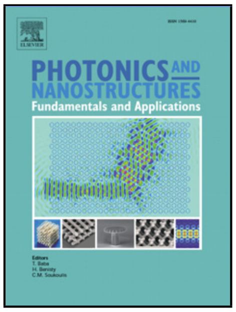

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Surface coil based on a dielectric resonator tuned to the higher-order modes

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Highlights

- The first demonstration of a dielectric resonator operating at third-order mode as receive coil for magnetic resonance imaging.
- Receive sensitivity of dielectric resonator is higher in comparison with a conventional metallic loop coil of the same dimensions.
- Spatial coverage of dielectric resonator is up to 9-fold more extensive than the coverage of the optimal small loop coil.
- Higher-order modes of dielectric resonator could be useful for skin magnetic resonance imaging that needs extensive spatial coverage combined with maximum receive sensitivity at the low depths.

Abstract.

Magnetic resonance (MR) images spatial resolution, which is a key factor in early diagnosis of many diseases, is fundamentally limited by the signal-to-noise ratio, which in turn depends upon the efficiency of the receive radiofrequency coils design. Many various multi-channel coils were designed to improve the quality of MR images. Another way to enhance the quality of magnetic resonance imaging (MRI) is the implementation of resonators based on novel materials, such as high-permittivity dielectrics. Here, we investigate the potential for the sensitivity enhancement with higher-order modes of dielectric resonators. We numerically show that because of the unique near field spatial distribution of a dielectric resonator third-order mode, the receive performance can be substantially improved in comparison with a conventional metallic loop coil of the same dimensions. Moreover, we study the performance of the dielectric resonator in comparison with a metallic loop coil, which size was optimized to match the sensitivity of the resonator at a particular distance. We demonstrate a 9-fold larger planar field-of-view with the dielectric resonator than with the loop coil. Our work provides the design guidelines for the improvement of near-field MRI sensitivity with the dielectric resonators.

Keywords: dielectric resonators, receive radiofrequency coils, MRI, SNR enhancement.

1. Introduction

Magnetic resonance imaging (MRI) is one of the most important non-invasive imaging techniques for human diagnostic medicine and monitoring of the efficacy of therapeutic interventions, as well as being widely used in preclinical studies for drug development, and fundamental neuroscience. Receive radiofrequency (RF) coils are used to receive magnetic resonance (MR) signal and, thus, provide a crucial contribution to the sensitivity (i.e., signal-to-noise ratio (SNR)) of an MR experiment. Standard volumetric and surface RF coils for MRI are usually constructed from the metallic conductors accompanied by the tuning and matching circuits based on the lumped elements [1]. The development of the RF equipment for MRI has resulted in a variety of designs optimized for specific clinical applications [2]. Most frequently, the RF surface coil design consists of wires or strips, with distributed capacitive elements for tuning the coil to the desired operating frequency. A combination of several surface coils or dipole antennas is called an array. The coil array represents a methodology to gain a higher SNR over a large region-of-interest and/or accelerate MR signal acquisition.

As an alternative, one can replace conventional metal coils with high permittivity dielectric materials [3]. Different dielectric materials can be used to form a resonator depending on a frequency and specific applications, for example, water-based resonators [4-6], ceramic-based structures [7-10], and even resonators based on an artificial dielectric [11]. These dielectric resonators can be used for local and global RF shimming (i.e., spatial shaping of the RF field), SNR enhancement, design of transmitting/receive arrays with a very low electromagnetic interaction between the elements. A frequency of operation of dielectric resonators is determined by the shape, dimensions, and permittivity of the dielectric material. While dielectric resonators may support a large number of electromagnetic eigenmodes [12], in all recent works, only the lowest frequency eigenmodes were considered. For example, dielectric resonators operating in the low-frequency transverse electric (TE) [13,14] and hybrid electromagnetic (HEM) [7,8] modes have been employed. On the other hand, higher-order modes have features in their near-field profile, which can be promising for SNR and field-of-view improvement for specific MRI applications.

In this paper, we present a detailed analysis of the potential usage of higher-order modes of dielectric resonators for MRI. For this purpose, we studied a compact rectangular dielectric resonator with the relative dielectric permittivity of 2500. Due to the unique spatial distribution of the near electromagnetic field of the dielectric resonator third-order mode, the receive sensitivity can be substantially improved in comparison with the regular metallic receive loop coil with the same spatial dimensions. Moreover, we revealed that a smaller metallic loop coil with the dimensions optimized to achieve the same level sensitivity as the studied dielectric resonator at a particular distance from the surface had a 9-fold smaller field-of-view in comparison with the dielectric resonator operating at the third-order mode.

2. Results & Discussion

The geometry of the studied rectangular dielectric resonator is shown in Fig. 1A. We considered the resonator with the following dimensions: lateral length $L_{dielectric}$=76 mm and height h=10 mm. The permittivity of dielectric material was ε=2500 and loss tangent tgδ=0.0004 (at 123 MHz). The material with similar properties (even with larger permittivity) can be potentially realized with the aid of ferroelectric ceramic materials based on $BaSrTiO_3$ (with some additives) [16-18]. The size and permittivity of the resonator were optimized to maintain compact dimensions. The resonator was placed on the surface of a phantom, imitating the loading by a human body, with a relative permittivity of 38 and electrical conductivity of 0.5 S/m, with a thickness of 150 mm, width of 300 mm and length of 300 mm.

We performed the full-wave numerical simulations of the electromagnetic field by using the frequency domain solver of the CST Microwave Studio 2019. Perfectly matched layer boundary conditions were used to prevent possible reflections. A hole with a 10 mm diameter was made in the middle of the dielectric resonator to place a small loop antenna with a diameter of 5 mm for the reception of the RF magnetic field (Fig. 1A). The loop itself has a resonance at the GHz frequency range, and therefore it did not interfere with the resonance of the dielectric resonator. Fig. 1B demonstrates the reflection coefficient (S_{11}) of the loop placed within the resonator. The minima of the reflection coefficient are associated with excitation of the three modes of the resonator. Each eigenmode is characterized by a certain distribution of the near magnetic field (see the inset in Fig. 1B) with different penetration depths. Here and below, we are interested in the area in close proximity to the resonator, so the distance between the resonator and the area of interest is 10 mm in the depth of the phantom. In practice, this can be used for skin MRI studies that assess skin morphology [19,20], characterize skin lesions and skin thickening as a preclinical sign of breast cancer [21].

The first eigenmode of the proposed dielectric resonator corresponds to the first TE mode of the dielectric resonator, which was well studied in MRI previously [10]. The second eigenmode has a non-uniform distribution of the near magnetic field, and therefore, it is not in the interest of our research. Thus, here the focus of our study is the third eigenmode, which is strongly localized near the dielectric resonator.

To characterize the receive sensitivity of the dielectric resonator, we considered the ratio of the left circularly polarized transverse component of the RF magnetic field (B_1^-) to the square root of the power loss within the phantom (P_{loss}). This ratio corresponds to the estimation of a direct impact of the receive coil on the SNR of the MR images [15]. RF magnetic field (B_1) is applied perpendicular to the main magnetic field (B_0) to excite and receive the MR signal. B_1^+ is a right circularly polarized transverse component of an RF magnetic field produced by the transmit coil. B_1^- is an RF magnetic field, which would create a receive coil if it were a source based on the principle of reciprocity [15]. The polarization of the B_1-field in the sample depends on the operating frequency of the MR scanner and the electrical properties of the sample [22].

To compare the dielectric resonator performance with standard approaches, we designed two conventional metallic loop coils. Both loops were optimized in the presence of the phantom (with the same parameters as in the case of the dielectric resonator). The biggest loop coil had the same dimensions as the dielectric resonator (see inset in Fig. 2). It was tuned to operate at the same frequency as the third mode of the dielectric resonator (i.e., 234.5 MHz) with the aid of additional capacitors (c1 = 5 pF for fine-tuning, and c2 = 13 pF; c3 = 145 pF placed in parallel for matching). It is worthwhile noting that depending on the nominal capacitor value, the losses were added to the simulation [23]. For designing the second loop, the target was to achieve the same sensitivity value as for the dielectric resonator tuned to the third eigenmode at a depth of 10 mm in a phantom. The simplest way to increase the sensitivity of the loop coil is to reduce its size. Therefore, loop coils with different sizes were considered, and their sensitivity profiles were calculated (see Fig. 2). The loop with a lateral length of L=23 mm has the same sensitivity value as for dielectric resonator (compare dark blue and light blue curves). To design the small loop coil the following capacitors values were used: c1 = 34 pF; c2 = 24 pF; c3 = 4 pF.

Figure 3A shows numerically calculated receive sensitivity maps for the different setups at the frequency of 234.5 MHz (the frequency of the third eigenmode of the dielectric resonator with current dimensions). The sensitivity value was considered in the entire area of interest at the 10 mm distance within the phantom (see the black dashed lines in Fig. 3A). The bigger loop (L=76mm) has the lowest sensitivity in the area of interest: 9-fold smaller in comparison with the dielectric resonator at a depth of 10 mm. For the smaller loop, the receive sensitivity value is similar to the value obtained with the dielectric resonator in the central point of the area of interest (see Fig. 3B). However, the field-of-view of this loop coil is 9-fold smaller in comparison with the dielectric resonator tuned to the third eigenmode (Fig. 3C). Thus, the dielectric resonator can be considered as an excellent alternative to the standard metallic loop coil in terms of efficiency and spatial coverage (field-of-view).

The reason for a better receive sensitivity of the dielectric resonator in comparison with a metal loop coil (of the same dimensions L=76mm) is caused by two factors. Primarily, the dielectric resonator allows redistributing the electromagnetic field more optimally, localizing the magnetic field in close vicinity to the structure while minimizing the electric field in this area. So, usage of the dielectric resonator tuned to the higher-order modes is a good solution for MRI studies at the surface layer (i.e., a 1-2 cm depth). Secondly, dielectric resonator with small electrical losses has a 6-fold higher Q factor at the frequency of 234.5 MHz than the metallic loop coil of the same size.

In order to investigate the influence of the loss level in the dielectric resonator on the receive sensitivity simulations were performed with different values of the loss tangent of the dielectric material (i.e., tgδ=0.004; tgδ=0.04 at 123 MHz). An increase of losses of the dielectric material by 10-fold leads to a decrease of receive sensitivity by 30% on average at the 1 cm depth. The higher losses value of 0.04 led to a 40% reduction of the receive sensitivity value in comparison with a small loop coil (L=23) in the central point of the area of interest. However, still, the receive sensitivity of the dielectric resonator (with tgδ=0.04) remained 90% higher in comparison with the loop coil of the same dimensions.

As mentioned above, the receive sensitivity of the large loop can cover a large region, but at the same time, the coil captures more thermal noise from the body. A small loop captures less noise than a large one, but its sensitivity profile is restricted to a very small region close to the loop. To realize the same planar coverage with the small loops as with a single dielectric resonator, an array of nine overlapping loops should be created. However, a resulting receive sensitivity of such array will be decreased by residual coupling of the loops and losses imposed by the decoupling elements. It was previously shown that dielectric resonators tuned to the lowest TE mode exhibit low coupling between adjacent resonators due to the field concentration within high permittivity materials and, therefore, can be used as MRI transmit arrays [10]. In order to investigate this effect for the third mode, we evaluated a coupling of two dielectric resonators. The second identical dielectric resonator was placed at a distance of 2 mm from the first one, and the transmission coefficient (S_{12}) between two small loop coils placed in the central holes was calculated. An inherent decoupling of the two dielectric resonators is below -10 dB for the third mode, which is slightly larger than values calculated for the first mode [10], but still appropriate

3. Conclusions

In this work, we have investigated a novel design of the surface MR coil based on a high permittivity dielectric material. The results show that the higher-order mode of the dielectric resonator is characterized by the higher receive sensitivity for shallow depths and thus may be more appropriate for specific MRI applications. With this, receive sensitivity of the dielectric resonator is 9 times higher than the conventional loop coil of comparable size (at a depth of 10 mm). At the same time, its spatial coverage is up to 9-fold more extensive than the coverage of the optimal small loop coil. The resonator of this type could be useful for specific applications that need extensive spatial coverage combined with maximum receive sensitivity at the low depths such as skin MRI [19-21].

The proposed here surface coil based on the dielectric resonator is receive-only. Thus, to detune it during the transmit stage, one can implement a method based on mode-disruption [24]. In particular, to perturb the electromagnetic field, several gapped copper strips interconnected via PIN diodes can be added to the sides of the dielectric resonator. The addition of such conductive strips alters the electromagnetic mode structure resulting in a frequency shift, which can be used to detune the dielectric resonator while the transmission is performed.

An approach of near-field MRI sensitivity enhancement with the dielectric resonators can be applied at different field strengths, including both clinical (3T) and ultra-high field (7T) scanners. Moreover, it is possible to use novel types of near field distributions of dielectric resonators, e.g., similar to anapole like [25], which in some cases [26] can be characterized by a near-zero electric field and maximized magnetic field amplitude in the center of the structure. The peculiarity of the anapole near field pattern is that the electromagnetic field concentrates inside the dielectric resonator and does not go beyond. In practice, such a redistribution of fields is well suited for dielectric resonators of cylindrical shape with a hole inside, where the studied object could be located, e.g., for MR microscopy [27].

Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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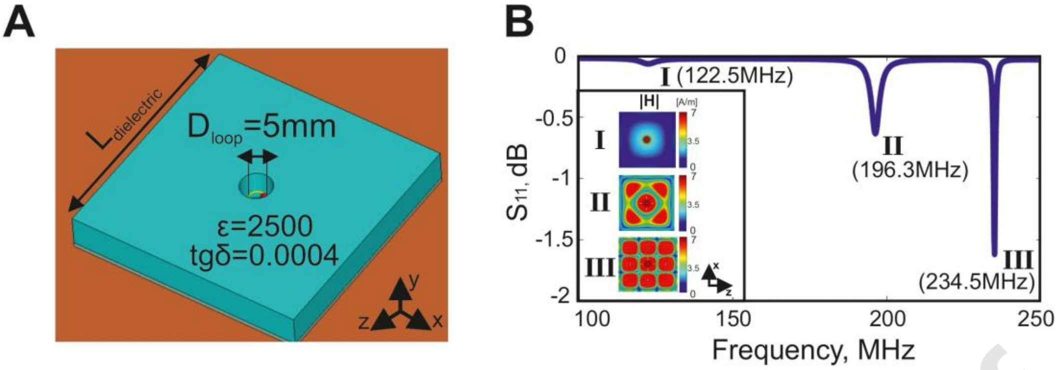

Fig. 1. A. Schematic view of the geometry of the dielectric resonator (light blue color) placed on the top of the body phantom (orange color). B. The reflection coefficient of a non-resonant small loop antenna placed in the middle part of the resonator. The inset shows the magnetic field distribution of different eigenmodes of the resonator.

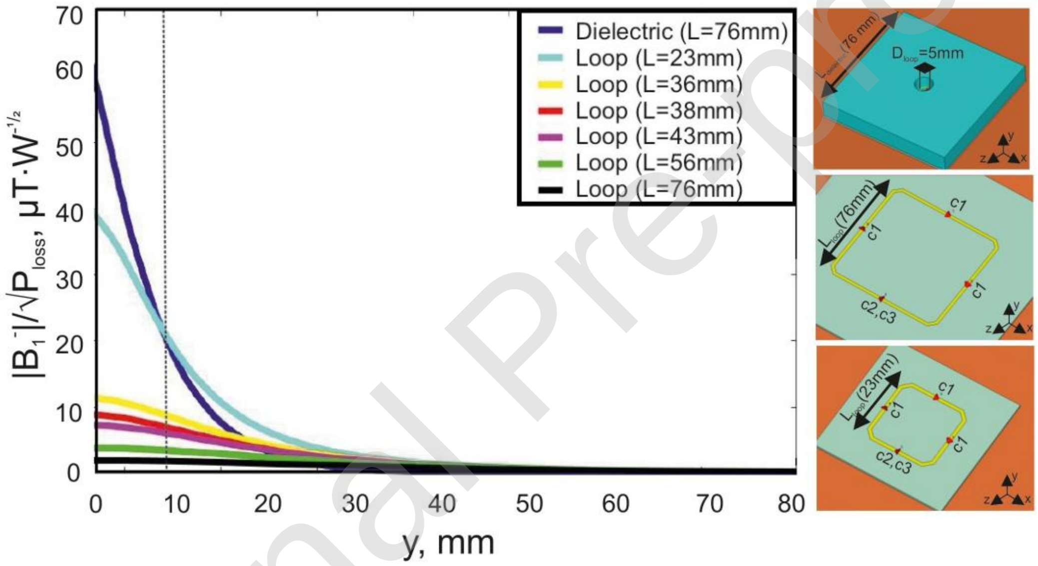

Fig. 2. The receive sensitivity ($|B_1^-|/\sqrt{P_{loss}}$) profiles at the center of the phantom along the y-axis for dielectric resonator and loops of different sizes. The black dashed line indicates a depth of 10 mm in the phantom. The insert schematically demonstrates the geometries of the dielectric resonator, big (L=76 mm), and small (L=23 mm) loop coils.

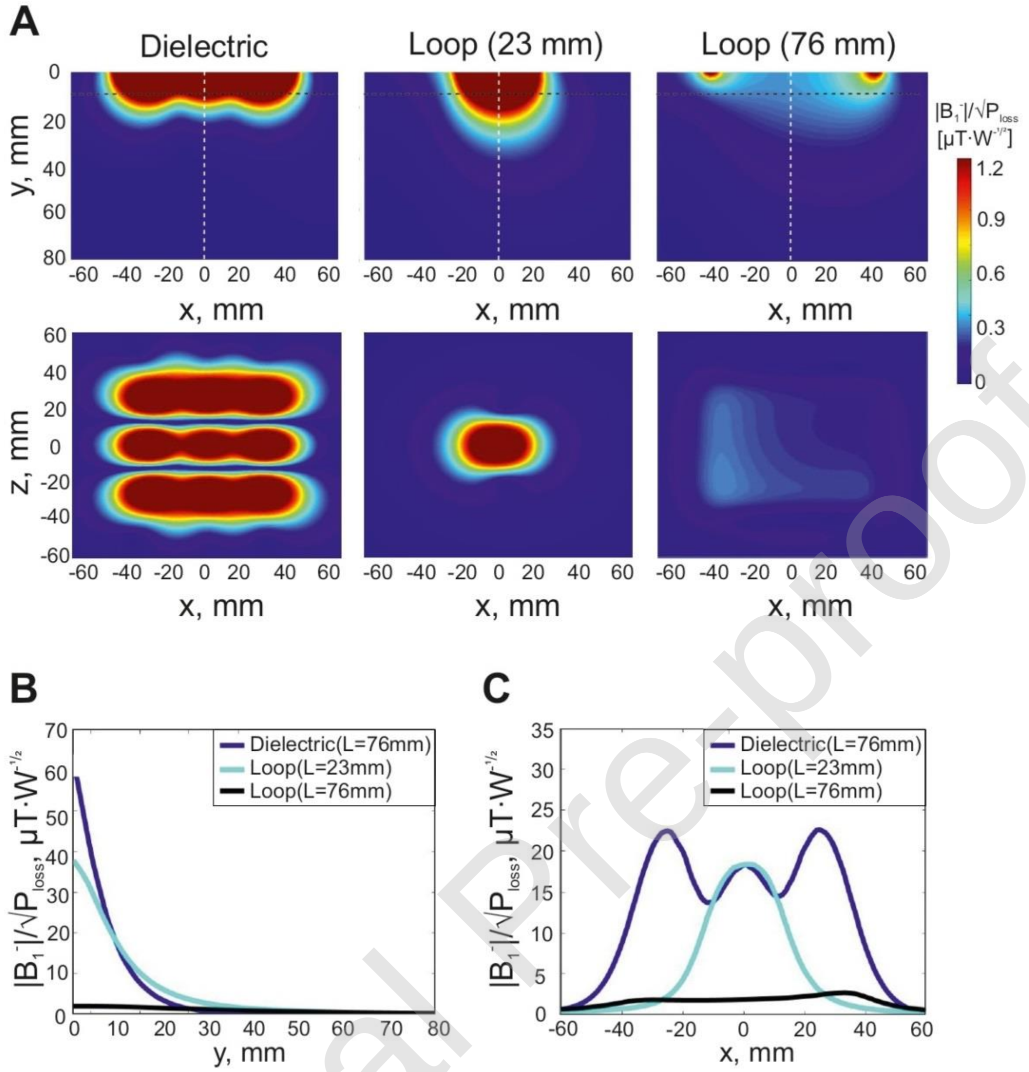

Fig. 3. A. The receive sensitivity ($|B_1^-|/\sqrt{P_{loss}}$) maps for three different structures: dielectric resonator, big (L=76mm), and small (L=23mm) loop coils located on the top of a rectangular phantom in xy-plane (from the beginning of the phantom and to a depth of 8 cm) and in xz-plane (at a depth of 10 mm). The receive sensitivity profiles (B) along the y-axis (along with the white dashed line), and (C) along the x-axis (along with the black dashed line) for the dielectric resonator (solid navy blue curve), small loop coil (solid blue curve), and big loop coil (solid black curve).