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A new quadrature annular resonator for 3 T MRI based on artificial-dielectrics

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ABSTRACT

Dielectric resonators have previously been constructed for ultra-high frequency magnetic resonance imaging and microscopy. However, it is challenging to design these dielectric resonators at clinical field strengths due to their intrinsically large dimensions, especially when using materials with moderate permittivity. Here we propose and characterize a novel approach using artificial-dielectrics which reduces substantially the required outer diameter of the resonator. For a resonator designed to operate in a 3 Tesla scanner using water as the dielectric, a reduction in outer diameter of 37% was achieved. When used in an inductively-coupled wireless mode, the sensitivity of the artificial-dielectric resonator was measured to be slightly higher than that of a standard dielectric resonator operating in its degenerate circularly-polarized hybrid electromagnetic modes (HEM_{11}). This study demonstrates the first application of an artificial-dielectric approach to MR volume coil design.

1. Introduction

Radiofrequency coils used for MRI are conventionally constructed from metallic conducting elements with appropriate lumped element tuning and impedance matching networks [1–3]. Common geometries include multi-rung volume coils such as the birdcage [4] and transverse electric mode (TEM) [5] resonators, circular/rectangular/hexagonal/pentagonal/triangular surface coils (either as single resonators [6] or as individual elements in a multiple element transmit [7] or receive [8] array), and dipoles for ultra-high field applications [9].

An alternative to using standard conductors is to construct dielectric resonators consisting of high permittivity materials [10]. When designed to operate using the two frequency-degenerate circularly polarized hybrid electromagnetic modes (HEM_{11}), resonators using either water [11] or high permittivity ceramics [12] have been shown to form electrically efficient and mechanically simple and robust structures. The sensitivities of these dielectric resonators have been compared to conventional structures of the same dimensions and been found to be essentially identical for volume resonators [11], and also when used as individual elements in a transmit array [13].

Dielectric resonators have primarily been demonstrated at ultra-high field strengths, where the dimensions of the resonators are tractable. However, at clinical field strengths (3 Tesla and below) the dimensions, specifically the outer diameter of the resonator, are too large to be practical. In the present study a novel design of a *compact* annular volume resonator based on the combination of high permittivity materials and an array of nonmagnetic metallic wires is presented. Throughout this paper we refer to this type of structure as an artificial-dielectric. Composite structures made of metal inclusions were actively investigated after the second world war and were named artificial-dielectrics [14–16]. These artificial materials were characterized by enhanced values of the effective permittivity and were mainly used as materials for microwave lenses. The development of artificial-dielectrics was an important step toward to the concept of 'metamaterials' – novel materials with artificially created electromagnetic properties [17,18]. Nowadays, the term metamaterial has expanded to include many classes of previously-developed materials such as artificial dielectrics, artificial magnetics, chiral and bi-anisotropic media which exhibit unusual features [19,20]. Although there have

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been many previous examples of using “metamaterial” structures for MRI, the vast majority have been surface elements [21–24]. In this work we demonstrate the first application of an artificial-dielectric in a volume coil design. The artificial-dielectric resonator operates as a passive wireless structure which is electromagnetically coupled with the body transmit coil on a commercial 3 Tesla clinical MRI system. Electromagnetic simulations and phantom verification of the performance of the proposed resonator are presented, and compared to those of a physically larger conventional dielectric resonator.

2. Methods

2.1. Electromagnetic simulations

Dielectric resonators support a large number of electromagnetic modes, the frequencies of which depend upon the particular geometry and relative permittivity of the material used [25]. For MRI it is ideal to use a mode which is circularly polarized, thereby taking advantage of the reduced transmit power and increased signal-to-noise of quadrature operation. A cylindrical dielectric resonator, shown schematically in Fig. 1(a) supports two such frequency-degenerate orthogonal hybrid electromagnetic (HEM_{11}) modes. An artificial-dielectric resonator, shown schematically in Fig. 1(b), also supports a set of eigenmodes, which are the result of electromagnetic coupling between identical resonant wires separated by a distance much smaller than the wavelength [24]. This type of structure is analogous to metamaterials proposed for optical applications [20]. Each mode is characterized by different distributions of magnetic and electric fields with a fundamental eigenmode, which is similar to the HEM_{11} mode of the conventional dielectric resonator and a produces a homogeneous magnetic field distribution in the region-of-interest.

In this investigation the mode-of-operation of the two resonators were as wireless coils, inductively coupled to the body coil and operated in quadrature for both transmit and receive. The exact dimensions of the annular dielectric resonator and artificial-dielectric resonator were derived numerically using the frequency domain solver in a commercial software package (CST Microwave Studio 2017, Darmstadt, Germany). Perfectly matched layer boundary conditions were used to prevent possible reflections. In the first set of simulations, the structures were excited by a linearly polarized plane wave propagating along the *x*-direction with the electric field parallel to the *z* axis. The permittivity of distilled water was set to a value of 78 with a conductivity of 0.006 S/m. The inner diameter and length of the annular dielectric resonator were fixed as d = 110 mm and h = 222 mm, respectively. Magnetic and electric field distributions of the fundamental modes and their resonant frequencies for both the annular dielectric resonator and artificial-dielectric resonator as a function of the outer diameter were calculated using a parametric sweep. The second (full) set of simulations used the frequency domain solver and included the transmit body (birdcage) coil (inner diameter 70 cm, length 173 cm), and a homogeneous cylindrical phantom with relative permittivity of 81 and electrical conductivity of 0.6 S/m, with a radius of 33 mm and length of 395 mm enclosed within a polymethylmethacrylate (PMMA) tube, thickness 5 mm and $\varepsilon_r = 3.5$. An additional space ($\lambda/2$) between the structure and the boundaries was used in order to prevent possible reflections.

For the conventional dielectric resonator the simulations using plane wave excitation showed that an outer diameter of 322 mm (without a sample load) produced degenerate circularly polarized HEM_{11} modes at 123.3 MHz. In the full frequency domain simulations the optimal outer diameter of the annular dielectric resonator increased to 352 mm to produce the same HEM_{11} modes.

For the artificial-dielectric resonator the inner diameter and length of the structure were the same as for the dielectric resonator. The length and diameter of each of the 96 brass wires were 182 mm (approximately a half-wavelength at 3 T) and 2 mm, respectively. The wires had a spacing of 4 mm and a distance from the air annulus of 10 mm. Using linear plane wave excitation the fundamental mode corresponded to an outer diameter of 214 mm (Fig. 2). In full simulations with the transmit body coil and phantom the diameter of the artificial-dielectric resonator was 220 mm, much smaller than the 352 mm required for the purely water-based dielectric resonator.

The B_1^+ field and specific absorption rate (SAR) distributions inside the phantom for both the annular dielectric resonator and artificial-dielectric resonator were derived from full electromagnetic simulations with the body coil and normalized to 1 W of total accepted power. The transmit efficiency was estimated, from the same simulation setup, as the ratio between the B_1^+ field averaged over the entire phantom to the square root of the maximum local SAR_{10g}.

2.2. Coil construction and testing

Both resonators were constructed from PMMA tubes with 110 mm inner diameter, 232 mm length and thickness of 5 mm, filled with distilled water. The array of 96 brass wires was fixed in thin

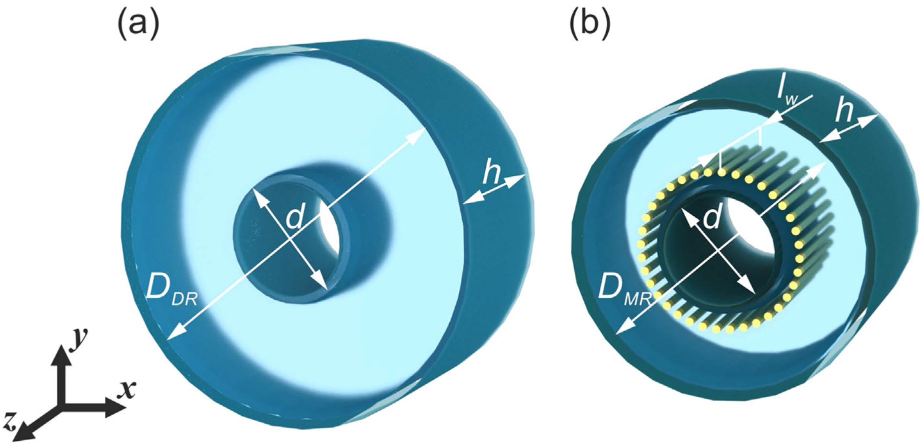

Fig. 1. Schematic view of the geometries of the annular dielectric resonator (a) and artificial-dielectric resonator (b) The inner diameter $d = 110$ mm and the height $h = 232$ mm are equal for both structures, while the outer diameters are different: dielectric resonator $D_{DR} = 352$ mm and artificial-dielectric resonator $D_{ADR} = 220$ mm. The length of wires $l_w = 182$ mm and the thickness of the PMMA is 5 mm.