Microstrip resonators for electron paramagnetic resonance experiments
A. C. Torrezan, T. P. Mayer Alegre, and G. Medeiros-Ribeiro

Citation: Rev. Sci. Instrum. 80, 075111 (2009); doi: 10.1063/1.3186054
View online: http://dx.doi.org/10.1063/1.3186054
View Table of Contents: http://rsi.aip.org/resource/1/RSINAK/v80/i7
Published by the AIP Publishing LLC.

Additional information on Rev. Sci. Instrum.
Journal Homepage: http://rsi.aip.org
Journal Information: http://rsi.aip.org/about/about_the_journal
Top downloads: http://rsi.aip.org/features/most_downloaded
Information for Authors: http://rsi.aip.org/authors
Microstrip resonators for electron paramagnetic resonance experiments

A. C. Torrenza,1,a) T. P. Mayer Alegre1,3,b) and G. Medeiros-Ribeiro1,c)  
1Laboratório Nacional de Luz Sincrotron, Caixa Postal 6192, Campinas, São Paulo 13084-971, Brazil  
2Faculdade de Engenharia Elétrica e de Computação, UNICAMP, Campinas, São Paulo 13083-970, Brazil  
3Instituto de Física Gleb Wataghin, UNICAMP, Campinas, São Paulo 13083-970, Brazil

(Received 22 April 2009; accepted 2 July 2009; published online 31 July 2009)

In this article we evaluate the performance of an electron paramagnetic resonance (EPR) setup using a microstrip resonator (MR). The design and characterization of the resonator are described and parameters of importance to EPR and spin manipulation are examined, including cavity quality factor, filling factor, and microwave magnetic field in the sample region. Simulated microwave electric and magnetic field distributions in the resonator are also presented and compared with qualitative measurements of the field distribution obtained by a perturbation technique. Based on EPR experiments carried out with a standard marker at room temperature and a MR resonating at 8.17 GHz, the minimum detectable number of spins was found to be $5 \times 10^{10}$ spins/GHz$^{1/2}$ despite the low MR unloaded quality factor $Q_0=60$. The functionality of the EPR setup was further evaluated at low temperature, where the spin resonance of Cr dopants present in a GaAs wafer was detected at 2.3 K. The design and characterization of a more versatile MR targeting an improved EPR sensitivity and featuring an integrated biasing circuit for the study of samples that require an electrical contact are also discussed. © 2009 American Institute of Physics. [DOI: 10.1063/1.3186054]

I. INTRODUCTION

Electron paramagnetic resonance (EPR) is a spectroscopic tool employed in many areas of science, including chemistry, biology, and physics, for the study of paramagnetic species.1 Traditional EPR systems employing waveguide X-band (8–12 GHz) cavities and inductive detection have sensitivity limited to about $10^{11}$ spins/GHz$^{1/2}$ at room temperature and are not adequate for the study of samples with smaller number of spins. As the minimum number of spins $N_{\text{min}}$ depends on the cavity volume $V_c$, angular resonant frequency $\omega_0$, and unloaded quality factor $Q_0$ as $N_{\text{min}} \propto V_c / (Q_0 \omega_0)^2$, a resonant structure that confines the microwave magnetic field in a smaller volume may increase the signal-to-noise ratio (SNR) at a given frequency.3–5

Unlike traditional EPR waveguide cavities operating in the transverse electric (TE) mode, on which both transverse and longitudinal dimensions scale with frequency, transmission-line resonators operating in the transverse electromagnetic (TEM) mode have their resonant frequency set only by the longitudinal dimension and the effective relative permittivity of the medium $\varepsilon_{\text{rel}}$. This enables the transverse dimensions to be shorter than a half wavelength and the resonator volume to be reduced.

Similarly to a waveguide cavity, transmission-line resonators also allow a paramagnetic sample to be placed in a position where the microwave electric field is minimum and

---

a)Present address: Plasma Science and Fusion Center, Massachusetts Institute of Technology, Cambridge, MA 02139, USA.

b)Present address: Thomas J. Watson Sr Laboratory of Applied Physics, California Institute of Technology, Pasadena, CA 91125, USA.

c)Present address: Hewlett-Packard Labs, Palo Alto, CA 94304, USA.
assess the minimum detectable number of spins at room temperature and to evaluate the functionality of the EPR setup at low temperature are also reported in this section. In Sec. IV we discuss the design and characterization of a MR for improved EPR performance and featuring an integrated biasing circuit. In the conclusion section we summarize the main findings of this work.

II. RESONATOR DESIGN

A. Simulation results

The MR consists of a strip conductor of width \( w \), length \( l \), and thickness \( t \), patterned on a substrate of relative permittivity \( \varepsilon_r \), thickness \( h \), with a ground plane of thickness \( t \), as depicted in Fig. 1(a). The mode of interest is the fundamental quasi-TEM with a half-wavelength longitudinal variation, which corresponds to an axial mode index \( n=1 \). The resonant frequency \( f_0 \) is given by \( f_0 = \frac{n c_0}{2 (l+\Delta l) \sqrt{\varepsilon_r}} \), where \( c_0 \) is the speed of light in vacuum and \( \Delta l \) is a correction due to the fringe electric field at the end of the resonator. The fundamental mode as well as modes with an odd axial mode index has a maximum magnetic field \( Hf_1 \) and a minimum electric field \( E_1 \) in the middle of the MR, which is a suitable location to place the sample. While the length \( l \) determines the resonant frequency, the width \( w \) can be chosen to maximize the quality factor \( Q_0 \). The gap \( g \) between the feed line and the MR determines the coupling of the resonator and its loaded quality factor.

The discontinuity in permittivity and the open structure of the MR makes its analysis involved. Although analytical expressions are available to estimate parameters such as \( \Delta l \) and \( \varepsilon_{ref}^{16} \), a detailed design required the use of the finite element method (FEM) solver HFSS (Ref. 17) for an adequate modeling of the structure. For a compact cavity design, an alumina substrate with permittivity \( \varepsilon_r = 9.4 \) and thickness \( h = 680 \ \mu m \) was employed. A loss tangent of \( 10^{-3} \) was assumed for alumina in simulation.\(^{18}\) The other design parameters of the MR are \( l=6.3 \ mm \), \( w=1 \ mm \), \( g=75 \ \mu m \), and a \( 2-\mu m \)-thick Cu layer. According to the simulated resonance curve shown as a solid black line in Fig. 2(a), the resonant frequency and quality factor of this structure are \( f_0 = 8.27 \ GHz \) and \( Q_0 = 76 \), respectively.

Both in simulation and experiment the unloaded quality factor \( Q_0 \) was computed from the reflection coefficient \( \Gamma \) data using \( Q_0 = (1+\kappa) \frac{f_0}{\Delta f} \). In this expression, \( \kappa \) denotes the coupling coefficient and \( \Delta f \) the frequency curve width at the level where \( |\Gamma| = (1+\kappa^2)^{1/2}/(1+\kappa) \). For an undercoupled resonator, one has \( \kappa = (1-|\Gamma(f_0)|)/(1+|\Gamma(f_0)|) \); for the overcoupled case, \( \kappa = (1+|\Gamma(f_0)|)/(1-|\Gamma(f_0)|) \).\(^{19}\) The Smith chart representation (not shown) of the calculated reflection coefficient indicated an overcoupled regime for this MR. The variation of \( Q_0 \) as a function of \( w \) at \( f_0 = 8.27 \ GHz \) is shown in Fig. 2(b). For small values of \( w \) the ohmic loss is dominant, while for larger values the radiation loss predominates.\(^{20}\)

Both asymptotic cases lead to a decrease in \( Q_0 \) with a maximum quality factor near the designed value \( w=1 \ mm \). The calculated electric and magnetic fields on the top of the alumina substrate are presented in Fig. 3.

B. EPR considerations

Despite its low quality factor \( Q_0 \), which is advantageous for pulsed EPR, the magnetic field and EPR sensitivity in MRs can be comparable to EPR systems employing cavities with much higher \( Q_0 \) due to the smaller MR volume. For a sample placed on the center of the strip conductor, simulation results indicated that an input power of 1 mW generates a microwave magnetic field \( B_1 = \mu_0 H_1/2 = 6 \ \mu T \) at the sample in the rotating frame, where \( \mu_0 \) is the vacuum permeability. This corresponds to a power-to-field conversion factor of \( \Lambda = 0.2 \ \text{mT/W}^{1/2} \). Other commonly employed resonators in EPR X-band setups have similar conversion factors such as \( \Lambda = 0.3 \ \text{mT/W}^{1/2} \) for cylindrical TE_{011} cavities\(^1\) and \( \Lambda = 0.5 \ \text{mT/W}^{1/2} \) for LGRs and dielectric resonators.\(^{21}\) A high conversion factor is desirable for faster spin operations and less sample heating.

With regard to sensitivity, the performance of the MR can be estimated by comparing with a similar EPR setup that employs as a resonant structure an empty TE_{011} cylindrical cavity with radius \( r \) and length \( l_c = 2r \).\(^{10}\)

FIG. 2. (Color online) (a) Measured and simulated resonance curves of the alumina MR with \( w=1 \ mm \) and \( l=6.3 \ mm \). (b) Simulated unloaded quality factor \( Q_0 \) as a function of the strip conductor width \( w \) at \( f_0 = 8.27 \ GHz \) (resonator parameters: \( \varepsilon_r = 9.4 \), \( h = 680 \ \mu m \), \( g = 75 \ \mu m \), and Cu layer thickness \( t=2 \ \mu m \)).

FIG. 3. (Color online) Resonator magnetic and electric fields on the top of the alumina substrate (simulation parameters: input power=1 mW and \( f_0 = 8.27 \ GHz \)).
\[
\frac{N_{\text{minMR}}}{N_{\text{mincyl}}} = \frac{(Q_0 \eta)_{\text{cyl}}}{(Q_0 \eta)_{\text{MR}}},
\]

(1)

where \(\eta = \int V_{\text{cyl}} |H_1| \, dV / \int V_{\text{cyl}} |H_1|^2 \, dV\) is the filling factor, with \(V_{\text{cyl}}\) and \(V_{\text{cyl}}\) denoting the sample and cavity volumes, respectively. The resonator filling factors were calculated from FEM simulations considering an empty cylindrical sample, radius 180 \(\mu\)m and height 40 \(\mu\)m, located at the position of maximum \(H_1\) on the MR conductor. This represents the same condition as in the room temperature EPR experiment described in Sec. III B. At \(f_0 = 8.27\) GHz, the filling factor of the MR was found to be \(\eta_{\text{MR}} = 1.7 \times 10^{-4}\). For a cylindrical cavity operating at the same frequency, the calculated parameters were \(Q_0 = 32.900\) and \(\eta_{\text{cyl}} = 4.9 \times 10^{-7}\) and are in good agreement with results obtained from analytical expressions available elsewhere. \(^1\) These numbers imply that \(N_{\text{minMR}} / N_{\text{mincyl}} \simeq 1\) and indicate a sensitivity on the order of \(10^{11}\) spins/GHz\(^{1/2}\) at room temperature for both configurations.

III. EXPERIMENTS

A. Resonator characterization

The MR was fabricated using standard optical lithographic techniques on a 680-\(\mu\)m-thick polished alumina substrate covered by a 2-\(\mu\)m-thick Cu layer coated with a 200 nm Au film. A picture of the fabricated resonator is shown in Fig. 1(b). The thickness of the metallic layer is greater than twice the skin depth of copper at 8.27 GHz. The employed modulation of the static magnetic field \(B_0\) on the order of few kilohertz can easily reach a sample under the strip conductor due to the open configuration and electrically thin conductive layers of the MR at this modulation frequency. Special arrangements to permit the penetration of the modulated field through the walls of cavities, for example, by inserting slots in the waveguide walls, \(^22\) are not needed here.

The resonance curve of the fabricated resonator was measured using a vector network analyzer, model Anritsu 37347D, and the result is shown as a solid red line in Fig. 2(a). The measured resonant frequency \(f_0 = 8.14\) GHz is in fair agreement with the simulated value \(8.27\) GHz. The quality factor of the cavity was measured to be \(Q_0 = 60\), which is close to the calculated value.

The field distribution on the MR surface was evaluated by means of a cavity perturbation technique. \(^23\) Perturbing a resonator in a region dominated by the electric field produces a downshift in the resonant frequency if the resonator volume is reduced due to the perturbation. The electric field strength in this region is related to the frequency shift by \(E^2 \propto 1 - (\omega / \omega_0)\), where \(\omega\) and \(\omega_0\) are the perturbed and unperturbed frequencies, respectively. An opposite effect should be observed in a region of high magnetic field. \(^24\) The perturbing object used in the mapping consists of a 300-\(\mu\)m-diameter metallic needle aligned in the \(z\)-direction and located 250 \(\mu\m\m\) above the MR surface. Two step motors were used to move the needle over the MR surface. The measured field distribution is shown in Fig. 4 and qualitatively agrees with the simulated one. A small upshift in the resonant frequency could also be observed in the central part of the MR where the magnetic field is maximum.

B. EPR experiments

The EPR spectrometer built in order to evaluate the minimum detectable number of spins is shown in Fig. 5. It consists of a water-cooled copper magnet with an external coil for magnetic field modulation, a solid-state microwave source Agilent 83731B stabilized by a rubidium atomic clock, and a heterodyne system with a lock-in detector SR830 to measure the reflected signal from the MR. The remaining components of the spectrometer are specified in the caption of Fig. 5. The sample used in the experiment at room temperature was a standard marker 1,1-diphenyl-2-picrylhydrazyl (DPPH), volume \(3.94 \times 10^{-12}\) m\(^3\), and it was placed in the middle of the MR on the strip conductor, a region of minimum electric field as observed in the measured field. As the spin density of DPPH is \(2 \times 10^{27}\) spins/m\(^3\), \(^25\) the total number of spins of the sample was \(N_{\text{spin}} = 7.9 \times 10^{15}\) spins.

The measured electron paramagnetic resonance of DPPH at 300 K is shown in Fig. 6(a). The corresponding SNR, defined as the ratio of the peak-to-peak signal amplitude to the root-mean-square value of the noise, was found to be...
SNR=30 000 and the peak-to-peak linewidth $\Delta H_{pp}$ =0.3 mT, in agreement with values reported for DPPH. The experimental minimum detectable number of spins $N_{\text{min}\_\text{exp}}$ was determined by:

$$N_{\text{min}\_\text{exp}} = \frac{N_{\text{spin}}}{\text{SNR} \Delta H_{pp}/\text{ENBW}},$$

(2)

where ENBW is the equivalent noise bandwidth of the lock-in amplifier. From the parameters of the filter set for the experiment, time constant of 30 ms and roll-off of 24 dB/octave, one had ENBW=2.604 GHz, yielding $N_{\text{min}\_\text{exp}}=5 \times 10^{10}$ spins/GHz. This sensitivity is comparable to EPR setups using waveguide cavities as it was suggested by the numerical calculations in Sec. II B.

The functionality of the EPR system was also tested at low temperature. In this condition, the sample consisted of a semi-insulating GaAs wafer with Cr impurities and it was positioned at the midpoint of an alumina MR with resonant frequency of 7.92 GHz. At low temperature, the Cr impurities become paramagnetic and the characteristic multiplet Cr spin resonance could be detected at 2.3 K as shown in Fig. 6(b).

![FIG. 6. (Color online) (a) Measured EPR signal of DPH sample (experimental parameters: microwave power=9.3 mW, $B_1=19$ $\mu$T, $f_0=8.17$ GHz, sample at 300 K, magnetic field modulation frequency =5.3 kHz, lock-in amplifier filter settings: time constant=30 ms, roll-off =24 dB/octave, and ENBW=2.604 Hz) and (b) Measured EPR signal of Cr dopants in a semi-insulating GaAs wafer (experimental parameters: $f_0=7.92$ GHz, sample at 2.3 K, and magnetic field modulation frequency =7.5 kHz).](https://example.com/fig6)

![FIG. 7. (Color online) MR including feed line and biasing circuit.](https://example.com/fig7)

As the microwave magnetic field scales as $H_1 \propto \sqrt{Q_0/V_c}$, the small MR volume compensated its low quality factor, yielding a high filling factor and a sensitivity similar to EPR setups using a high-$Q_0$ cavity. Better performance may be obtained by increasing the resonator filling factor. Following this guideline, an improved MR design was made and is presented in Fig. 7. This design utilizes a GaAs substrate with permittivity $\varepsilon_r=12.9$ and thickness $h=365 \mu$m, covered by a 1.5-$\mu$m-thick Au layer. The GaAs substrate was selected due to its higher permittivity, allowing a further reduction in the resonator size, and by the fact that GaAs substrates are utilized in many mesoscopic devices where the study of spin-related phenomena is of interest. A loss tangent of $2 \times 10^{-4}$ was used for GaAs in simulation. The resonator parameters $l=3.2$ mm, $w=200 \mu$m, and $g=40 \mu$m were tailored for $f_0=15$ GHz and maximum $Q_0$ as shown in Fig. 8.

A dc bias network was also included, allowing EPR experiments in samples that require biasing such as quantum dots. The biasing circuit consists of a radial stub, dimensions $r_{dc}=1.36$ mm and $\theta=26.5^\circ$, and a quarter-wavelength transformer with line width $w_{dc}=30 \mu$m. The circuit is located in a region of minimum electric field, as shown in the calculated field distribution in Fig. 9, in order to minimize any interference in the resonance curve.

The measured resonant frequency $f_0=14.97$ GHz is in good agreement with the simulated value 14.95 GHz, while the measured unloaded quality factor $Q_0=60$ is close to the calculated value 96. Unlike the alumina cavity, the GaAs MR was found to be undercoupled. The measurement was per-
formed directly on a GaAs wafer by means of a coplanar-to-microstrip transition and a coplanar probe connected to a vector network analyzer, model HP8510C. The main advantage of this transition is a virtual ground provided by the radial stub, which has dimensions $l_r=885 \, \mu m$ and $w_r=100 \, \mu m$. This simplifies the fabrication process since no via holes are required to connect the coplanar and microstrip grounds. Comparison between measurements in MRs with and without the dc network showed no perturbation in the resonance curve due to the inclusion of the biasing circuit.

The field distribution was measured in a resonator built on the same 365-\mu m-thick GaAs substrate but with different parameters, $l=4.37 \, mm$, $w=1 \, mm$, and $g=70 \, \mu m$. The measured resonant frequency of this MR is 10.05 GHz and the quality factor $Q_0=50$. The field distribution was measured at $z=100 \, \mu m$ from the MR surface and the result is presented in Fig. 10. Similar to the map obtained for the microstrip transition and a coplanar probe connected to a vector network analyzer. A.C.T. Process No. 04/01228-6, SPM Brazil network, CNPq, and HP-Brazil. The authors are grateful to M. H. Piazzetta and A. L. Gobbi from the microfabrication facility at LNLS for assisting with the fabrication of the resonators and CCS-UNICAMP for the use of the vector network analyzer. A.C.T. acknowledges the receipt of a CAPES fellowship and an IEEE MTT-S Undergraduate/Pregraduate scholarship.

V. CONCLUSIONS

In this work we evaluated experimentally the performance of an EPR setup using a MR. Utilizing a standard marker at 300 K and a MR resonating at 8.17 GHz, the sensitivity of the setup was determined to be $5 \times 10^{10}$ spins/GHz$^{1/2}$. The low MR unloaded quality factor $Q_0=60$, useful for pulsed EPR experiments, was compensated by its high filling factor, yielding a sensitivity comparable to EPR systems using cavities with much higher quality factors such as waveguide cavities. The functionality of the EPR setup was also evaluated at low temperatures where a Cr-doped semi-insulating GaAs was utilized to demonstrate Cr-related spin resonance at 2.3 K using a MR tuned to 7.92 GHz. Scans of the field distribution performed over the MR substrate confirmed that the samples were located in a region of minimum electric field. MRs are easy to fabricate and allow the integration of components close to the paramagnetic sample in a single substrate. An example of such integration was implemented using an integrated dc bias, which allows an electrical contact to the resonator without cavity loading. An improved MR design with higher filling factor and operating at 15 GHz was also explored. The power-to-field conversion factor of this design reached $\Lambda=1.3 \, mT/W^{1/2}$ in the rotating frame according to simulations and the sensitivity was theoretically estimated to be $10^{9}$ spins/GHz$^{1/2}$ at 300 K.

ACKNOWLEDGMENTS

We acknowledge the financial support from FAPESP Process No. 04/01228-6, SPM Brazil network, CNPq, and HP-Brazil. The authors are grateful to M. H. Piazzetta and A. L. Gobbi from the microfabrication facility at LNLS for assisting with the fabrication of the resonators and CCS-UNICAMP for the use of the vector network analyzer. A.C.T. acknowledges the receipt of a CAPES fellowship and an IEEE MTT-S Undergraduate/Pregraduate scholarship.

17 High Frequency Structure Simulator (HFSS), Ansoft LLC, 2005.