

UNIVERSIDADE ESTADUAL DE CAMPINAS
SISTEMA DE BIBLIOTECAS DA UNICAMP
REPOSITÓRIO DA PRODUÇÃO CIENTÍFICA E INTELLECTUAL DA UNICAMP

Versão do arquivo anexado / Version of attached file:

Versão do Editor / Published Version

Mais informações no site da editora / Further information on publisher's website:

<https://onlinelibrary.wiley.com/doi/full/10.1002/mop.27199>

DOI: 10.1002/mop.27199

Direitos autorais / Publisher's copyright statement:

©2012 by John Wiley & Sons. All rights reserved.

DIRETORIA DE TRATAMENTO DA INFORMAÇÃO

Cidade Universitária Zeferino Vaz Barão Geraldo

CEP 13083-970 – Campinas SP

Fone: (19) 3521-6493

<http://www.repositorio.unicamp.br>

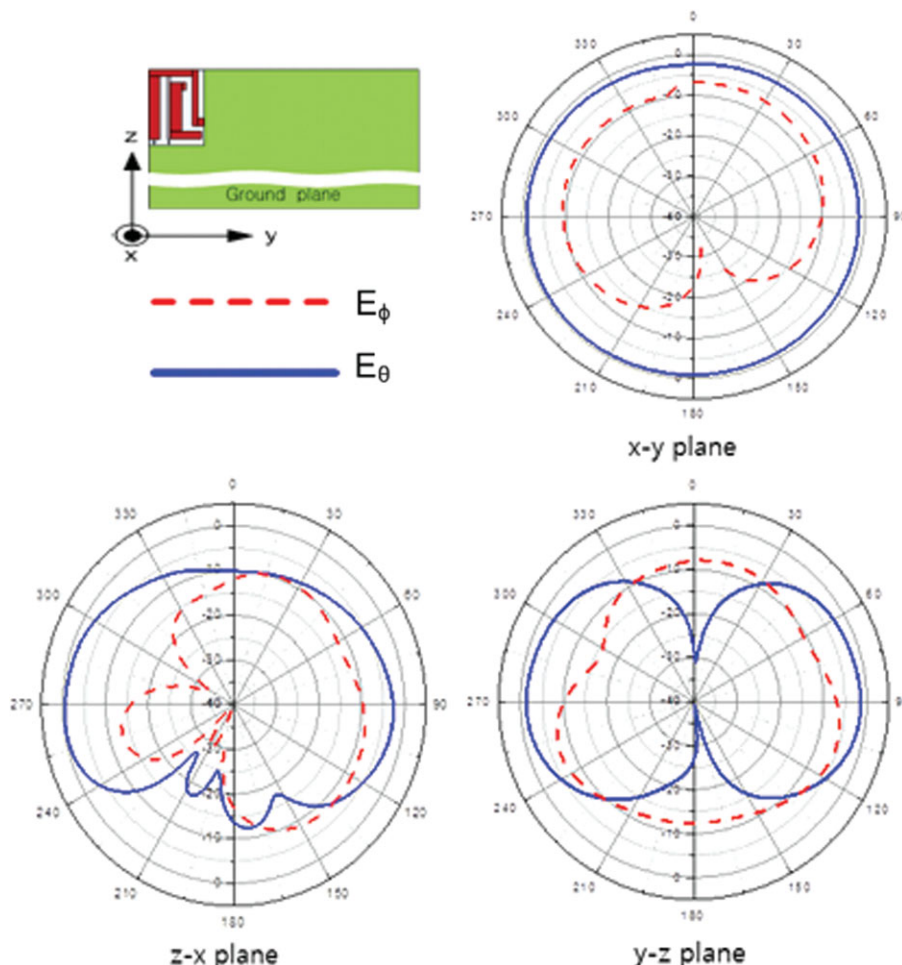


Figure 5 Measured radiation patterns at 1600 MHz. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com]

4. CONCLUSION

In this letter, a printed GPS/GLONASS internal antenna for mobile phone has been proposed. The antenna has a compact structure and is easy to print on the PCB ground of a mobile phone because of its small area of $5 \text{ mm} \times 9 \text{ mm}$. In order to reduce its size, the antenna utilizes a chip capacitor. By adding a parasitic inverted element, this antenna can cover fully the GPS and GLONASS operation band. Although the antenna has a simple structure and compact volume, a good gain and radiation efficiency have been obtained. The proposed antenna may be especially applicable for modern thin mobile phones as an internal antenna.

REFERENCES

1. M.V. Chufarov, L.A. Lvova, and A.V. Babushkin, Double-band circularly-polarized antenna for GLONASS-GPS applications, In: Microwave and Telecommunication Technology Symposium, 2011, pp. 549–550.
2. J.X. Liu and W.Y. Yin, A compact interdigital capacitor-inserted multiband antenna for wireless communication applications, *IEEE Antennas Wireless Propag Lett* 9 (2010), 922–925.
3. H. Choi, S. Jeon, L. Yang, D. Yun, and H. Kim, GPS antenna using a system ground as a radiator, *IEEE International Workshop on Antenna Technology Small Antennas and Novel Meta-materials*, In: Radio Wireless Symposium, 2011, pp. 235–238.
4. M.C. Scardelletti, G.E. Ponchak, S. Merritt, J.S. Minor, and C.A. Zorman, Electrically small folded slot antenna utilizing capacitive

loaded slot lines, In: *IEEE Radio Wireless Symposium*, 2008, pp. 731–734.

5. HFSS Ansoft Corp, User Manual, Version 12, 2005.

© 2012 Wiley Periodicals, Inc.

GENERATION OF QUATERNARY-AMPLITUDE MICROWAVE SIGNALS BY USING A NEW OPTICAL HETERODYNE TECHNIQUE

A. T. P. Villena,^{1,2} S. Arismar Cerqueira Jr.,^{2,3} Marcelo L. F. Abbade,⁴ H. E. Hernandez-Figueroa,^{1,2} and Hugo L. Fragnito^{2,5}

¹Faculdade de Engenharia Elétrica e de Computação, UNICAMP, Campinas-SP, Brazil; Corresponding author:

pwll@dmo.fee.unicamp.br

²Optics and Photonics Research Center, UNICAMP, Campinas-SP, Brazil

³National Institute of Telecommunications, INATEL, Santa Rita do Sapucaí-MG, Brazil

⁴Faculdade de Engenharia Elétrica, PUC-Campinas, Campinas-SP, Brazil

⁵Instituto de Física Gleb Wataghin, UNICAMP, Campinas-SP, Brazil

Received 22 March 2012

ABSTRACT: We propose and experimentally investigate a new technique, based on optical heterodyne generation, which converts two optical binary amplitude-shift keyed (2-ASK) into a single microwave

Key words: optical heterodyne generation; quaternary amplitude; multi-amplitude signals; microwave communications

1. INTRODUCTION

Mobility has become an essential issue for Internet users. As a consequence, a major challenge is to deploy wireless services with a quality similar to that experienced in cabled connections. This is not a trivial task when some presently deployed high bandwidth applications, such as video-on-demand and high definition television are considered. Yet, it is easy to conceive several near-term new services that will need even higher bandwidths. This is the case, for instance, of three-dimensional games with remotely interacting players and of the uncountable applications of virtual reality. It is, thus, quite evident that very robust and spectrally efficient techniques are necessary to support such high-quality mobility services [1].

From an infrastructure point of view, a central office (CO) needs to receive data from Internet and send them to a remote site (RS), where one or more antennas provide wireless access to mobile users. Radio-over-fiber (RoF) is an attractive solution for this situation [2]. In this case, Internet data collected by the CO are converted to the radio-frequency (RF) domain and used to modulate an optical carrier. Signal is then transmitted through an optical fiber to the RS where it is photo-detected and returned to the RF domain. Then, after being filtered and amplified, signal may feed to an antenna and be transmitted to the mobile users. Such RoF solution allows the concentration of several RF equipment (radio base stations) in a single CO. Therefore, it concentrates network intelligence and management in a site where environmental conditions are easily controlled, and maintenance does not require the move of specialized teams to the RS [3, 4]. Furthermore, RoF technology may also be used for upstream communication [5].

In spite of its pros, RoF systems also face some disadvantages for future applications. This happens because, as new wireless applications emerge, the RF spectrum becomes more congested; hence, it is necessary to use carriers with frequencies, possibly in the range of microwave or even millimeter waves. Such move to higher frequencies spectral regions is also stimulated by the need to accommodate the aforementioned high-bandwidth new services. However, as frequency increases, fiber dispersion and the nonlinear response of photodetectors lead to fading in RoF systems. This effect, for instance at 30 GHz, reduces signal propagation to 1 or 2 km before RoF signal turns to be severely attenuated.

An alternative to keep the advantages of RoF systems and to avoid their cons is to transmit data through the fiber and use photonics to generate the microwave (or millimeter wave) carrier only at the RS. Such a technique is known as optical heterodyne generation (OHG) of microwaves and is commonly mentioned in literature [6–10]. In this letter, we propose and experimentally investigate a new technique that uses OHG to convert two optical binary amplitude-shift keyed (2-ASK) into a single microwave quaternary ASK (4-ASK) one. This technique is interesting because it doubles the spectral efficiency provided by OHG and, thus, is in compliance with the requirements for

supporting new high-bandwidth wireless services. The technique performance was experimentally evaluated in a back-to-back configuration and also after signal propagation through an optical link from a geographically distributed field-trial optical network, called KyaTera Network [11, 12]. Such evaluation allows us to infer how the technique operates under real conditions of temperature, pressure, humidity, and wind. Although we have recently reported some very preliminary results [13], to the best of our knowledge, this is the first time that the proposed technique is systematically investigated in literature.

The organization of this letter is as follows. Section 2 presents a review on OHG of microwaves; this section also approaches our proposal on using OHG to convert two 2-ASK optical signals into a single 4-ASK microwave one. In Section 3, we describe our experimental setup, whereas in Section 4 our experimental results are shown. Section 5 approaches some applications and discussions regarding extensions of the proposed technique. At last, our conclusions and final remarks are presented in Section 6.

2. THEORY

2.1. Review of OHG of Microwave Signals

We begin our calculations by considering two copolarized optical waves, at frequencies f_1 and f_2 , propagating through an optical fiber. In this case, the instantaneous magnitude of the electrical field associated with them is given by:

$$E(t) = E_1 \cos[2\pi f_1 t + \varphi_1] + E_2 \cos[2\pi f_2 t + \varphi_2] \quad (1)$$

where E_i and φ_i ($i = 1, 2$) are, respectively, the amplitude and phase of wave i -th wave. When such signals incur over a photodiode, and dark current may be neglected, it is found that

$$i(t) \propto |E(t)|^2 \quad (2a)$$

$$i(t) \propto E_1^2 + E_2^2 + 2E_1 E_2 \cos(2\pi f_{MW} t + \Delta\varphi) \quad (2b)$$

where $f_{MW} = |f_2 - f_1|$ and $\Delta\varphi = \varphi_1 - \varphi_2$. If a microwave band-pass filter centered at f_{MW} is used at the photodiode output, the two DC terms on the right-hand side of Eq. (2b) are blocked and only the third term, that is a microwave signal whose carrier is at f_{MW} , is sustained. This is the principle of OHG of microwave signals. In fact, this process is able to generate not only microwave, but also RF and millimeter waves, depending on the magnitude of $|f_2 - f_1|$.

It should be noted that if both input optical signals are continuous waves (cw), then the generated microwave is also a cw. On the other hand, when only one of the input optical signals is a cw and the other one is modulated, such modulation is

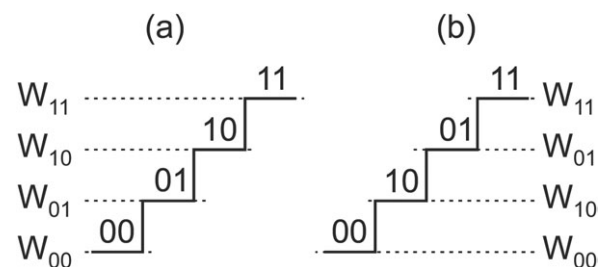


Figure 1 Power level distributions for the generated quaternary-amplitude signal when (a) (level “10” above level “01”) and (b) (level “01” above level “10”)

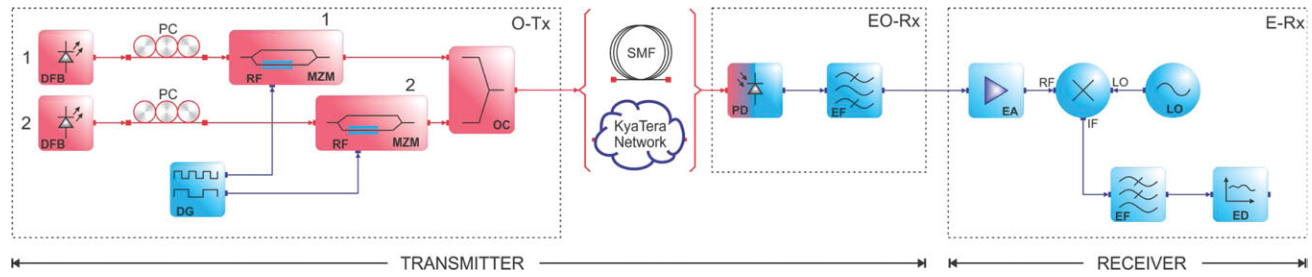


Figure 2 Experimental setup. DFB: distributed feedback laser, PC: polarization controllers, DG: digital pattern generator, MZM: Mach Zehnder modulator, OC: optical coupler, SMF: single mode fiber, PD: photodetector, EF: electrical filter, EA: electrical amplifier, LO: local oscillator, ED: envelope detector. O-Tx: optical transmitter, EO-Rx: electro-optical receiver, E-Rx: electrical receiver. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com]

replicated on the generated microwave signal. Both of these approaches had already been considered in literature [8, 14].

2.2. OHG of Microwave Signals with Modulation Multiplexing

Here, we show that OHG may also be used to multiplex information from two modulated optical signals. In particular, in this letter, we focus on the usual situation where such signals correspond to binary 2-ASK. We designate by P_{iz} the optical power of the i -th ($i = 1, 2$) optical wave when it conveys a bit z ($z = 0$ or 1); similarly, E_{iz} is the magnitude of the electrical field associated with P_{iz} . Using the fact that $P_{iz} \propto |E_{iz}|^2$ and Eq. (2b), it is easy to show that

$$i_{00}(t) \propto 2\sqrt{P_{10}P_{20}}\cos[2\pi f_{MW}t + \Delta\varphi] \quad (3a)$$

$$i_{01}(t) \propto 2\sqrt{P_{10}P_{21}}\cos[2\pi f_{MW}t + \Delta\varphi] \quad (3b)$$

$$i_{10}(t) \propto 2\sqrt{P_{11}P_{20}}\cos[2\pi f_{MW}t + \Delta\varphi] \quad (3c)$$

$$i_{11}(t) \propto 2\sqrt{P_{11}P_{21}}\cos[2\pi f_{MW}t + \Delta\varphi] \quad (3d)$$

where $i_{xy}(t)$ is the electric current at the microwave filter output when the optical signal at f_1 sends a bit x ($x = 0$ or 1) and the one at f_2 transmits a bit y ($y = 0$ or 1). Traditionally, optical binary signals use on-off keying (OOK) modulation, where $P_{10} = P_{20} = 0$; in this case $i_{xy}(t) = 0$ and there is no microwave signal at the output of the bandpass filter. However, if we intentionally provide an offset to the powers of bits 0, then $i_{xy}(t)$ becomes nonnull and the microwave signal becomes a quaternary 4-ASK one, containing information from both optical input signals. In fact, the power levels of this signal, W_{ix} , are proportional to the mean squared value of $i_{xy}(t)$ and may be written as

$$W_{00} \propto P_{10}P_{20} \quad (4a)$$

$$W_{01} \propto P_{10}P_{21} \quad (4b)$$

$$W_{10} \propto P_{11}P_{20} \quad (4c)$$

$$W_{11} \propto P_{11}P_{21} \quad (4d)$$

In particular, in the case where $P_{11}P_{20} > P_{10}P_{21}$ illustrated in Figure 1(a), the relative extinction ratios (ERs) between the consecutive power levels of the 4-ASK signal become

$$\Gamma_1 = W_{00}/W_{01} = r_2 \quad (5a)$$

$$\Gamma_2 = W_{01}/W_{10} = r_1/r_2 \quad (5b)$$

$$\Gamma_3 = W_{10}/W_{11} = r_2 \quad (5c)$$

where $r_i = P_{i0}/P_{i1}$ denotes the ER of the i -th optical wave. Similarly, if $P_{11}P_{20} < P_{10}P_{21}$

$$\Gamma_1 = W_{00}/W_{01} = r_1 \quad (6a)$$

$$\Gamma_2 = W_{10}/W_{01} = r_2/r_1 \quad (6b)$$

$$\Gamma_3 = W_{01}/W_{11} = r_1 \quad (6c)$$

This situation is illustrated in Figure 1(b). Equations (5) and (6) indicate that the power level distribution of the 4-ASK microwave signal depends solely on the ERs of the input optical signals and not on the absolute values of the optical signal powers.

3. EXPERIMENTAL SETUP

To investigate the technique presented in subsection 2.2, we used the experimental setup illustrated in Figure 2. Basically, the transmitter is our microwave generator, that provides multi-level signal, and the receiver is mounted to evaluate the performance of the generated signal. Two distributed feedback laser (DFB) lasers generate optical carriers at $f_1 = 193.208$ THz and $f_2 = 193.228$ THz, which are intensity modulated by two 10

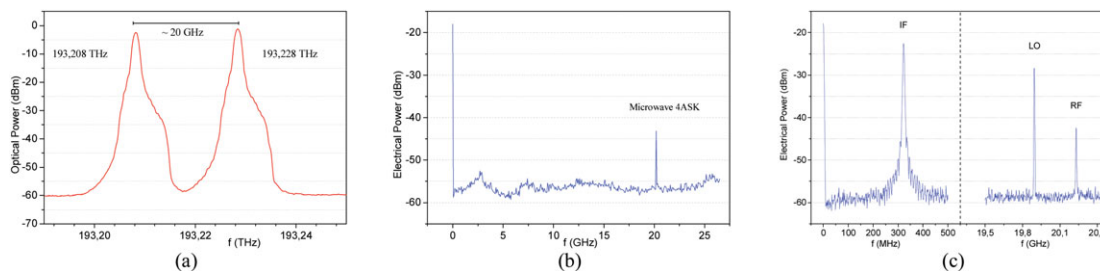


Figure 3 (a) Optical spectrum at the fiber input; electrical spectra at the (b) photodiode output and (c) mixer output. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com]

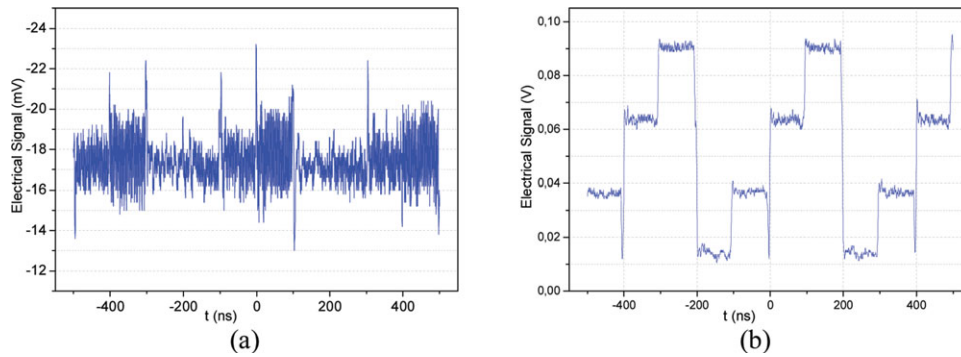


Figure 4 (a) IF signal, (b) signal after the ED circuit for $L = 0$ km. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com]

Mbits/s $2^{10}-1$ code words; the ERs of these signals are regulated by changing the bias voltage of the external modulators. Both signals are coupled and propagated through an optical fiber. Tests are performed for fiber lengths of $L \sim 1$ m (back-to-back tests) and 25 km. In a second moment, the signals are propagated through an optical link from the KyaTera Network, which is a field-trial network located in São Paulo state (Brazil). In this case, L is either 10 or 40 km and an optical preamplifier is used to compensate optical losses. After (back-to-back or KyaTera Network) fiber propagation, signals are photo-detected, band-pass filtered at $f_{\text{MW}} = (193.228-193.208)$ THz = 20.0 GHz, and amplified by an electronic amplifier (EA). The band-pass filter is centered at 21 GHz and presents a bandwidth of 3.0 GHz. For a given amplifier gain, polarization controllers at

the output of the DFB lasers are set to provide the maximum power at the EA output. The amplified signal is further transmitted to a mixer that converts the microwave carrier to an intermediate frequency (IF) of ~ 166 MHz. Finally, this IF signal is filtered again and an envelope detector (ED) receives the quaternary-amplitude signal.

4. RESULTS

Figure 3 presents signal spectra at (a) fiber input, (b) photodiode output, and (c) mixer output. The optical spectra of signals at f_1 and f_2 , shown in Figure 3(a), are distorted from the typical OOK signals profile because of the reduced ERs of the input binary signals. An optical signal-to-noise ratio higher than 55 dB is

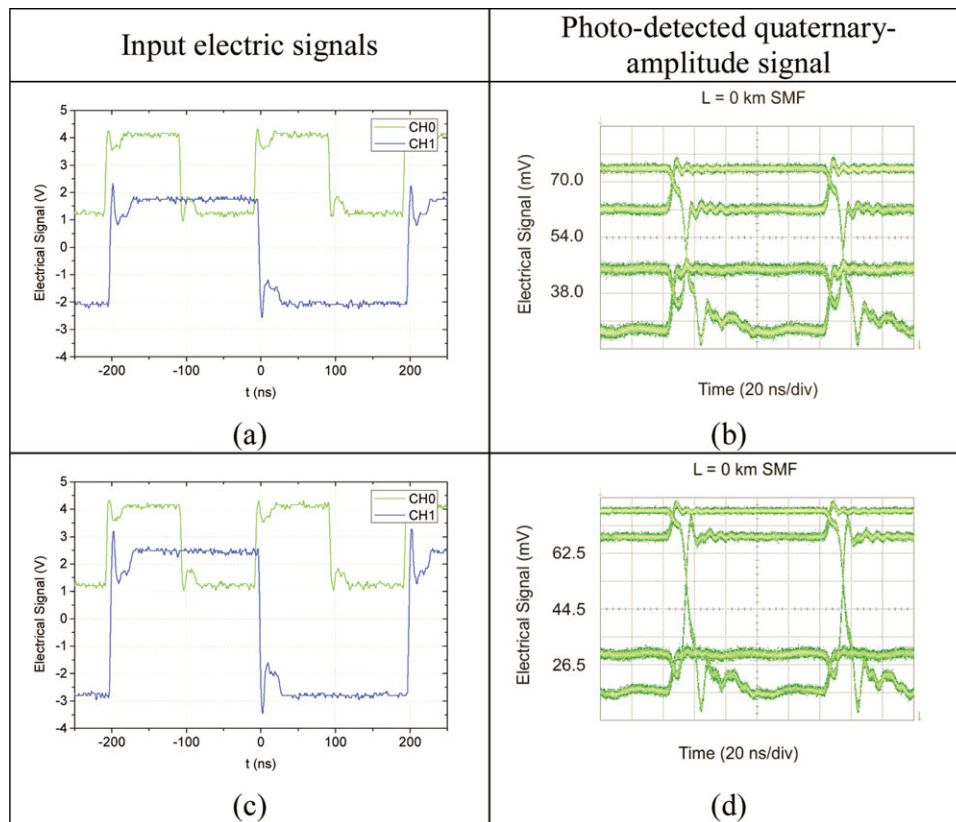


Figure 5 (a) Input electronic signals and (b) level distribution for $r_1 = 6.0$ dB and $r_2 = 3.1$ dB; (c) input electronic signals and (d) level distribution for $r_1 = 10.5$ dB and $r_2 = 3.1$ dB. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com]

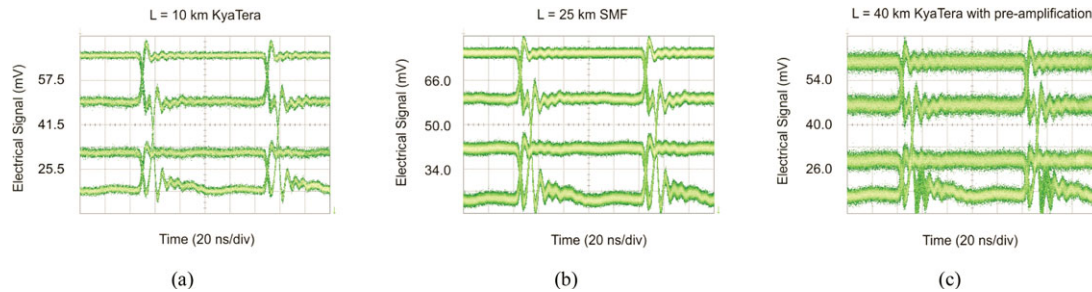


Figure 6 Eye diagrams after (a) 10, (b) 25, and (c) 40 km of propagation through standard SMF. Cases presented in (a) and (c) were evaluated in KyaTera Network. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com]

observed and peaks are clearly 20 GHz apart from each other. Figure 3(b) shows the 20 GHz frequency component obtained at the photodiode output; this is where the microwave 4-ASK signal is generated. The spectra on the right-hand side of Figure 3(c) show such ~ 20 GHz frequency component again as well as the one associated with the local oscillator (LO). The IF component, whose envelope is detected, presents a signal-to-noise ratio around 28 dB.

Figure 4 illustrates (a) the microwave 4-ASK-signal, proposed in this work, translated to the IF domain and (b) the correspondent quaternary signal obtained after the envelope detection. The stairway-like profile observed in Figure 4(b) was achieved by setting the bit sequences sent by the input signals at f_1 and f_2 , respectively, as 0011 and 0101. The four very definite observed power levels indicate the good quality and practical feasibility of the proposed technique.

To verify the theory presented in Section 2, we evaluated how the quaternary signal was affected by changing the ER of the input binary signals. Figure 5 exhibits the electric input binary signals and the output quaternary one for the situations where (a, b) $r_1 = 6.0$ dB ≈ 0.5 and $r_2 = 3.1$ dB ≈ 0.7 and (c, d) $r_1 = 10.5$ dB ≈ 0.3 and $r_2 = 3.1$ dB ≈ 0.7 . In the first of these cases, the ERs of the consecutive power levels are $\Gamma_1 = 0.66$, $\Gamma_2 = 0.72$, and $\Gamma_3 = 0.82$, whereas in the second one they are $\Gamma_1 = 0.66$, $\Gamma_2 = 0.44$, and $\Gamma_3 = 0.86$. Following Eq. (5), these values should be $\Gamma_1 = \Gamma_3 = 0.70$, and $\Gamma_2 = 0.71$ for the case of Figure 5(b) and $\Gamma_1 = \Gamma_3 = 0.70$, and $\Gamma_2 = 0.42$ for the situation of Figure 5(d). This shows that the theoretical values of Γ_1 and Γ_2 are in a rather good agreement with the experimental ones. The difference between the theoretical and experimental values for Γ_3 is explained by the fact that the sensibility of the used photodetector was of only ~ -4 dBm and so the optical powers associated with the highest power level of the 4-ASK microwave signal were high enough to saturate this receiver.

Finally, the input binary signals were propagated through standard single mode fibers with lengths of 10, 25, and 40 km and we investigated the behavior of the generated 4-ASK signal. The intermediate case of $L = 25$ km was performed in a fiber; propagations by 10 and 40 km were performed in the KyaTera Network, where real conditions of temperature, pressure, humidity, and wind that could affect the performance of the generated signal are found. To compensate the highest experienced losses, an optical preamplifier was used in the case of $L = 40$ km. Figure 6 presents the obtained quaternary signals eye diagrams after such propagations. As before, four well definite power levels are observed for all the considered lengths; this evidences the robustness of the proposed tech-

nique and its applicability to situations where RSs are 10 km apart from the CO. As the propagation distance increases, the intensity width of the power levels of the quaternary-amplitude signal becomes wider. This is a consequence of signal distortion caused by fiber chromatic dispersion and could be easily eliminated by using dispersion compensating fibers or fiber Bragg gratings.

5. APPLICATIONS AND DISCUSSION

The proposed technique could be applied to a situation where two Internet users, whose traffic is in the optical domain, need to send data to mobile users in a region illuminated by radio, micro-, or millimeter waves. In this case, information from optical signals is multiplexed and simultaneously transmitted to the mobile users, which, then, uses proper detection rules to recover information dispatched by its conversation pair. For example, for the case illustrated in Figure 1(a), the mobile user that receives information from data at f_1 interprets that a “bit 0” or a “bit 1” is received whenever the two lowest or two highest power levels are detected. Similarly, the mobile user who receives information from data at f_2 interprets that a “bit 0” is received whenever the lowest and third highest power levels are sensed and that a “bit 1” is received when the other two power levels are detected. In another application, information from two optical binary signals could also be multiplexed and transmitted from an antenna to another through a given microwave link.

Although Eqs. (3)–(6) hold for the amplitude multiplexing of two 2-ASK optical signals, it should be noted that Eq. (2) also allows the multiplexing of two m -ASK or m -phase-shift keying (PSK) signals, where m is an arbitrary integer. Therefore, the proposed technique is, in principle, able to generate microwave PSK or quadrature amplitude modulation (QAM) signals with an arbitrary number of levels. Furthermore, Eq. (2) may also be used to show that information related to three or more input binary signals may be multiplexed. Therefore, the proposed technique could be extended to encompass the multiplexing of n optical signals with m multilevels into a single microwave signal with mn multilevels. This improves the interest on the previously mentioned applications.

6. CONCLUSIONS

We have proposed and analyzed a new technique that able to multiplex two optical signals into a single multilevel microwave signal. In particular, we investigated the case where two 2-ASK optical signals generate a single microwave 4-ASK one. Experimental results indicated very definite power levels even when the optical signals are propagated through distances as

large as 40 km in a field-trial network. This shows that the proposed technique is robust against real conditions of temperature, pressure, humidity, and wind that could affect the performance of the generated quaternary signal. We also developed a theoretical model to predict the power level distribution of the 4-ASK signal; this model satisfactorily explained such distribution in the situations where the photodetector is not saturated.

Although, in this letter, we focused in the case of signal amplitude multiplexing, the proposed technique could also be used to multiplex phase-modulated signals. In this case, microwave m -phase or m -QAM signals would be obtained.

ACKNOWLEDGMENTS

This work was performed in the scope of CEPOF and Fotonicom Programs. Authors thank the financial support from FAPESP, CNPq, and CAPES, under grants 574017/2008-9, 309031/2008-7, and 301627/2009-6.

REFERENCES

1. A. Goldsmith, *Wireless communications*, Chapter 1, Cambridge University Press, Cambridge, UK, 2005, pp. 1–5.
2. A. Ng'oma, *Radio-over-fibre technology for broadband wireless communication systems*, Technische Universiteit Eindhoven, 2005.
3. H.B. Kim, *Radio over fiber based network architecture*, Doctoral Dissertation Thesis, Berlin, Germany, 2005.
4. D. Opatić, GSOC Croatia, *Radio over fiber technology for wireless access*, Ericsson Nikola Tesla d.d., Krapinska 45, HR-10001 Zagreb.
5. S. Arismar Cerqueira, Jr., D.C. Valente e Silva, M.A.Q.R. Fortes, L.F. da Silva, O.C. Branquinho, and M.L.F. Abbade, Performance analysis of a Radio over Fiber system based on IEEE 802.15.4 standard in a real optical network, *Microwave Opt Technol Lett* 51 (2009), 1876–1879.
6. W.S.C. Chang, *RF photonic technology in optical fibers*, Chapter 10, Cambridge University Press, Cambridge, UK, 2002, pp. 298–315.
7. G.P. Agrawal, *Fiber-optic communication systems*, 3rd ed., Chapter 10, John Wiley & Sons, USA, 2002, pp. 478–481.
8. X. Wang, W. Mao, M. Al-Mumin, S.A. Pappert, J. Hong, and G. Li, Optical generation of microwave/millimeterwave signals using two-section gain coupled DFB lasers, *IEEE Photon Technol Lett* 11 (1999), 1292–1294.
9. R.-P. Braun, G. Grosskopf, M. Rohde, and F. Schmidt, Optical millimetre-wave generation and transmission experiments for mobile 60GHz band communication, *Electron Lett* 32 (1996), 626–628.
10. G. Keiser, *Optical fiber communications*, 2nd ed., McGraw-Hill, Singapore, 1991.
11. www.kyatera.fapesp.br, KyaTera.
12. J.D. Marconi, S. Arismar Cerqueira, Jr., J. Robison, N. Sherwood-droz, Y. Okawachi, H.E. Hernandez Figueroa, M. Lipson, A. Gaeta, and H.L. Fragnito, Performance investigation of microphotonic-silicon devices in a field-trial all-optical network, *Opt Commun* 282 (2009), 849–855.
13. T.P. Villena A., S. Arismar Cerqueira, Jr., M.L.F. Abbade, H.E. Hernandez Figueroa, and H.L. Fragnito, A new optical heterodyne technique for generating multi-amplitude microwave signals In: *Proceedings of IQEC/CLEO Pacific Rim 2011*, 2011, Sydney, 2011.
14. R. Sambaraju, D. Zibar, A. Caballero, I.T. Monroy, R. Alemany, J. Herrera, 100-GHz wireless-over-fiber links with up to 16-Gb/s QPSK modulation using optical heterodyne generation and digital coherent detection, *IEEE Photonics Technol Lett* 22 (2010) 1650–1652.

DUAL BAND-NOTCH SQUARE MONOPOLE ANTENNA WITH A MODIFIED GROUND PLANE FOR UWB APPLICATIONS

Nasser Ojaroudi¹ and Mohammad Ojaroudi²

¹ Faculty of Electrical & Computer Engineering, Shahid Rajaei Teacher Training University, Tehran, Iran

² Young Research Club, Ardabil Branch, Islamic Azad University, Ardabil, Iran; Corresponding author: m.ojaroudi@iauardabil.ac.ir

Received 28 March 2012

ABSTRACT: This paper presents a novel small square monopole antenna for UWB applications with dual band-notch function. By cutting an S-shaped slot in the ground plane, additional resonance is excited and hence, much wider impedance bandwidth can be produced, especially at the higher band that provides a wide usable fractional bandwidth of more than 120% (2.98–12.25 GHz). To generate a single frequency band-stop performance, we add a pair of C-shaped parasitic structures in the ground plane, and also in order to create the second notch frequency, we insert a horizontal rectangular strip in the center of two C-shaped parasitic structure in the ground plane. The measured results reveal that the presented dual band-notch monopole antenna offers a wide bandwidth with two notched bands, covering all the 5.2/5.8 GHz wireless local area network, 3.5/5.5 GHz WiMAX, and 4 GHz C bands. Good and radiation behavior within the UWB frequency range have also been obtained. The antenna has a small dimension of $12 \times 18 \text{ mm}^2$. © 2012 Wiley Periodicals, Inc. *Microwave Opt Technol Lett* 54:2743–2747, 2012; View this article online at wileyonlinelibrary.com. DOI 10.1002/mop.27209

Key words: square monopole antenna; S-shaped slot; dual band-notch function; ultra wide band applications

1. INTRODUCTION

In UWB communication systems, one of the key issues is the design of a compact antenna while providing wideband characteristic over the whole operating band [1]. Consequently, a number of microstrip antennas with different geometries have been experimentally characterized. Moreover, other strategies to improve the impedance bandwidth which do not involve a modification of the geometry of the planar antenna have been investigated [2–4].

The frequency range for UWB systems between 3.1 to 10.6 GHz will cause interference to the existing wireless communication systems, such as, the wireless local area network (WLAN) for IEEE 802.11a operating in 5.15–5.35 GHz and 5.725–5.825 GHz bands, WiMAX (3.3–3.6 GHz and C-band (3.7–4.2 GHz), so the UWB antenna with a single and dual band-stop performance is required. Recently, to generate the frequency band-notch function, modified planar monopoles have been recently proposed [5–8]. In Ref. 5 and 6, different shapes of the slits (i.e., W-shaped and folded trapezoid) are used to obtain the desired band notched characteristics. Multiple and single half-wavelength U-shaped slits are embedded in the radiation patch to generate the single and multiple band-notched functions, respectively [7].

In this article, a novel and compact square monopole antenna with dual band-notch characteristic for UWB applications has been designed and manufactured. In the proposed structure, using an S-shaped slot in the ground plane, we can give an additional resonance at upper frequencies and hence, much wider impedance bandwidth can be produced. A single frequency band-notched characteristic is obtained by applying a pair of