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Microarticle

Application of a capacitively-loaded split-ring metamaterial lens in a 0.3 T magnetic resonance imaging system

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ABSTRACT

In this work, it is demonstrated that metamaterial lenses can help to increase the signal-to-noise ratio of magnetic resonance imaging coils in low-field magnetic resonance imaging systems. In low-field magnetic resonance imaging systems, the dominant source of noise in the signal-to-noise ratio comes from the metallization of the coil and the noise sample or tissue is negligible, unlike high-field magnetic resonance imaging systems. A metamaterial lens consisting of a three-dimensional array of capacitively loaded split rings was fabricated and tested on a 0.3 T MRI system. The experiment was performed for a configuration in which the metamaterial lens is far enough from the coil so that the additional losses that can be introduced into the coil by the metamaterial lens are also negligible, as are the tissue losses.

Introduction

Metamaterials (MMs) are a new class of artificial electromagnetic composites consisting of periodic arrays of sub-wavelength resonant elements [1,2]. MMs can be engineered to achieve exotic electromagnetic properties. One of the most striking properties is the ability of a MM slab with negative permittivity/permeability to behave as a lens with subwavelength resolution for the electric/magnetic field [2]. MMs exhibit an inherent narrow-band response due to the resonant nature of its constituent elements. This narrowband response is usually considered the main drawback of MMs in different fields of application. However, this is not the case for an application with an inherent narrow band of operation such as magnetic resonance imaging (MRI), which involves the detection of radiofrequency (RF) signals ranging from tens to hundreds of MHz with bandwidths of tens of kHz [3]. MM slabs made up of elements consisting of split metallic rings loaded with lumped capacitors, or capacitively loaded rings (CLR), have been previously investigated by the authors for its application in MRI [4–9]. In particular, it was investigated the use of these devices as lenses with permeability equal to −1 that are able to focus the RF magnetic field of MRI coils. This ultimately leads to a local increase in the signal-to-noise ratio (SNR) of the coils, which is the main figure of merit in MRI [3]. These lenses were designed to work in high-field MRI systems of 1.5 T and 3 T [4–9], where tissue-induced losses in the coil are dominant and losses due to coil metallization are negligible at operating frequencies, 63.6 and 123.2 MHz, respectively, unlike low-field systems, below 1 T, where the opposite is the case and losses from the metallization coil are dominant [3]. In all these previous works, it was experimentally and numerically shown that, for high-field MRI systems, CLR MM lenses can provide an increase in the SNR of MRI coils whether the CLR MM lens is placed far from the coil and, therefore, the losses introduced by the lens in the coil are negligible, or even whether the CLR MM lens is close to the coil and then the losses introduced by the lens are not negligible, but the noise losses are compensated by the strong enhancement of the field produced by the lens. In [8] it was demonstrated by means of numerical results that in low-field MRI systems a configuration where the CLR MM lens is placed very close to the MRI coil cannot effectively increase the SNR due to the losses introduced by the lens. However, it has not been numerically or experimentally tested for low-field MRI systems if a CLR MM lens can increase the SNR of a coil in a configuration where the lens is far from the coil. This is precisely the goal of the present work, that is, to experimentally check in a low-field MRI system if a CLR MM lens can provide an increase in the SNR of MRI coils in a configuration where the MM lens is far enough from the coil, so that the dominant losses are the metallization coil losses, and the losses introduced by the lens in the coil are negligible. Thus, a CLR MM lens was designed with an accurate model [5] to exhibit a permeability equal to −1 at the operating frequency of 12.77 MHz of a 0.3 T Airis Hitachi MRI system and was fabricated to perform an experiment. The fabricated CLR MM lens consists of the array of $8 \times 8 \times 2$ unit cells with periodicity 20 mm shown in Fig. 1. This figure also shows a sketch of the resonant

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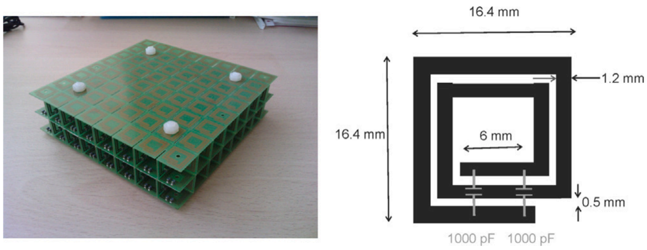

Fig. 1. Left: photograph of the fabricated CLR MM lens consisting of a cubic array of 8 × 8 × 2 unit cells. The size of the unit cell is 20 mm. Right: sketch and dimensions of the CLR.

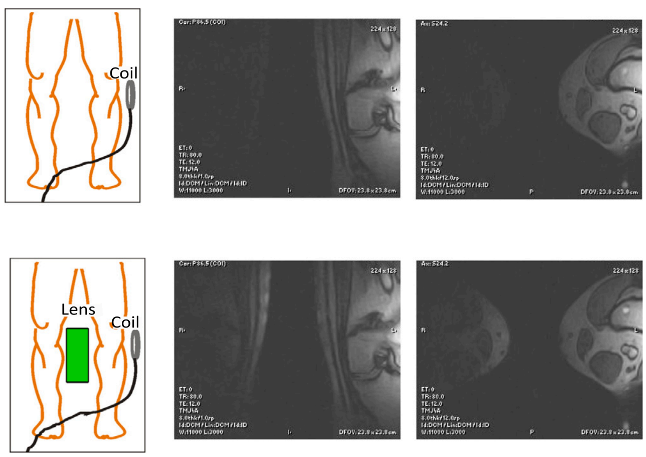

Fig. 2. Sketch of the experiment performed in a 0.3 T Airis Hitachi MRI system and MR images obtained (coronal and axial views) of the legs of a volunteer. The experiment was carried out with a 3 in. coil in the absence (top) and in the presence (bottom) of the CLR MM lens.

elements arranged in the three faces of the cubic cells of the array and that consists of a copper squared spiral ring photoetched on a printed-circuit board, with two nonmagnetic 1000 pF capacitors by American Technical Ceramics placed in parallel in the gap of the spiral.

Results

Fig. 2 shows a sketch of the experiment performed together with the coronal and axial MR images obtained. This experiment is similar to one previously reported by the authors in a high-field system (1.5 T) [4]. In the present experiment, the body coil was used for excitation and a 3 in. diameter circular coil was used for reception. In the experiment, the coil was placed first next to one of the legs of a volunteer, as shown in the sketch in Fig. 2, to image this leg. The lens was then placed between the legs and the surface coil was used in the same position to image both the closest leg and part of the far leg, as shown by the MR images in Fig. 2. In MRI, windowing is the process in which the contrast and brightness of the grayscale component of an MRI image is adjusted. The brightness of the image is adjusted by setting the window level. The contrast is adjusted via the window width. The MR images shown in Fig. 2 correspond to the same width and level values. The direct comparison between the MR images with the same width and level values makes it obvious that the signal in the leg far from the coil is greatly increased compared to the case in the absence of the lens. Furthermore, the noise remains similar in the presence and absence of the lens because the lens does not introduce additional noise. The metallization of the coil is the main source of noise. In fact, there was no detuning or mismatch in the surface coil due to the presence of the lens in the experiment. In summary, the lens helps to increase the sensitivity of the coil beyond the spatial range of the coil.

CRediT authorship contribution statement

Manuel J. Freire: Designed and fabricated the reported device, Conducted the experiment. **Jesus Tornero:** Conducted the experiment. **Ricardo Marqués:** Designed and fabricated the reported device.

Declaration of competing interest

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.

Data availability

The authors do not have permission to share data.

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