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New Metamaterial: Provoked MRI Technique Tested on Humans

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Abstract

Developments in metamaterials and allied structures such as metasurfaces have opened up novel potential in designing materials and devices with unique properties. Here we report a new hybrid metasurface structure, comprising a two-dimensional metamaterial surface and a very high permittivity dielectric substrate, which has been designed to enhance the local performance of an ultra-high field MRI scanner. This new flexible and compact resonant structure is the first metasurface which can be integrated with multi-element close-fitting receive coil arrays that are used for all clinical MRI scans. We demonstrate the utility of the metasurface acquiring in-vivo human brain images and proton MR spectra with enhanced local sensitivity on a commercial 3Tesla system. Magnetic resonance imaging (MRI) is a widely used medical technique for examination of internal organs, as well as playing a major role in oncology. However, due to its intrinsically lower signal-to-noise ratio, an MRI scan takes much longer to acquire than a computed tomography or ultrasound scan. This means that a patient must lie motionless within a confined apparatus for up to an hour, resulting in significant patient discomfort, and relatively long lines in hospitals.

Keywords: Metamaterial, dual-band, magnetic resonance imaging, ultrahigh field.

Introduction

Magnetic resonance imaging (MRI) is one of the most important modalities for clinical disease diagnosis, and it plays a key role in fundamental preclinical research. Its major advantages include nonionizing radiation, lack of penetration effects, ability to acquire fully isotropic three-dimensional (3D) data, and ability to produce a variety of image contrasts between tissues using different data acquisition parameters. The major disadvantage of MRI arises from its low sensitivity, which is a result of the small energy difference between energy levels. Alternative noninductive detection methods have been explored at very low magnetic fields (≪1 T), including optical atomic magnetometers1 and superconducting quantum interference devices, but these are not suitable for the much higher field strengths (1.5–3 T) used in human imaging. Magnetic resonance force microscopy, which uses a nanoscale cantilever for mechanical detection of the MR signal, is a method that has extremely high sensitivity, with the ability to detect single electronic spins, but it is not applicable to human imaging because the sample must be placed in a vacuum at low temperatures.

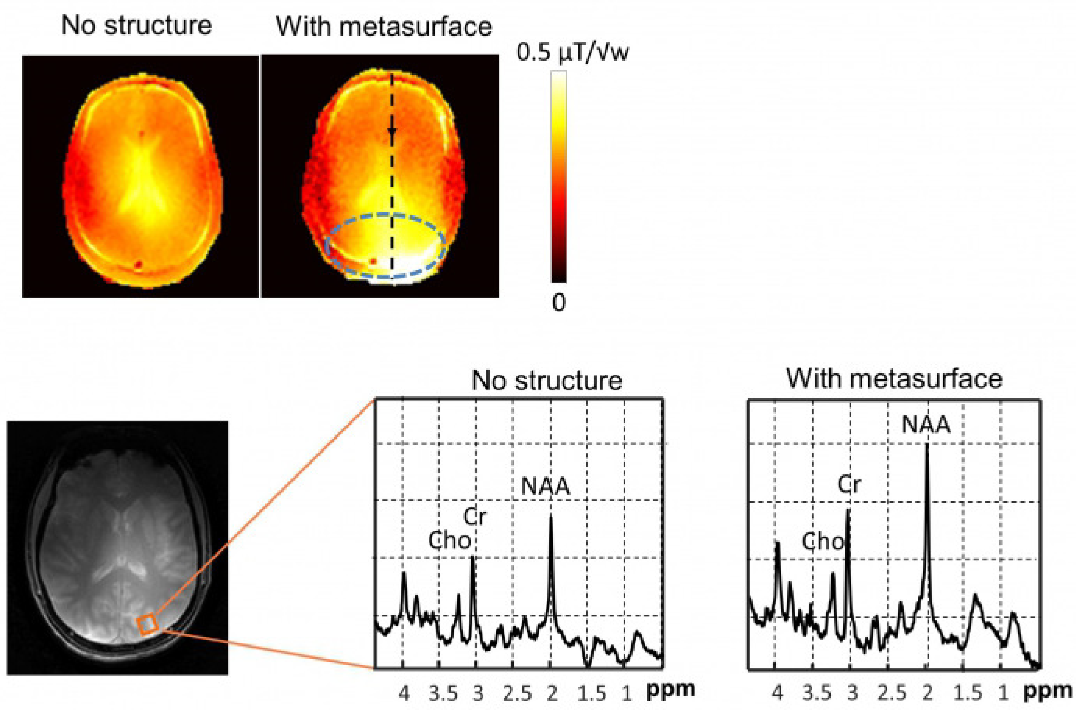

Fig. 1. Comparison of MRI scans with and without the use of metasurface

An alternative method to increase the sensitivity is to incorporate novel materials into the setup: one such example is a metamaterial. Metamaterials and artificial materials represent a novel group of structures, creating new means to control wave propagation. Applications commenced with optical superlensing, continued with transformation optics and invisibility cloaking, and presently have incorporated a wide range of device miniaturization and efficiency enhancements. Several studies in MRI have investigated potential improvements using metamaterials in the detection sensitivity, RF transmit efficiency, and decoupling between the individual coils in a multicoil array. In this study, we explore a completely new metamaterial implementation for MRI, namely, a dual-nuclei resonant structure. We have designed a hybrid metamaterial, comprising a two-dimensional (2D) metamaterial surface and a high permittivity dielectric substrate, and explored the properties controlling the two resonant modes corresponding to the Larmor frequencies of the two different nuclei. Most of the nonproton nuclei that are of interest for in vivo acquisition have a Larmor frequency that is far away from that of protons, due to the very different gyromagnetic ratios.

Several studies have demonstrated metamaterial designs for MRI, which have included swiss-rolls, split-rings, wires, and magnetoinductive waveguides. These structures shape the RF magnetic field, enabling local increases in the MRI transmit and receive efficiency. Two proposed metamaterials have recently garnered interest. One is based on a metamaterial with negative permeability implemented using split-rings, and its feasibility has recently been demonstrated at 3 T using a thin (11 mm) metamaterial slab.

The second proposal is based on a metamaterial with negative permittivity, using a metasurface based on a set of wires or conductive strips: this has been demonstrated at 1.5 and 3 T and showed a local enhancement in SNR. Both designs are based on a quasi-static approximation applicable for relatively low RF frequencies relevant for MRI (≲300 MHz). In this approximation, the magnetic and electric fields can be analyzed separately, and therefore, a system of either magnetic dipoles (split-rings or short wires that function equivalently to split-rings or electric dipoles (long wires) can support resonant modes at the frequencies of interest. In our study, at 3 T, the quasi-static approximation is well-suited for P (121 MHz) but is marginal for ^{1}H (298 MHz). Therefore, full electromagnetic (EM) simulations were used to determine the resonant modes. Our main aim in this study was to design a new type of metamaterial with the capability to enhance the signal for both nuclei (^{31}P and ^{1}H), using the same structure. This new feature arises from a combination of the above two types of metamaterials, creating a novel dual-nuclei metamaterial.

Design of the Dual-Nuclei MRI Metamaterial

Such structures rely on different characteristics depending on the RF frequency range, for example, using 3D structures (with perpendicular setups for dual bands)36 or a subunit that incorporates dual dimension settings.34 For the frequency range in the applications in optics and microwaves, the metamaterials were devised to generate negative refraction, requiring both negative permittivity and negative permeability. For the lower frequencies, which are of interest in our work, implementation based on previous works would result in large 3D structures that are not well-suited to the very restricted space in the MRI environment.

In contrast to previous works, two frequency bands can be realized based on the same substrate at the frequencies relevant for MRI: one frequency band produced via coupling with a set of long strips and the other with a set of short strips. Such a metamaterial does not require the property of negative refraction. A set of long strips produces resonant modes for the low frequency band of interest, and a set of short strips produces resonant modes for the high frequency band of interest. In this study, the two structures are harnessed to generate a unique single metamaterial structure for dual-nuclei purposes. In a previous study, we reduced the dimensions of a hybrid metamaterial based on copper strips combined with a high dielectric substrate by using a $CaTiO_3$ suspension. In the current work, we further reduced the metamaterial dimensions by utilizing zigzag-shaped copper strips instead of straight-line strips. The zigzag shape enables extension of the electric dipole to the length required by the desired frequency while maintaining the physical dimensions of the pad.

Metamaterial Based Coils

Metamaterials are artificially engineered media whose electromagnetic responses are different from those of their constituent components [3]. The metamaterials have been proven to exhibit unique electromagnetic characteristics that do not occur in natural materials. Over the last decade, an incredible amount of research and application base on metamaterials has been explored. Wave interactions with subwavelength metamaterials size have been particularly useful to the antenna community. Most of the metamaterials research has been concentrated in the microwave region and above for far-field characteristics while fewer studies are carried out for near-field applications, especially at frequencies lower than Giga Hertz.

Coil with metamaterial lens

It is known that the metamaterial lens, with negative r = -1εrefraction index has material properties of permittivity r = -1, is able to focus electromagnetic fieldμor permeability and this effective phenomenon can provide sub-wavelength imaging resolution. Inside the phantom, the magnetic field intensity generated by the coil with metamaterial lens is obviously stronger than that of the conventional coil.

Characterization of Materials

The metamaterial prototype included two long strips of 26 cm in total length and a 3 × 3 matrix of short strips (6 cm length). The distance between the strips was 2.5 cm. The implemented structure was constructed from 25 μm thick copper strips, 5 mm wide each. The full structure size was 14 × 23 × 1.1 cm^3 including a 1.1 cm thick water layer. The dielectric layer and the copper strips were sealed in a plastic container. The pad was placed under the calf muscle of the leg to assess the local enhancement of the prototype.

Phantom and in Vivo Experiments

Phantom and in vivo images of a volunteer were acquired on a Philips Achieva 3 T MRI system. The phantom setup consisted of a plastic cylinder containing polyvinylpyrrolidone (∼1.8 M) in water and salt added to achieve dielectric properties of $\varepsilon_r = 48$ and $\sigma = 0.3$ S/m (in order to mimic the electric properties of calf muscle), in which 500 mM phosphoric acid was dissolved.

All experimental protocols were approved by the Leiden University Medical Centre Medical Ethics Committee, and all methods were carried out in accordance with Leiden University Medical Centre guidelines and regulations. The ^1H images were produced by a low-tip-angle gradient-echo sequence with the following scan parameters: field-of-view (FOV) = 24 × 24 cm^2, spatial resolution = 1.5 × 1.5 × 5.0 mm^3, TR/TE = 10/3.4 ms, and flip angle = 5°. The ^{31}P spectroscopic imaging consisted of a nonselective 2D CSI sequence. The CSI scan parameters for the phantom were as follows: FOV = 13 × 13 cm^2, phase encoding matrix = 13 × 13, flip angle = 45°, echo time = 1.2 ms, repetition time = 2000 ms, and number of averages = 2. For the in vivo scans, the parameters were as follows: FOV = 20 × 20 cm^2, phase encoding matrix = 10 × 10, flip angle = 45°, echo time = 1.3 ms, repetition time = 2000 ms, and number of averages = 12.

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