For obtaining the SMS structure, the NCF fiber with length 58.2 mm was spliced between the SMF containing the FBGs and to another SMF.
Fig. 1. (a) Sensor schematic diagram. (b) FBG1, FBG2; and (c) MMI spectral response as a function of applied strain. (d) Wavelength shift as a function of the applied strain.

The sensor principle of operation is based on the differential sensitivity of FBGs and MMI spectral responses to temperature, strain and external refractive index variations. These differential sensitivities allow obtaining a 3x3 linear system for discriminating the parameters variations, as shown in Eq. 3 where, $\Delta \lambda_{FBG}$, $\Delta \lambda_{MMI}$ and $\Delta \lambda_{FBG2}$ stands for the wavelength shifts of the Bragg peaks from the FBGs in the untapered and tapered fiber and $\Delta \lambda_{MMI}$ represents the wavelength shift of the MMI transmitted spectrum. $K_n$, $K_T$ and $K_s$ are respectively the strain, temperature and refractive index sensitivities coefficients. Subscripts FBG, FBG2 and MMI identify the FBG in untapered fiber, FBG in tapered fiber and SMS structure contributions. $\Delta \varepsilon$, $\Delta T$ and $\Delta n$ are the strain, temperature and refractive index variations which are desired to be estimated.

$$\begin{align*}
\Delta \lambda_{FBG} & = K_{n,FBG} \Delta \varepsilon + K_{T,FBG} \Delta T + K_{s,FBG} \Delta n \\
\Delta \lambda_{FBG2} & = K_{n,FBG2} \Delta \varepsilon + K_{T,FBG2} \Delta T + K_{s,FBG2} \Delta n \\
\Delta \lambda_{MMI} & = K_{n,MMI} \Delta \varepsilon + K_{T,MMI} \Delta T + K_{s,MMI} \Delta n
\end{align*}$$

In order to obtain $K_n$, the device is subjected to incremental strain variations (at fixed temperature and external refractive index) and the peak wavelength shifts of both FBGs and MMI are taken into account. Fig. 1b and Fig 1e show the spectral response variation of FBGs and MMI as the strain condition is altered – distinct $K_n$ values for the untapered and tapered fiber are due to differential stress distribution on them [3]. Fig. 1d shows a wavelength shift versus applied strain plot from where $K_n$ values are attained.

$K_T$ and $K_s$ are obtained following an analogous procedure, i.e., the spectral shifts were taken into account for situations in which the temperature was varied while the other two parameters were maintained constant and in which the external refractive index was varied and the strain and temperature conditions were maintained. Is worth reporting that the external refractive index variations were attained by putting the system into a bath of isopropanol-water solutions with different concentrations. Experimentally measured sensitivities $K_n$, $K_T$ and $K_s$ are presented in Eq. (3). $K_{s,FBG}$ and $K_{n,FBG2}$ are assumed to be zero since the core mode in the untapered and tapered fibers do not interact with the external medium.

$K_n$, $K_T$ and $K_s$ values exposed in Eq. 3 allows obtaining the desired $\Delta \varepsilon$, $\Delta T$ and $\Delta n$ by simply solving the resulting linear system. Strain, temperature and external refractive index variations can, therefore, be simultaneously monitored and estimated. Considering an optical spectrum analyzer with 10 pm resolution, one can estimate the system resolution as 4.3 με, 1.6 °C and 4 x 10^{-3} RU for strain, temperature and refractive index respectively. An extensive analysis of the sensor has been submitted for publication [4].

3. Intensity-based liquid level monitoring

Another opportunity provided by the proposed in-series FBG and MMI configuration is the performance of an intensity-based liquid level sensing measurement. For doing this, a configuration as depicted in Fig. 2a is used, where the SMS fiber structure, containing a 58.2 mm long NCF, is followed by a standard fiber Bragg grating (FBG). The FBG signal is measured in reflection by the leading SMF fiber when the sensor is immersed in a container filled with water. Here, the NCF section (58.2 mm long) sensitivity to external refractive index is explored and its influence on the reflected Bragg peak power is analyzed. FBG0 act as a reference for taking into account light source power oscillations.

As the sensor is immersed in the liquid, FBG1 reflection peak is not shifted since the fundamental mode is strongly coupled into the fiber core. However, the SMS spectral response is blue-shifted due to the change of the external refractive index [5]. The spectral shift produced by this fiber structure will, therefore, act as a filter over the reflection signal from FBG1. This will then lead to power variations in FBG1 reflection peak. Fig. 2b shows the system reflected power as a function of the wavelength for different immersion depths. Fig. 2c, in turn, presents the Bragg peak power variation as a function of liquid level. A sensitivity of 0.25 dB/mm was attained.
The measurement shown in Fig. 2 provides the possibility of measuring liquid level variations using very simple setups. That’s because the only need is to measure the reflected power as the fiber is dipped into the liquid, avoiding the necessity of employing expensive spectral interrogators. Moreover, as FBG0 is placed outside the liquid, power fluctuations from light source can also be taken into account. A journal paper which will provide a more detailed report of the referenced sensor is to be submitted [6].

4. Conclusions

In this paper, we report two sensor applications by using fiber Bragg gratings and fiber multimode interferometers set in an in-series configuration. The first demonstration deals with the simultaneous determination of strain, temperature and refractive index variations. To do this, two FBGs are employed (one inscribed in a untapered fiber and the other in a 50 μm thick tapered fiber) spliced to a SMS structure. Differential sensitivities to the parameters variations were crucial for performing the sensing experiment and attain the variations of the parameters of interest. Resolutions of 4.3 μɛ, 1.6 °C and 4 x 10⁻¹ RIU could be calculated for strain, temperature and refractive index respectively.

In the second demonstration, FBGs and a SMS structure were again concatenated and an intensity-based measurement was performed for monitoring liquid level variations. MMI sensitivity to external refractive index changes influenced the power level of the Bragg peak of a FBG which followed the SMS structure. The dependency of the FBG reflection power level was characterized as a function of the immersion depth and a sensitivity of 0.25 dB/mm was obtained. This is a very interesting demonstration since it provides the possibility of the performance of liquid level probing measurements with low cost equipment and with a very simple setup.

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5. References

Surface-core fiber gratings

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ABSTRACT

In this paper, we report, to our knowledge, the first demonstration of the induction of long-period and Bragg gratings on surfac-core optical fibers. Surface-core fibers described herein were fabricated from commercial silica tubes and germanium-doped silica rods by employing a very simple procedure. Being the core on the fiber surface, it can be sensitive to refractive index variations in the environment in which the fiber is immersed. Thus, results concerning the sensitivity of these gratings to environmental refractive index variations are presented. Besides, simulation data are presented for comparison to the experimental behavior and for projecting future steps in this research.

Keywords: long-period grating, Bragg grating, refractive index sensor, surface-core fiber

1. INTRODUCTION

Building up fiber optics sensors based on long-period (LPG) and Bragg (FBG) gratings is very interesting since these gratings can provide means for probing a great variety of physical parameters of interest. Refractive index variations, temperature, strain, curvature and vibration are examples of parameters which can be monitored by the use of fiber gratings.1,2

Both long-period and Bragg gratings consist of longitudinal periodic modulation of the refractive index of an optical fiber which can be achieved, for instance, by UV and CO₂ laser irradiation and electric arc application. This refractive index modulation, which has a period of hundreds of microns in long-period gratings and of hundreds of nanometers in Bragg gratings, allows the existence of coupling, at determined wavelengths, between, in general, the fundamental core mode to co-propagating cladding modes in LPGs and between the fundamental core mode to a counter-propagating core mode in FBGs.1,2

Eq. (1) and Eq. (2) describes the wavelengths \( \lambda_{LPG} \) and \( \lambda_{FBG} \) at which coupling will happen in LPGs and FBGs, respectively. In these equations, \( n_{co} \) indicates the effective refractive index of the core mode and \( n_{cl} \) the one associated to the coupled cladding mode. \( \Delta n_{FBG} \) and \( \lambda_{FBG} \) mean the LPG and FBG refractive index modulation periods.1,2

\[
\lambda_{LPG} = (n_{co} - n_{cl}) \Delta \lambda_{LPG}
\]

\[
\lambda_{FBG} = 2 \pi n_{co} \Delta \lambda_{FBG}
\]

In order to obtain gratings based sensors, one has to evaluate physical parameters whose variation alters the effective refractive index values of the considered modes or the grating period. These changes imply on spectral variations in the measured LPGs and FBGs optical response. In this paper, LPGs and FBGs induced on surface-core optical fibers are studied as platforms for refractive index sensing. Employing gratings induced on this kind of fiber is appealing since the core mode can easily probe the external environment without the need of tapering the fiber or removing the silica cladding with chemical attack or polishing, for example.

In the subsequent sections, fiber fabrication, grating inscription and sensing results are presented. Besides, simulated data are shown for comparison to the observed experimental behavior. To our knowledge, this is the first demonstration of induction of long-period and Bragg gratings in surface-core fibers.
2. FIBER FABRICATION AND GRATINGS INDUCTION

The fibers used in the study reported herein were produced from standard cylindrical silica tubes with inner diameter of 12 mm and outer diameter of 18 mm and from a germanium-doped silica rod 21 mm thick. Initially, the germanium-doped silica rod (Figure 1a) was pulled in a fiber drawn tower in order to reduce its diameter to 0.8 mm. In sequence, it was merged to the tube by using a flame from a blowtorch (Figure 1b). The resulting preform was drawn to a 150 μm diameter fiber whose cross section is exposed in Figure 1c – a zoom of the core region is provided in Figure 1d. Brighter regions in Figures 1c and d identify the fiber core. Its major and minor axes measure 7.3 and 3.4 microns respectively.

![Image](image_url)

Figure 1. (a) Germanium-doped silica preform used for obtaining the fiber core. (b) Schematic diagram for merging procedure. (c) Cross-section of the 150 microns diameter surface core fiber. (d) Zoom of the fiber core.

The approach proposed in this paper is similar to some previous reported papers, where D-type and embedded-core fibers gratings were studied. Using surface core fibers is advantageous over D-type fibers because they are fabricated from commercial silica tubes and doped silica rods by employing a very simple technique. Their advantage on embedded-core fibers is centered on the fact that a surface-core fiber is sensitive to external environment refractive index variations. They have, however, the drawback of offering difficulties for fiber splicing. Also, the fiber reported herein resembles the near-surface-core fibers whose characteristics were recently reported.

In order to provide the longitudinal refractive index pattern for obtaining the LPGs, radiation from a CO₂ laser was shone on the fiber. The employed setup is computer assisted and allows the user to choose the desired grating period (by controlling the space between two consecutive incidences of the laser on the fiber). For the reported experiments, a period of 1000 microns was used. For inducing the FBGs, an industrial-LN excimer laser (KrF Bragg Star), with 248 nm operating wavelength, was used. The phase mask method was employed to create an interferometric pattern on the fiber and generate the grating on the fiber core. Laser parameters were set to be 500 Hz, with 3mJ and the phase mask pitch was 1075.34 nm, suited to produce Bragg gratings in the infrared region. Moreover, prior to the Bragg grating production, the fiber was hydrogen loaded at 70 bar during one week in order to enhance its photosensitivity to UV light.

Figure 2 shows the spectra of the obtained gratings – Figure 2a is a transmission spectrum of the LPG and Figure 2b consists of a reflection spectrum of the FBG. In Figure 2a, the dips at 689 nm, 764 nm and 895 nm correspond to the wavelengths at which coupling between core and cladding modes was attained. In Figure 2b, there are three reflection peaks (at 1560 nm, 1564 nm and 1569 nm) at which coupling between forward and backward core modes was satisfied. The existence of more than one peak in the Bragg grating reflection spectrum reveals the few mode nature of the fiber.

![Image](image_url)

Figure 2. (a) LPG transmission spectrum. (b) FBG reflection spectrum. (c) Zoom of the interval between 1566 nm and 1572 nm for visualization in detail of the Bragg peak at 1569 nm; Δλ = 0.29 nm.
Nevertheless, a closer look to each of the reflection peaks shows two Bragg peaks separated by a spectral distance $\Delta \lambda$. Figure 2c is a zoom of the FBG spectrum around 1569 nm. Here, it can be clearly seen the peak separation (measured as 0.29 nm) due to fiber birefringence. From $\Delta \lambda$, fiber phase birefringence ($B$) can be easily calculated from $B = \Delta \lambda / 2\Delta n$, giving a value of $2.7 \times 10^{-7}$ at 1569 nm.

3. ENVIRONMENTAL REFRACTIVE INDEX VARIATIONS PROBING

As both LPG and FBG were induced on a fiber whose core is located on its surface, it is straightforward to use these gratings as platforms for refractive index sensing experiments. The sensitivity for performing environmental refractive index variation probing arises from the fact that both core and cladding modes effective refractive index are dependent on the refractive index of the medium in which the fiber is immersed. This dependency affects the spectral location of the dips and peaks in LPG transmission and FBG reflection spectrum causing them to shift.

In order to perform refractive index sensing experiments, the sections of the fibers where the LPG and the FBG were induced were immersed in baths of different refractive index ces Cargille® oils and aqueous glycerin solutions respectively. For each immersion situation, corresponding to a different environmental refractive index, a spectrum was taken and the wavelength shifts of dips and peaks were monitored.

Figure 3 presents the obtained results for the LPG sensitivity to external refractive index variations. In Figure 3a, one can observe that as the external refractive index increases, the resonant wavelength blue shifts. A plot of this shift versus the external refractive index is shown in Figure 3b. For the refractive index interval between 1.33 and 1.40, the refractive index sensitivity is calculated to be 95 nm/RIU and, for the interval between 1.38 and 1.45, a sensitivity value of 210 nm/RIU is attained.

![Figure 3](image-url) (a) LPG transmission spectrum for different external refractive index values $n$. (b) LPG resonance wavelength shift as a function of the external refractive index.

Analogously, the Bragg wavelength shift of the fundamental mode was monitored as the environmental refractive index was altered. Results concerning the Bragg wavelength shift as a function of the external refractive index change are shown in Figure 4a. For the refractive index interval between 1.33 and 1.40, a sensitivity of 0.5 nm/RIU was obtained and, for the interval between 1.43 and 1.45, a sensitivity of 2.7 nm/RIU was estimated.

Besides, simulated results for the wavelength shift as a function of the environmental refractive index change are also shown. Simulations, which were performed by using a commercial finite element-based software, indicate a higher refractive index sensitivity (1.2 nm/RIU for the refractive index interval 1.33 to 1.40 and 7.5 nm/RIU for the refractive index interval 1.42 and 1.45). This discrepancy between simulated and experimental can be due to the fact that the fiber structure employed in simulations was idealized.

The obtained sensitivity results are comparable to the ones obtained for non-etched D-fibers Bragg gratings (2.5 nm/RIU) but are lower than the ones reported for other fiber processing technologies such as interferometric LPG setups (930 nm/RIU), multimode interference sensors (2946 nm/RIU) and birefringent microfibers configurations (30000 nm/RIU). If it is desirable to enhance the presented Bragg gratings sensitivity, the fiber can be made with a thinner silica cladding around the doped core or can be tapered down. Due to the fact that a higher fraction of the evanescent field of the core mode will permeate the external medium, the effective refractive index of the fundamental core mode will be more dependent on environmental refractive index variations. Simulations results for the expected wavelength shift of a Bragg grating induced on a 112.5 $\mu$m thick surface core fiber (25% diameter reduction) are shown in Figure 4b. A 5-fold sensitivity increase is observed in the refractive index range between 1.43 and 1.45. The possibility of inducing Bragg gratings on tapered surface-core fibers will be explored in our future experiments.
Figure 4. (a) Bragg wavelength shift versus the external refractive index plot. Black dots identify experimental data and the red ones simulation results. (b) Simulation results of the Bragg wavelength shift versus external refractive index for 150 µm and 112.5 µm diameter fibers.

CONCLUSIONS

In this paper, LPGs and FBGs induced on surface-core fibers were studied for the first time. Surface core fibers were fabricated from commercial silica tubes and germanium-doped silica rods by employing a very simple technique. As the core of this kind of fibers is on the fiber edge, the evanescent field of the propagating modes permeates the external medium. Thus, changes in the environmental refractive index cause the effective refractive index of these modes to alter.

Both LPG and FBG sensitivity to refractive index changes was measured. Maximum sensitivity values of 210 nm/RIU and 2.7 nm/RIU were obtained respectively for the LPG and FBG for refractive indexes around 1.43. FBG response was simulated and the results showed good resemblance to the experimental behavior. Furthermore, simulated data provided the information that a tapered fiber presents an enhanced sensitivity to refractive index variations. Future experiments will test this prediction.

Ergo, one can observe that a new configuration was studied aiming the performance of sensing measurements. Results are appealing due to its novelty and improvement possibilities shows up as an important route to be followed. Moreover, authors would like to acknowledge G. Chesini for his help in fiber fabrication and CNPq, São Paulo Research Foundation (Fapesp, grant #2014/50,632-6) and Fundação para a Ciência e Tecnologia (FCT, under projects UID/EEA/50008/2013, Pest-EEI/UI008/2013, and scholarship SFRH/BD/88472/2012) for financial support.

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Hydrostatic pressure sensing with surface-core fibers

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ABSTRACT

In this paper, we report the employment of surface-core fibers for hydrostatic pressure sensing. To our knowledge, this is the first demonstration of the use of these fibers for the referenced purpose. Theoretical simulations of the fiber structure were performed in order to estimate fiber phase and group birefringence values and its pressure sensitivity coefficient. In order to test fiber performance when acting as a pressure sensor, the same was placed in an polarimetric setup and its spectral response was measured. A sensitivity of 4.8 nm/MPa was achieved, showing good resemblance to the expected sensitivity value (4.6 nm/MPa).

Keywords: pressure sensor, surface-core fiber, birefringence

1. INTRODUCTION

The development of pressure sensors based on optical fibers is very important due to the numerous advantages provided by this sort of setups. Among them, one can identify their intrinsic electromagnetic immunity, robustness, tunable sensitivity and dynamic range and the possibility of being set in a compact size. Optical fiber pressure sensors are, thus, very useful for acting in harsh environments such as underwater petroleum exploration sites.\textsuperscript{1}

Specially designed birefringent optical fibers, such as the photonic crystal ones, are often used for this purpose.\textsuperscript{2,3,4} Usually, they are set in polarimetric configurations which allow the orthogonal modes that travel along them to interfere. The spectral response of these configurations is characterized by the existence of interferometric fringes whose spectral position shifts according to the pressure conditions to which the fiber is subjected (as a manifestation of the photo-elastic effect). To characterize the relation between this wavelength shift and the applied pressure, one defines a sensitivity coefficient ($C_S$) as expressed in Eq. 1.\textsuperscript{5}

$$\frac{\Delta \lambda}{\Delta P} \equiv C_S \approx \frac{\lambda}{G} \frac{\partial B}{\partial P}$$ (1)

In Eq. 1, $\Delta \lambda$ is the spectral wavelength shift of an interferometric fringe caused by the application of an external hydrostatic pressure variation $\Delta P$. Besides, $\lambda$ is the central wavelength of the considered fringe. $G$ and $\partial B/\partial P$ are respectively the fiber group modal birefringence and the phase birefringence derivative with respect to pressure.

In this paper, we report, to our knowledge, the first demonstration of a hydrostatic pressure sensor based on a surface-core optical fiber.\textsuperscript{6} The main advantage of using surface-core optical fibers instead of employing photonic crystal fibers in pressure sensing measurements is the ease of fabrication. Preparation of photonic crystal fibers can be very demanding and time consuming. The fabrication method of surface-core fibers is, in turn, very simple since it is based on the merging of a germanium doped silica rod to a silica tube followed by a standard fiber drawing process.\textsuperscript{6} The off-center core, on the other hand, can not be trivially spliced to standard single mode fibers – an issue to be addressed in future if all-fiber setups are desired.

In the next sections, the performance of the proposed sensor is analyzed. To do this, a theoretical study of fiber characteristics is firstly provided and then compared to the experimentally measured data.

2. STUDY OF FIBER PRESSURE SENSITIVITY

In order to study the surface-core fiber pressure sensitivity, whose measure is given by the $C_S$ coefficient (Eq. 1), one needs to obtain information about fiber phase and group birefringence. To attain this goal, one proceeded with the performance of numerical simulations by using a commercial finite element-based software. Figure 1 presents the simulated idealized fiber structure. The core region (darker area) was assumed to have an elliptically symmetric graded

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refractive index profile. Pure and doped silica optical and mechanical properties were simulated using a model developed in Cerqueira S, Jr. et. al.10

Simulation results provided us with the effective refractive index of the fundamental core modes in the orthogonal polarization states – one emphasize that although the fiber supports a few high order modes in the visible wavelength range, our analysis was centered to the fundamental core mode. The knowledge of the orthogonal modes effective refractive index allowed obtaining Figure 1b plot, which exposes the fiber phase birefringence dependency on wavelength. Here, it is seen that the fiber phase birefringence has the order of $10^{-4}$.

The observed phase birefringence behavior versus wavelength is found to be linear. Thus, it is possible to estimate the phase birefringence derivative with respect to the wavelength, $\frac{\partial B}{\partial \lambda}$, as the angular coefficient of a line fitted to the simulated points. This derivative is then calculated to be $7.5 \times 10^{-6}$ nm$^{-1}$. Furthermore, the fiber group birefringence, $G$, which is given by $G = B - \lambda \frac{\partial B}{\partial \lambda}$, could be obtained as $1.43 \times 10^{-4}$ in the studied wavelength range showed in Figure 1b.

In order to account for $C_G$, it is also necessary to study the birefringence dependence on pressure variations. Thereby, one performed simulations of the fiber effective refractive indexes for different pressurization conditions (at 815 nm wavelength). Results are presented in Figure 1c where it is seen an increase in fiber phase birefringence as the pressure applied on the fiber is incremented. It happens due to the fact that the fiber core structure is asymmetrically exposed to the external environment (one of its axis suffers direct influence of the applied pressure and the other axis is partially shielded by the fiber structure). Thus, the modes on orthogonal polarizations that travel along the fiber core experiences different effective refractive index changes if the pressurization conditions are varied. For low pressures range, up to 10 MPa, one obtains $8.0 \times 10^{-2}$ MPa$^{-1}$ for the birefringence derivative with respect to pressure $\frac{\partial B}{\partial P}$. For higher pressures range, from 10 MPa to 25 MPa, we calculated $3.1 \times 10^{-2}$ MPa$^{-1}$ for $\frac{\partial B}{\partial P}$.

From the obtained values for group birefringence and for the derivative of the phase birefringence with respect to pressure, it is possible to calculate an expected value for $C_G$ around the wavelength of 815 nm for low pressures values: 4.6 nm/MPa. In the subsequent sections an experimental measure for $C_G$ will be presented for comparison to the expected one.

![Diagram](image)

Figure 1. (a) Fiber structure used in simulations with doped core region in dark grey with dimensions 3.3 μm x 6.6 μm. (b) Numerical phase birefringence versus wavelength plot. (c) Numerical phase birefringence versus applied pressure plot.
3. PRESSURE VARIATIONS MONITORING

For performing hydrostatic pressure variations probing measurements, an experimental setup as depicted in Figure 2a was used. Broadband light from a supercontinuum (SC) is used as the light source and an optical spectrum analyzer (OSA) is employed as the detection system. The surface-core fiber is placed in a pressure chamber connected to a pressure pump so it can be subjected to different pressure conditions. Two polarizers (P1 and P2) are also used in the experimental configuration: the first one provides the excitation of modes on the two orthogonal polarizations and the second one allows these modes to interfere.

Surface-core fibers tested herein were fabricated at UNICAMP and the details can be found elsewhere. Figure 2b shows the cross section of the referenced fiber and Figure 2c presents a zoom of the core area. Brighter regions in Figure 2b and c identifies the fiber core.

Figure 2. (a) Experimental setup. SC: supercontinuum; P1 and P2: polarizers; OSA: optical spectrum analyzer. (b) Surface-core fiber cross section. (c) Core region zoom.

As the orthogonal modes that travel along the fiber are associated to different effective refractive indexes, the transmission spectrum measured in the experimental setup of Figure 2a is characterized by the existence of interferometric fringes. The spectral position of the interferometric fringes is dependent on the pressure conditions to which the fiber is subjected. Therefore, when one alters the applied pressure value on the fiber, the fringes are expected to experience a spectral shift.

Figure 3a shows the transmission spectra measured in Figure 2a setup for different pressurization conditions from 0 to 0.4 MPa. One can observe that as the pressure applied on the fiber is increased, the interferometric fringes blueshift. Figure 3b presents the fringes wavelength shift versus applied pressure plot. By fitting this plot data, one can calculate the fiber sensitivity to pressure variations. A sensitivity of 4.8 nm/MPa was found.

The attained pressure sensitivity value is slightly higher than the one found for PM-1550-01 fiber (3.42 nm/MPa, measured around 1550 nm), which is a commercial fiber fabricated by NKT Photonics and usually employed in pressure sensing experiments. The highest pressure sensitivity value remains being, to our knowledge, the one reported by Amaszkiernicz et al. when studying rocking-filters induced on microstructured-fibers (177 nm/MPa).

Figure 3a data also allows obtaining an experimental measure for fiber group birefringence. For calculating it, one uses $G = \frac{\lambda}{2}(S \cdot L)$, where $\lambda$ is a central wavelength between two consecutive maxima (or minima) in the transmission spectrum, $S$ is the spectral distance between the considered maxima (or minima) and $L$ is the fiber length. At 815 nm, one obtained $2.63 \times 10^{-4}$ for group birefringence. The measured value is higher than the one predicted by simulations ($1.43 \times 10^{-4}$). We believe that simulated and measured values are different because the fiber structure used in simulations was idealized.
CONCLUSIONS

In this paper, a hydrostatic pressure sensor based on surface-core optical fibers was presented. To our knowledge, this is the first time that this kind of fibers is studied under this approach.

Firstly, fiber sensitivity to pressure variations, which is mediated by the photo-elastic effect, was theoretically characterized by simulating the fiber properties using a commercial finite-element-based software. Fiber phase and group birefringence was estimated and then the expected value for sensitivity coefficient $C_p$ was calculated as $4.6 \text{ nm MPa}^{-1}$.

A polarimetric setup was employed for testing the surface-core fiber sensitivity to pressure variations. The spectral response of the setup was analyzed for different pressurization conditions and the spectral shift of the interferometric fringes was accounted. We obtained $4.8 \text{ nm MPa}^{-1}$ for the surface-core fiber pressure sensitivity. One can observe that a good resemblance between experimental and simulated values was attained.

As future steps in this study, we plan adjusting fiber characteristics in order to optimize its response to pressure variations. Other configurations, as rocking filters induced on the fiber reported herein, are also to be tested.

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Dual-environment pressure sensor using a photonic-crystal fiber

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ABSTRACT

In this paper, we report the development of a side-hole photonic-crystal fiber (SH-PCF) based dual-environment pressure sensor. SH-PCF sensitivity to pressure variations was measured and compared to simulated data. SH-PCF sensitivity was found to be 2.8 times higher than the one presented by the commercial PM-1550-01 fiber. For probing two environments, one spliced two sections of the studied SH-PCF with different lengths in a sole-filter-like configuration. Individual responses of the first and second fiber can be independently obtained in this setup. Therefore, making use of SH-PCF sensitivity to pressure variations, a pressure sensor for dual environment monitoring is built up.

Keywords: Pressure sensor, photonic-crystal fibers, birefringent fibers

1. INTRODUCTION

Photonic crystal fibers (PCF) design versatility allows obtaining a great variety of PCF-based sensors. Fiber characteristics can be tailored by adequately choosing its microstructure. Thus, fiber physical properties can be explored and its performance optimized in order to sense different physical quantities (e.g., hydrostatic pressure, strain, and curvature).

If PCFs are chosen in such a way that their optical response are dependent on hydrostatic pressure variations, a pressure sensor can be built up. Photoelastic effect mediates this dependence, which has PCF microstructure geometry as an important parameter. Hydrostatic photonic-crystal fibers pressure sensors are often based on birefringent fibers, as reported in previous papers. In these papers, authors probe pressure by monitoring phase birefringence dependence on pressure variations or by observing the spectral behavior of a fiber on which pressure is applied.

When the measurement is performed by observing the spectral response of the system to pressure variations, authors usually employ a broadband light source and the experiment is done in an interferometric fashion. The spectral response is characterized by interferometric fringes whose spectral position is dependent on the pressure applied on the fiber. In other words, fringes spectral position shifts as the pressure is altered. To characterize this dependence, a sensitivity coefficient $C_S$ is defined as shown in Eq. (1):

$$\frac{\Delta \lambda}{\Delta \rho} \equiv C_S \approx \frac{\lambda}{G \frac{\partial \rho}{\partial P}}$$

where $\lambda$ is the central wavelength of a local minimum in the spectrum, $\Delta \lambda$ is the wavelength shift that takes place when external hydrostatic pressure is applied, AP is the pressure variation, G is the group modal birefringence and $(\partial \rho / \partial P)$ is the phase birefringence derivative with respect to pressure.

In this paper, the sensitivity of a side-hole photonic-crystal fiber (SH-PCF) to hydrostatic pressure variations is theoretically and experimentally studied. Moreover, the fiber is used in a dual environment pressure sensing measurement. To build the sensor, we employ a simple technique developed in our group at UNICAMP. In this technique, two birefringent fibers are set in an in-series configuration and an input and an output polarizers have its angles chosen in such a manner that the first or the second fiber individual responses are independently obtained. Thus, we demonstrate the performance of a hydrostatic pressure sensor with two probing regions for dual environment monitoring by separately measuring the first and second fiber responses.
2. FIBER CHARACTERIZATION

As already referenced, a side-hole photonic-crystal fiber (SH-PCF) was used for the hydrostatic pressure sensing experiment. Fiber cross section is presented in Figure 1(a). Inset exposes a magnified image of the microstructured region. Hole diameter \( d = 1.7 \, \mu m \) and hole separation \( l = 2.8 \, \mu m \) are represented.

The experimental setup for fiber characterization measurements is represented in Figure 1(b). The SH-PCF is firstly spliced to standard single mode fibers at its both ends and then placed into a pressure chamber. Broadband light from the source (supercontinuum from a photonic crystal fiber) is polarized by the first polarizer \( (P_1) \) and coupled into the SH-PCF so that both orthogonal modes of the birefringent fiber are excited. The output polarizer \( (P_2) \) allows the light from the orthogonal modes to interfere and the optical response is measured by an optical spectrum analyzer (OSA). A typical spectrum is shown in Figure 2(a). We emphasize that curvatures in the standard fibers are minimal in order to avoid degrading the polarization state of the light to be coupled in the SH-PCF.

Experimental \( C_s \) values are obtained after taking spectra for situations in which different pressure values were applied on the fiber. To do this, we observe a particular fringe wavelength shift. Performing the division between the wavelength shift by the pressure variation, we obtain \( C_s \) = Eq. (1). Experimental results for \( C_s \) are presented in Figure 2(b) – at 1550 nm and 633 nm, \( C_s \) values are 12.2 nm/MPa and 44.8 nm/MPa, respectively. Theoretically values for \( C_s \) were also calculated by employing a commercial finite-element method based software. Results are presented as a line in Figure 2(b). It is seen that \( C_s \) is higher for lower wavelengths. It happens mainly because group birefringence is lower for shorter wavelengths.

Moreover, we simulated \( C_s \) values for the commercial PCF PM-1550-01 by NKT Photonics, which is usually employed as a platform for pressure sensing measurements. We found that the SH-PCF proposed in this paper has higher sensitivity coefficient than the commercial PCF. At \( \lambda = 1550 \, \text{nm} \), for instance, the sensitivity coefficient for the SH-PCF is about 2.8 times higher than the one for the commercial PCF.

**Figure 1.** (a) Cross-section of the SH-PCF used in the experiments. Inset shows a magnified image of the microstructured region. Hole diameter \( d = 1.7 \, \mu m \) and hole separation \( l = 2.8 \, \mu m \) are presented. (b) Experimental setup for SH-PCF hydrostatic pressure sensitivity characterization. BL: broadband light; \( P_1 \) and \( P_2 \); SMF: standard single mode fiber; SH-PCF: side-hole photonic-crystal fiber; OSA: optical spectrum analyzer.

**Figure 2.** (a) Typical spectrum for the transmittance as a function of the wavelength. (b) Experimental and simulation results for the sensitivity coefficient \( C_s \) as a function of the wavelength.

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3. DUAL ENVIRONMENT PRESSURE SENSING

To build up a sensor able to sense two different environments, we employ the technique recently reported by some of us, where two birefringent fibers are spliced with rotated principal axes in relation to each other and set as schematized in Figure 3.

In this setup, one can obtain single fiber responses by conveniently adjusting the input and output polarizers, i.e., it is possible to measure the first or the second fiber responses by simply tuning the polarizers angles. In order to attain the first fiber response, the second polarizer must be aligned to one of the principal axes of the second fiber. The condition for obtaining the second fiber response is coupling light in the fiber with the input polarization along one of the principal axes of the first fiber.6

In the experiment reported in this paper, two SH-PCF sections (with total lengths \( L_1 = (22.5 \pm 0.02) \) cm and \( L_2 = (58.5 \pm 0.02) \) cm) were spliced and placed into pressure chambers (Figure 3). After obtaining the first fiber response, different hydrostatic pressure values were applied on this fiber and its spectral response was measured – Figure 4(a) top. Likewise, after attaining the second fiber response, spectra were recorded while subjecting the fiber to different pressure conditions – Figure 4(a) bottom. Figure 4(b) shows the wavelength shift of a particular fringe versus the pressure applied on the fiber for both described situations. \( C_s \) values of \( 1.69 \pm 0.04 \) nm/MPa and \( 2.22 \pm 0.04 \) nm/MPa were found for the first and second fiber, respectively. As different fractions of the lengths of the fibers were pressurized (Pressurized lengths: \( L_{p1} = 2 \) cm and \( L_{p2} = 8 \) cm), one do expected that the measured \( C_s \) values were different. The predicted value for the relation between the \( C_s \) values to be measured (\( R \)) is given by Eq. (2).

\[
R \equiv \frac{C_{s1}}{C_{s2}} = \frac{L_{p1}}{L_{p2}} \frac{L_2}{L_1}
\]

By Eq. (2), one find \( R_{\text{predicted}} = (0.65 \pm 0.08) \) (predicted value of \( R \)). Experimental data from Figure 4(b) provides \( R_{\text{experimental}} = (0.76 \pm 0.03) \). It is possible to note that the predicted and experimentally obtained values of \( R \) are consistent.

Thus, one can conclude that a pressure sensor for monitoring two different regions was demonstrated. The configuration studied herein allows independently measuring hydrostatic pressure in two disconnected environments. Also, pressure sensing measurements can be done with higher sensitivity when compared to setups that employs the commercial PM-1550-01 fiber.

Figure 3. Experimental setup for dual environment pressure monitoring.

Figure 4. (a) First and second fiber spectral response as the applied pressure is varied. (b) Wavelength shift as a function of the pressure applied on the fiber.
4. CONCLUSION

In this paper, we presented the study of a pressure sensor with two sensitive regions for dual environment probing. In order to build up the sensor, two sections of a side-hole photonic-crystal fiber with different lengths were spliced and set in a soli-filter-like configuration. In this setup, the input and output polarizers are tuned in such a way that it is possible to obtain the first and second fiber responses separately.

Initially, fiber sensitivity to pressure variations was characterized. The sensitivity parameter $C_2$ was measured and compared to simulated values showing good resemblance. At 1550 nm and 633 nm, $C_2$ values was found to be 12.2 nm/MPa (1.22 nm/bar) and 4.8 nm/MPa (4.48 nm/bar), respectively. Moreover, pressure sensitivity of the side-hole PCF was compared to the one presented by the commercial fiber PM-1550-01 manufactured by NKT Photonics (often used in pressure sensing measurements). SH-PCF sensitivity was found to be about 2.8-fold the PM-1550-01 respective value at the wavelength of 1550 nm.

Hence, a pressure sensor for dual environment monitoring performance was demonstrated. The system reported herein allows performing independent pressure measurements in two disconnected environments since the sensor has two sensitive regions.

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