Efficient Probes for Ultra-high-field Magnetic Resonance Microscopy Based on Coupled Ceramic Resonators

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***Abstract*—In this contribution, we present a new radio-frequency probe, a dual dielectric resonator used for transmission and reception of RF signals in Magnetic Resonance Microscopy. The probe is designed as a pair of magnetically coupled ceramic rings with the permittivity of 530 resonating at the Larmor frequency of protons at the magnetic field 17 T (730 MHz). The resonators are made of a unique low-loss ferroelectric composite ceramics, which allows doubling the scanned volume with increased signal-to-noise ratio in comparison to a metal solenoid probe. By adjusting the distance between the resonators and the position of the loop feed placed between them, the probe can be tuned and impedance-matched and does not require capacitors.**

***Index Terms*—Magnetic resonance microscopy, dielectric probe, MRI, ceramics**

I. Introduction

Magnetic Resonance Microscopy (MRM) aims at visualizing tiny details of structured biological samples [1], [2] using the nuclear magnetic resonance effect of protons. In other words, this technique is a special case of Magnetic Resonance Imaging (MRI) adapted for scanning samples with the resolution of better than 100 μm [3]. The achievable resolution is proportional to the static field of the magnet and the Larmor frequency. Therefore, MRM is typically performed on ultra-high-field MR systems with the magnet field of 14-21 T having the frequencies from 600 to 900 MHz.

The microscopy resolution if mainly limited by the Signal-to-Noise Ratio (SNR), which characterizes the capability of the MR-system to distinguish weak RF-signals of spins relaxation over the noise level. The reception is done using special compact resonators called RF-coils or in the case of microscopy, RF-probes. To maximize SNR in the whole sample so-called volume probes are used that are typically designed to fit the sample sizes and minimize the intrinsic noise and the received sample noise. SNR can be increased by time averaging of scanned images, but this approach is time-expansive. As biological samples typically have relatively short life times, increasing SNR by optimizing the probe is one of the most important tasks in MRM. One of approaches is to develop probes with better SNR performance based on new materials.

A standard volume probe used for samples with the dimensions from 1 to 10 mm is the solenoid resonator. It is a copper-wire solenoid wound around the sample and tuned to the Larmor frequency using lumped capacitors. The signal level received by a solenoid probe depends on the density and thickness of wire turns, and its maximization is achieved by following the known guidelines [4]. The intrinsic noise and the sensitivity to the sample noise both can be minimized by proper choice of the solenoid parameters. However, as it was recently shown the SNR provided by the optimal solenoid can be overcome by using all-dielectric resonators instead of copper-wire ones [5]–[8]. The reason for this superior performance is in lower sensitivity to the sample noise (higher loaded Q-factor of the resonator for the same size of the sample). Higher SNR of a ceramic probe, however, requires the dielectric loss tangent of the dielectric to be sufficiently low, and the permittivity to be high [8]. In our previous work we have demonstrated a two-fold SNR enhancement in 17 T MRM over the optimal solenoid by using a single annular-ring dielectric resonator made of the ferroelectric ceramics based on (Ba,Sr)TiO_3 solid solution with Mg-contained additives (BSM) [9]. The resonator was build and tested for a cylindrical sample of diameter 4.5 mm and length 12 mm with $\varepsilon_{\mathrm{s}} = 50$ and $\sigma_{\mathrm{s}} = 1$ S/m. The ceramics had the permittivity $\varepsilon_r = 536$ and the dielectric loss tangent $\tan\delta = 8 \cdot 10^{-4}$ at the Larmor frequency of 730 MHz. Due to the reciprocity principle, the reduced sample noise can be explained by lower electric field in the sample created by the ceramic probe in the transmit mode than one of the optimal solenoid.

In this work we demonstrate that it is possible to increase the SNR in 17 T MRM using low-loss ceramic resonators not only within the same scanned volume, but even in an enlarged

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one. With this aim we numerically analyze the dual probe based on two coupled BSM ring resonators. Both resonators are similar to one used in the previous work and the new dual probe is compared in this work with the same optimal solenoid. We demonstrate that the dual probe can be easily tuned and matched without lumped capacitors and provides higher SNR than the optimal solenoid over a double field of view.

II. Description and Simulation of Dual Ceramic Probe

A. Design, tuning and matching

As follows from the numerical comparison of the single BSM-ring probe with the optimal solenoid from our previous work, the benefit in SNR was equal to 2.2 [8]. Here we propose to make a probe of two identical ring resonators excited by a small loop feed, symmetrically placed between the two resonators as shown in Fig. 1(a). The arrangement of the resonators and loop is similar to one proposed in [6]. However, in our case both resonators have central holes so that two samples of the same size (4.5-mm thickness and 12-mm length) can be simultaneously accommodated by the probe. In the numerical simulations made with CST Microwave Studio, we used the same ceramics and the same sample material properties as specified above. Moreover, for comparison we consider the same solenoid as in our previous work optimized for the chosen sample (hereinafter referred to as the reference probe). It has the length $L = 12$ mm, $N = 4$ turns, average diameter $D = 7$ mm, and is made of copper wire with the diameter of 1.5 mm. Unlike the proposed dual ceramic probe, the reference solenoid contains only one sample of the given size.

While for tuning to 730 MHz the solenoid required a lumped capacitor (with capacitance of approximately 1 pF), the proposed dual probe is self-resonant. Indeed in the system of two magnetically-coupled dielectric ring resonators two eigenmodes can be excited: the even and odd modes coming from hybridization of the $TE_{01\delta}$ of a single ring resonator. In the considered symmetric feeding configuration only the even mode can be excited, where a strong magnetic field with the same magnitude and phase is induced in both resonators. The axial shift d of the feed in z-direction changes the coupling of the 50-Ohm port connected to the loop with the even mode. As a result, by adjusting d one can control the impedance of the dual probe at the resonance. At the same time, the separation s of the two ring resonators affects the mutual coupling between them, and, therefore, can be used to finely tune the resonance frequency of the even mode.

The numerically calculated frequency dependencies of $|S_{11}|$ of the probe based on two resonators with height $H = 10$ mm, outer diameter $D_\mathrm{o} = 18$ mm and inner diameter of $D_\mathrm{i} = 5.6$ mm for different d and s are shown in Fig. 1(b) and Fig. 1(c) correspondingly. The feeding circular loop had the average diameter of 4 mm and was made of a 0.5-mm0thick copper wire. It is clearly seen that the feed shift d mostly controls matching, while the separation s is responsible fore fine tuning. The matched probe tuned to 730 MHz has $d = 0.5$ mm and $s = 11.25$ mm and did not require any lumped capacitors to operate at 730 MHz.

B. RF-field and comparison to reference probe

When the proposed probe is tuned to 730 MHz and matched to 50 Ohm, one can numerically calculate the ratio between the RF magnetic field magnitude in the center of each sample $|H_0|$ and the square root of the accepted power P_acc when the port in the transmit mode is driven by the port. This ratio called the transmit efficiency due to the reciprocity principle is proportional to SNR when the same probe is used for reception. Therefore, to compare two different probes in terms of SNR it is sufficient to compare their $|H_0|/P_\mathrm{acc}$ values. Here we compare the proposed dual probe with the reference probe by calculating the magnitude distribution of H-field created by each probe with the same 1 W accepted power. In Fig. 2(a) the geometry of the reference solenoid probe is presented with the same given sample placed within. The field of the reference probe in YZ-plane is shown in Fig. 2(b) and the field of the dual probe can be found in Fig. 2(c). From the comparison of the field patterns it is clearly seen that the proposed dual probe creates higher H-field magnitude simultaneously in two samples than the reference probe creates only in one sample. This effect can be explained by a drastically higher loading Q-factor of the proposed probe than the reference one due to lower electric fields created in the sample in the transmit mode for the same accepted power along with low intrinsic losses. Indeed, the H-field of the proposed probe is 378 A/m, while the reference probe provides only 245 A/m for the same power. The ratio of the fields is 1.55 which is the estimation of the SNR gain provided by the proposed probe in comparison to the reference one in the receive mode.

III. Conclusion

Our numerical simulations have shown that the proposed dual probe based on two coupled ring BSM ceramic resonators provides the SNR gain of more than 1.5 over the optimal solenoid being capable of scanning two samples simultaneously. Moreover the advantage of the proposed probe is that it does not require any capacitors for tuning to the Larmor frequency and matching to 50 Ohm. Instead, both settings are done by adjusting the resonators' and loop's positions. The future work is the analysis of the SNR gain as a function of the sample material properties and experimental comparative study in MRI. The proposed dual probe due to low losses in the ceramic material and low received sample noise can be a useful solution for obtaining microscopy images of two biological sample at the same time, with higher SNR than microscopy of a single sample with the optimal solenoid probe.

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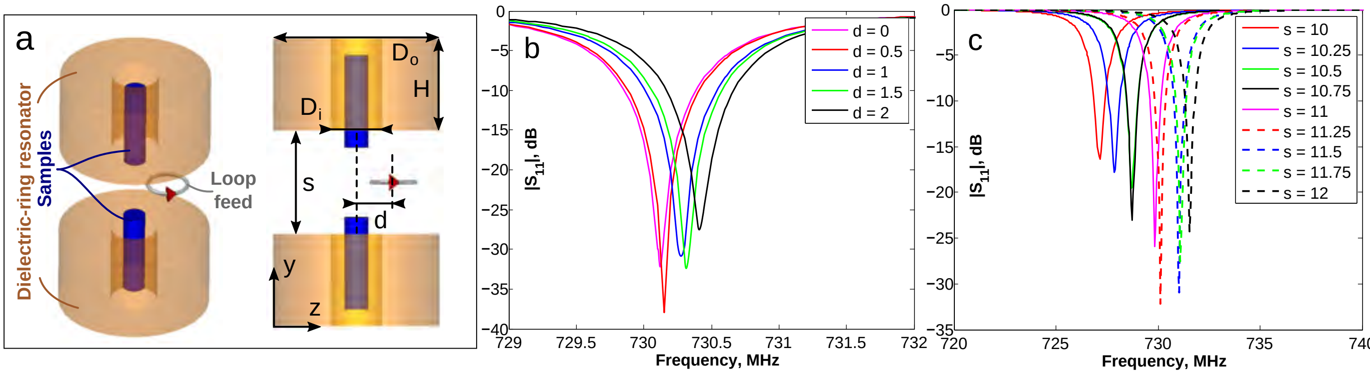

Fig. 1. Proposed dual probe based on two ceramic ring resonators fed by a loop with 50-Ohm port: (a) geometry of probe; numerically calculated S_{11} vs. frequency for different axial shifts d of feed (b) and separations s of resonators (c).

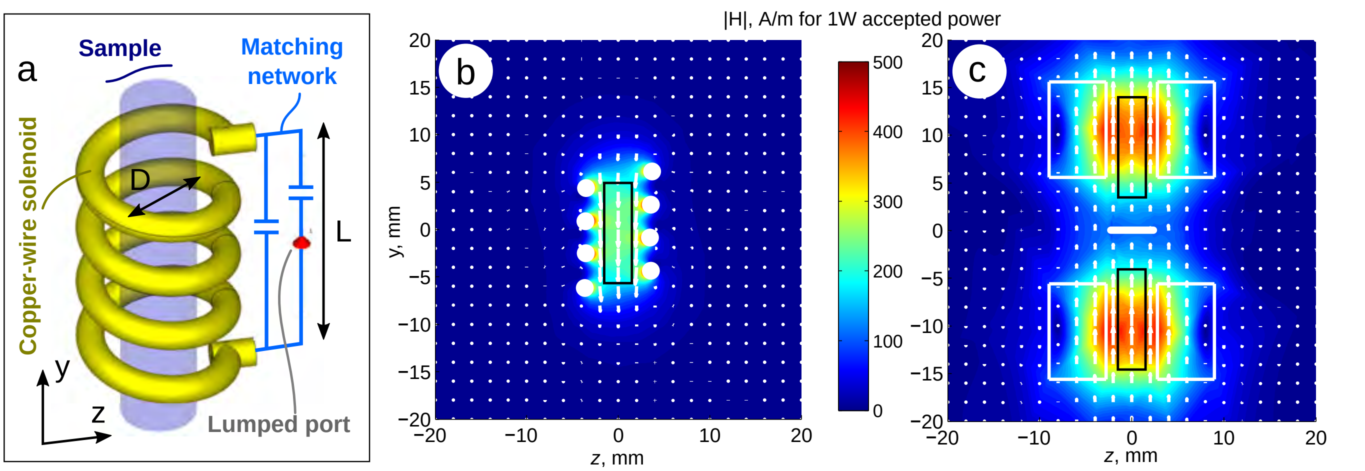

Fig. 2. Reference solenoid probe (a) and numerically calculated magnetic field magnitude distributions in YZ-plane created by the reference probe (b) and the proposed dual probe (c) for 1 W of accepted power.

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