Tuner and radiation shield for planar electron paramagnetic resonance microresonators

Ryszard Narkowicz and Dieter Suter
Fakultät Physik, TU Dortmund, 44221 Dortmund, Germany

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Planar microresonators provide a large boost of sensitivity for small samples. They can be manufactured lithographically to a wide range of target parameters. The coupler between the resonator and the microwave feedline can be integrated into this design. To optimize the coupling and to compensate manufacturing tolerances, it is sometimes desirable to have a tuning element available that can be adjusted when the resonator is connected to the spectrometer. This paper presents a simple design that allows one to bring undercoupled resonators into the condition for critical coupling. In addition, it also reduces radiation losses and thereby increases the quality factor and the sensitivity of the resonator. © *2015 AIP Publishing LLC.* [http://dx.doi.org/10.1063/1.4906898]

I. INTRODUCTION

Planar microresonators (PMRs) were developed as alternatives to standing-wave cavities for applications with mass-limited samples.[1,2] For these types of samples, they greatly increase the sensitivity. The resonator designs are based on half-wavelength microstrips (Fig. 1), so that the standing wave fits into the layout in one dimension, while the other dimensions can be significantly smaller. Additionally they contain structures with dimensions smaller than the wavelength, which concentrate the magnetic field in the sample area. Figure 1 shows some examples of these designs.

The lateral dimensions of the microresonator are defined by optical lithography. The metalized traces on top of the dielectric substrates are created by electrodeposition of gold. The ground plane on the bottom of the substrate consists of aluminum, covered by a thin layer of gold.

The designs of the PMRs are optimized to work at a specific resonance frequency and the parameters are chosen such that, at this resonance frequency, most of the microwave power from the transmission line enters the resonator, while the reflection is minimized. The technological process allows to specify the design parameters with a precision of $\approx 1\ \mu$m. The remaining differences between design and implementation result in shifts of the resonator frequency from the target frequency and/or they cause reflections at the target frequency that exceed the level of -30 dB considered to be ideal for electron paramagnetic resonance (EPR) resonators. Some of these deviations can be compensated by placing dielectric materials at specific points of the resonators. This approach is, however, limited. Adjustment of the coupling, while the resonator is operated in the spectrometer, is quite complicated. Most of the planar resonator designs presented in literature do not include variable coupling, but some designs offer this possibility. A fine adjustment of the coupling by inserting quartz rods through the side-holes in the stripline substrate, drilled in the vicinity of the coupling gaps, was implemented in Ref. 3. Drilling holes in the plane of the stripline was facilitated by a rather thick (6.4 mm) stripline stack used. In Ref. 4, the authors coupled microstripline to the waveguide by a ridgeguide transformer and used a tuning stub in the waveguide for coupling adjustments. Another possibility was exploited in Ref. 5. Their folded stripline resonator was rotated with respect to the central conductor of the feedline, thus altering the capacitive coupling between them. In Refs. 6–8, the coupling to the planar loop-gap resonators was achieved by changing the position of the microstrip feedline with respect to the resonator, using a piezoelectric XY stage.

In this paper, we describe an alternative, which allows us to adjust the coupling between the transmission line and the resonator during operation. It is mechanically simple and does not require high-precision positioning devices. We do not alter directly the width of the coupling gap or dielectric permittivity in the vicinity of it but use a movable copper plate that is placed above the planar resonator. In addition to adjusting the coupling, this plate serves as a radiation shield that reduces radiative losses from the open structure of the resonator.

II. THEORY

For optimal sensitivity and microwave power to magnetic field conversion efficiency, it is important to reduce reflections of the resonator at the operation frequency. Best results can be achieved with the adjustable coupling system. It allows to compensate not only for the resonator parameters spread but also for the influence of the sample as well as changing experimental conditions, like temperature, at which measurements are performed. Undercoupled microresonators can be matched by placing dielectric materials above the coupling gap and thus increasing the coupling up to the critical condition. Positioning of the dielectric has to be very precise, which imposes very stringent requirements on the mechanical system used for this purpose. Checking the influence of the shielding on the resonance position and depth, we concluded

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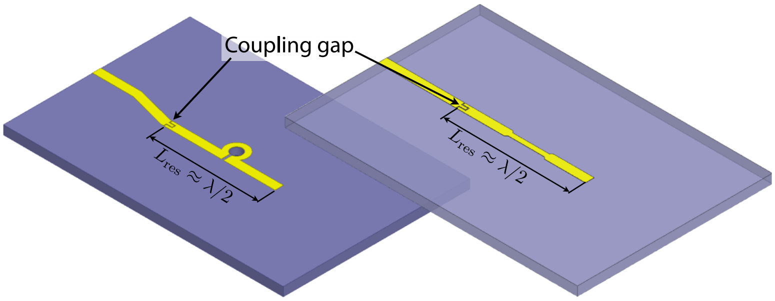

FIG. 1. Design examples of planar microresonators. Ω-shaped microresonators include undersized structures like a loop with the diameter D_s (left panel). Alternatively, a constriction of the length L_s (right panel) can be used to concentrate the microwave magnetic field on the sample. Dimensions of these elements can be adjusted to accommodate point-like or elongated samples, respectively.

that metallic shield above the structure allows for much less restrictive control of the coupling (Fig. 2).

Figure 2 shows the basic design idea for the tuner plate. The dimensions of the tuner plate ($16 \times 12 \times 1$ mm^3) exceed the dimensions of the PMR substrate to ensure effective radiation shielding. The distance between the plate and the sample holder is adjustable, e.g., by a micrometer screw, allowing for fine tuning of the reflection coefficient at the resonance frequency.

For the simulation of this matching system, we used an Ω-shaped PMR with a 500 μm loop on a 0.55 mm thick 12×8 mm^2 C-cut sapphire substrate. A 4.2 mm long Ω-shaped PMR is coupled by a 70 μm gap to the feedline. The PMR is connected to the spectrometer by an SMA connector. Using the commercial simulation software HFSS V.15 (ANSYS), which is based on the finite element method, we checked the conditions necessary to achieve optimal coupling with such a matching element by simulating the system for different distances between tuner plate and resonator.

Figure 3 shows the results of this parametric sweep. The first trace corresponds to a distance of 6 mm between the plate and the PMR (light blue curve). In this case, the PMR is overcoupled with a reflection coefficient of −30 dB. Shifting the plate closer to the PMR increases the coupling, and critical coupling is achieved at a distance of 4 mm. Even smaller distances result in undercoupling, as evidenced by the increase in the reflection and the effective impedance exceeding 50 Ω in the Smith chart. Reducing the distance between the plate and the chip by another 1 mm increases the reflections by 13 dB. Over the whole tuning range of 6-3 mm, the frequency shifts upwards by 17 MHz.

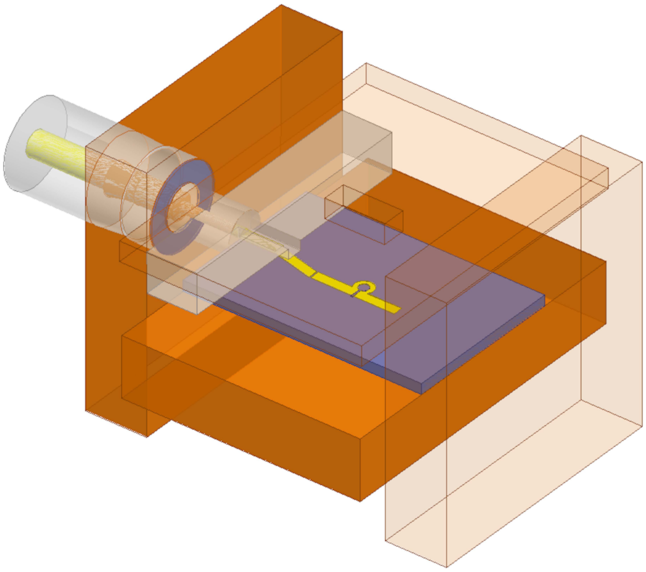

FIG. 2. Design of the tuner plate. A copper plate is placed above the microresonator chip. Moving the plate with respect to the PMR changes the matching of the structure.

III. RESONATOR LOSSES

As an additional benefit, the tuner also reduces radiation losses and therefore increases the sensitivity. The largest losses in the microstrip resonator occur in the metallization. The loss rate resulting from conduction losses $r_r = \frac{\omega_0}{Q_c}$ can be estimated using the expression given in Ref. 9. Here, ω_0 is the resonance frequency and Q_c is the quality factor due to the conduction loss only. In our calculation, we used implementation of similar expression in the transmission line utility (TRL) available in Designer 8.0 (ANSYS). It allows for separate calculation of the conduction and dielectric losses of the microstrip line. The latter are negligible for sapphire substrates. Thick metallization and smooth interfaces of the sapphire substrates contribute to the reduction of conductive losses, so that the radiation losses become comparable to the conductive losses and can strongly influence the quality factor of the PMR. Most of the radiation losses occur through the open space above the plane of the resonator, since the bottom of the substrate is metalized. The tuning plate acts therefore as a radiation shield that eliminates most of this loss mechanism.

The loss rate due to the radiation can be written as[10]

$$r_r = \frac{\omega_0}{Q_r} = \frac{\omega_0 32 Z_0 h^2}{3\epsilon_{eff} Z \lambda_0^2}. \quad (1)$$

Here, Q_r is the quality factor related solely to the radiation, ϵ_{eff} is the effective dielectric constant of the microstrip line, $Z_0 \approx 377$ Ω represents the impedance of free space, $Z = 50$ Ω is the characteristic impedance of the resonator, λ_0 is the free-space wavelength, and h is the thickness of the substrate. Using the value $\epsilon_{eff} \approx 6.71$ and $h = 0.55$ mm, we obtain a radiative loss rate of 0.14 ns^{-1}.

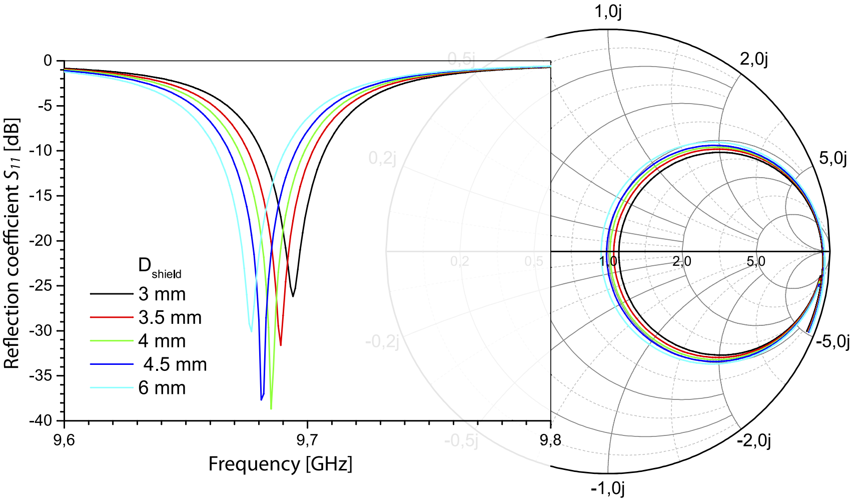

FIG. 3. Simulated coupler performance. The left-hand part shows the reflection coefficient S_{11} as a function of the input frequency, and the right-hand part shows the complex impedance in the form of a Smith chart. In both parts, the distance between the tuner plate and the resonator is varied from 3 to 6 mm.

For the resonator used in the experiment, the radiative and the conductive losses are similar in magnitude. Using the total $Q_{cr} = 76$ from the full-wave simulations, we calculate the total loss rate at the critical coupling condition

$$r = \frac{\omega_0}{Q_{cr}} = \frac{2\pi \cdot 9.7 \cdot 10^9}{76} \mathrm{s}^{-1} \approx 0.8\,\mathrm{ns}^{-1}.$$

For critical coupling, this loss is balanced (50%/50%) between the source and the resonator, so the total resonator losses are half of this value, $r_{res} \approx 0.4$ ns^{-1}. According to the simulation, roughly half of this is due to radiation and the other half due to conductive losses, which results in $r_r \approx 0.2$ ns^{-1}, slightly more than obtained from analytical formula (1). This difference may be due to additional losses in the resonator, which are not included in the analytical calculations. Assuming that analytical formula (1) is exact, the loss rate from non-radiative processes is 0.26 ns^{-1}. The same loss rate was obtained in the full-wave simulations of the critically coupled microresonator with the tuner plate. Enclosing the microresonator in a full metallic shield results in a loss rate of 0.25 ns^{-1}. Thus, full shielding of the microresonator does not significantly reduce radiative losses compared to the tuner plate. Keeping the sides open simplifies the design, allows not only for magnetic field modulation at 100 kHz but also for easy access for RF irradiation in ENDOR experiments or for optical excitation.

IV. EXPERIMENTAL PERFORMANCE

For the resonator used in the experiment, we measured a Q-factor $Q_e \approx 76$ in the absence of the tuner plate. At resonance, the structure was undercoupled with a reflection coefficient of −19 dB. At the critical coupling condition, this corresponds to $Q_{ecr} \approx 68$, slightly smaller than the simulated value.

Figure 4 shows a picture of the mounted resonator, together with a schematic (semi-transparent) representation of the shield, whose distance from the resonator plane can be adjusted by a micrometer screw. As described in Sec. II, the resonator was an Ω-shaped PMR with a 500 μm loop on a 0.55 mm thick 12×8 mm^2 sapphire substrate. For this structure, we measured the reflected power for various distances between the shield and the PMR plane.

Figure 5 shows the resulting tuning curves for different distances between the tuner and the PMR plane. When the tuner plate is mounted at a distance of 6.5 mm, the Q increases from the unshielded value of 76 to ≈100 and the coupling changes from undercoupling to overcoupling. As the distance between the tuner plate and the resonator is reduced, the depth of the resonance increases and the coupling strength decreases, until critical coupling is reached for a distance of 4.5 mm. Closer distance again results in undercoupling. Clearly, the adjustment allows one to optimize the coupling, resulting in an optimal reflection on the order of −39 dB, which is in excellent agreement with the theoretical prediction.

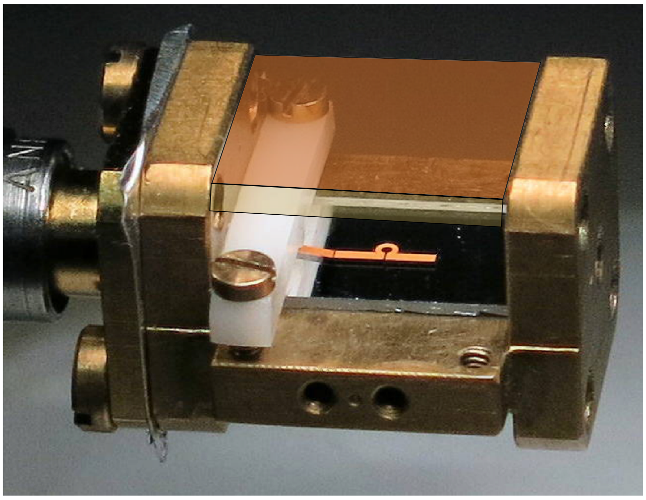

FIG. 4. Picture of the mounted resonator. The shield is shown as a semi-transparent plate. The distance from the PMR plane can be adjusted by a micrometer screw (not shown).

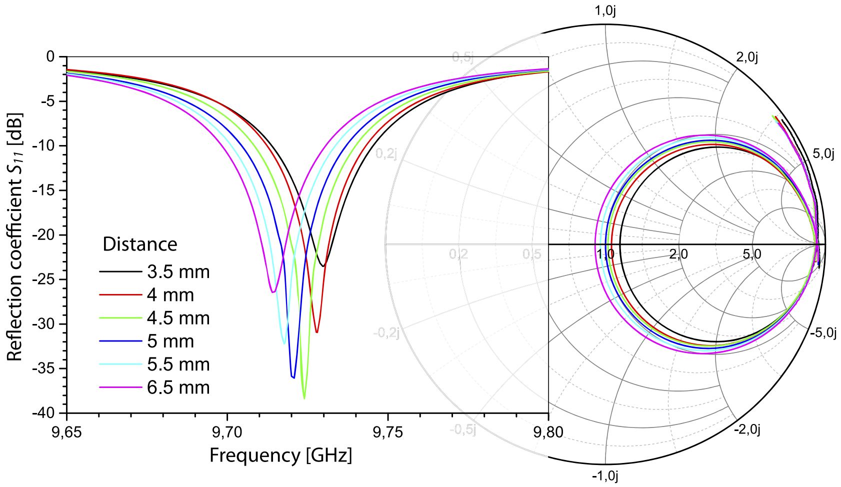

FIG. 5. Resonator tuning curves (reflected power) as a function of the distance between the tuning plate and the plane of the resonator. The right-hand part shows the Smith-chart representation of the same data.

Fig. 6 summarizes the most important parameters from the reflection curves: the depth and the position of the dip. As shown in the figure, the tuner reduces the reflection from the resonator by ≈9 dB. It also slightly shifts the resonance frequency, by approximately 15 MHz, which is comparable to the width of the resonance. The measured and calculated curves show very similar behavior, apart from a shift between the curves.

The measured Q-factor of ≈100 with the tuning plate corresponds to loss rate of $r_{sh} \approx 0.3$ ns^{-1}. Assuming that the non-radiative losses remain constant at 0.26 ns^{-1}, the radiative losses are therefore reduced from 0.14 to 0.04, i.e., by ≈70%.

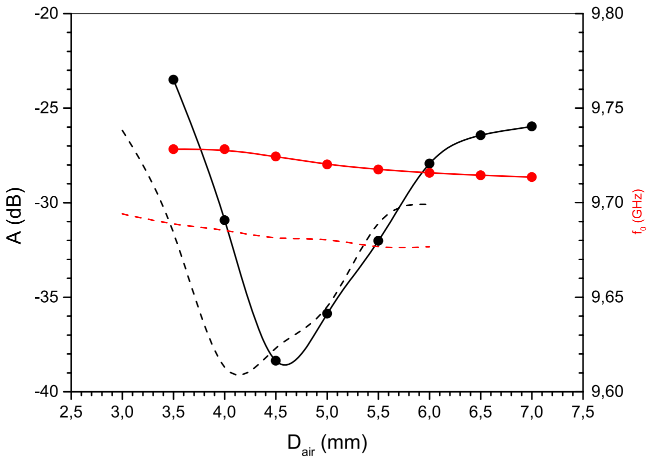

FIG. 6. Simulated (dashed lines) and measured (solid lines) values of minimal reflected power and resonance frequency as a function of the distance between tuner plate and PMR.

V. DISCUSSION AND CONCLUSION

The goal of this work was to find a simple and robust mechanisms for fine-tuning the coupling between planar microresonator structures for EPR and the microstrip-feedline that connects it to the spectrometer. A conducting plate at a distance of a few millimeters above the resonator fulfills these requirements. It allows one to reach critical coupling for slightly undercoupled resonators by first overcoupling them and then gradually reducing the overcoupling when the distance between the tuner plate and the chip is reduced. In addition, it reduces radiative losses by about one order of magnitude. The adjustment can be made online, with the sample loaded and the resonator inside the pole shoes of the magnet. The design does not require modifications to the resonator design, and it can be used with different resonator designs or different substrates.

ACKNOWLEDGMENTS

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