Traveling-Wave MRI at Lower B_0 Field Strengths Using Metamaterial Liners

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Introduction: The advent of ultra-high-field MR scanners has led increasingly to the use of techniques native to RF/microwave engineering. Most notably, Brunner et al. introduced the concept of traveling-wave (TW) NMR, which treats the bore of an MR scanner as a cylindrical electromagnetic waveguide (CWG) capable of supporting TWs that may be both excited and detected at long range using conventional RF antennas [1]. However, a CWG large enough to accommodate the human body cannot propagate TWs at frequencies below a natural cutoff frequency, f_c, of several hundreds of megahertz. As a result, existing clinical MR scanners simply cannot exploit this intriguing new detection paradigm. Previous works have sought to reduce the cutoff frequencies by partially filling the bore with high-permittivity materials [2] or introducing an additional conductor for coaxial-like propagation [3]; however, these approaches occupy valuable space within the bore and can lead to claustrophobia. Metamaterials are artificial materials that can be engineered to possess properties that are unavailable in nature, such as extreme, negative, or even near-zero values of electric permittivity (ε) and magnetic permeability (μ), and have become a subject of intense interest in the RF/microwave and optics communities over the last decade. In particular, negative-refractive-index transmission-line (NRI-TL) metamaterials have found several applications in planar circuits [4], and 3D topologies have demonstrated intriguing electromagnetic phenomena such as subdiffraction imaging [5]. In this work, we report that a thin metamaterial liner applied to the interior of the MR scanner bore can substantially reduce f_c, thereby enabling TW-based imaging using lower B_0 field strengths without occupying a significant amount of space within the bore. Furthermore, we demonstrate that such liners may simultaneously provide dramatically improved image quality through increased spatial uniformity of the electric and magnetic fields within the bore.

Materials and Methods: Reference [1] examined the propagation of the circularly polarized TE_{11} mode inside a 58-cm-diameter MR scanner bore, for which f_c can be analytically determined to be 303.3 MHz. In this work, we employ Ansys HFSS, an FEM-based full-wave electromagnetic simulator, to model this environment as a CWG consisting of an air-filled cylindrical region of the same diameter surrounded by a perfect electric conductor (PEC), as shown in Fig. 1(a). The PEC boundary is lined with an annular metamaterial region of 2-cm thickness possessing relative permittivity ε_r and relative permeability μ_r, as well as loss tangents typical of low-loss metamaterials, such as the NRI-TL metamaterial [4]. The metamaterial-lined CWG is rendered infinitely long using periodic boundary conditions at the input and output faces. This approach enables determination of the eigenmodes of the system without having to consider issues such as reflections and mechanisms of excitation which require larger simulations. For simplicity, the present analysis is limited to the linearly polarized TE_{11} mode, but the results may be straightforwardly extended to circular or elliptical polarizations. One potential implementation of the metamaterial liner is depicted in Fig. 1(b), and consists of a radial arrangement of several NRI-TL layers running the length of the MRI bore, similar to metamaterials proposed for antenna radomes [6].

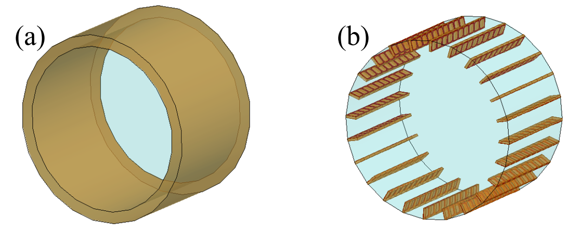

Figure 2: (a) CWG representing a metamaterial-lined MR scanner bore; (b) NRI-TL metamaterial implementation.

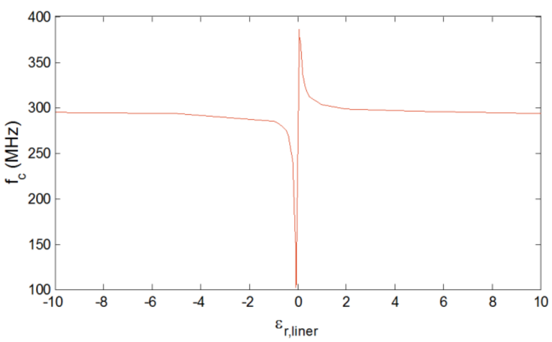

Figure 3: CWG cutoff frequency, f_c, versus the relative permittivity, ε_r, of the metamaterial liner.

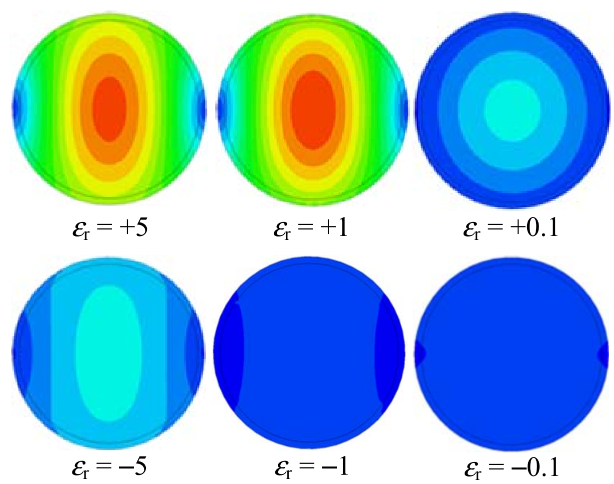

Figure 1: Transverse magnetic-field magnitudes for various ε_r.

Results and Discussion: Figure 2 presents f_c of the TE_{11} CWG mode as a function of ε_r of the metamaterial liner, with μ_r maintained at the free-space value of 1. As a validation of the accuracy of the simulation, the empty bore, described by $\varepsilon_r = 1$, yields the correct result of $f_c = 303.3$ MHz. At both extreme negative and extreme positive values of ε_r, the metamaterial liner effects a slight decrease in f_c, which is to be expected, given the small fraction of cross-sectional area occupied by the liner. However, dramatically different behaviour is observed when $|\varepsilon_r|$ nears zero: in particular, a substantial reduction in f_c is achieved when ε_r is between –1 and 0. Figure 3 presents magnitudes of the transverse magnetic-field components for the TE_{11} mode propagating slightly above cutoff, for several representative values of ε_r. All data is normalized to the same magnitude/colour scale as the TE_{11} field distribution in the empty bore ($\varepsilon_r = 1$). It is observed that the field distributions are substantially more uniform for negative values of ε_r, and that the greatest spatial uniformity is observed as $|\varepsilon_r|$ tends to zero. It has also been observed that the metamaterial liner enriches the spectrum of modes supported by the MR scanner bore, which may prove useful for parallel imaging or RF shimming. These results suggest that TW-based imaging may be achievable at lower field strengths, simply by retrofitting these scanners with a relatively inexpensive metamaterial liner. For example, designing the metamaterial liner for $\varepsilon_r = -0.08$ results in $f_c = 101.8$ MHz, which is well below the Larmor frequency of conventional 3T scanners.

References

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