Zero-permeability nonlinear split-ring metamaterials for magnetic resonance imaging applications

M. J. Freire[1], M. A. Lopez[1], J. M. Algarin[1], V. C. Behr[2], P. M. Jakob[2] and R. Marques[1]

[1]Department of Electronics and Electromagnetism, University of Seville
Facultad de Fisica, Avda. Reina Mercedes s/n, 41012, Seville, Spain
Fax: + 34954239434; email: freire@us.es
[2]Department of Experimental Physics 5 (Biophysics), University of Würzburg
Institute of Physics, Am Hubland, 97074, Würzburg, Germany
email: behr@physik.uni-wuerzburg.de

Abstract

Split-ring metamaterial slabs with zero permeability can reject the radiofrequency magnetic field in magnetic resonance imaging systems. Nonlinear elements consisting of pairs of crossed diodes are inserted in the split-rings to automatically switch the slab permeability between a value close to unity when interacting with the strong field of the transmitting coil, and zero value when interacting with the weak field produced by protons in tissue. Split-ring slabs are designed and fabricated to work in a 1.5T system and a experiment is shown to illustrate how these slabs can help to locally increase the signal-to-noise-ratio.

1. Introduction

Several works have explored the application of metamaterials in magnetic resonance imaging (MRI) making use of different elements as swiss-rolls [1]-[5], wires [6] or capacitively-loaded split rings [7]-[9]. Most of them deal with the sub-wavelength imaging ability of metamaterials with negative permeability ($\mu < 0$). In previous works of the authors, metamaterials slabs with $\mu = -1$ have been fabricated and tested in MRI systems to show the ability of these slabs to increase the sensitivity of surface coils [7, 8] and to improve the field localization of these coils, a fact that may find applications in parallel MRI [9]. Metamaterials can be engineered to tailor whatever value of μ at the desired frequency. However, little attention has been paid to values of μ different from negative ones. In the present work, it is explored the application in MRI of capacitively-loaded split-ring metamaterials which show zero permeability ($\mu = 0$) at the operating frequency. $\mu = 0$ slabs can reject the radiofrequency (RF) magnetic field, as sketched in Figs. 1-a-b. This property can help to locally increase the signal-to-noise-ratio (SNR) of surface coils. In the present work, this has been experimentally checked.

2. Design and fabrication

MRI acquisitions consist of the excitation of tissue with an uniform RF field of high amplitude which is generated by a transmitting body coil. After the excitation, surface coils are used to detect the weak field generated by protons in tissue. The split-ring device previously reported by the authors consisted of a slab with $\mu = -1$ [7]-[9]. The transfer function of this slab [10] is such that uniform fields are transmitted without distortion through the slab. However, $\mu = 0$ slabs can actually distort uniform fields, that is, the excitation field in the MRI system. Therefore, it is necessary to implement the $\mu = 0$ slabs in a way that

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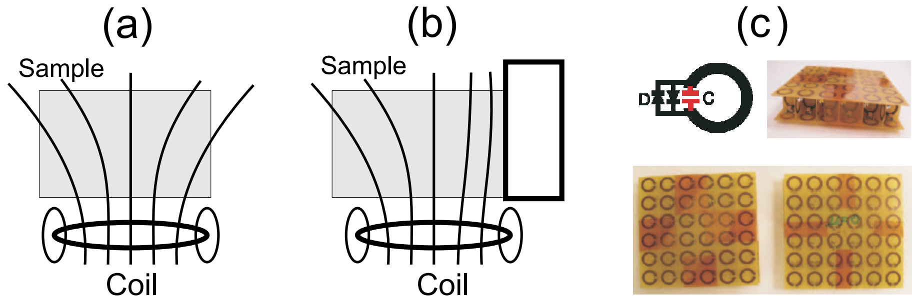

Fig. 1: Sketch of the magnetic field lines for (a) a single coil, (b) a $\mu = 0$ slab perpendicular to the coil, (c) Sketch of the constituent element and photographs of the slab. The slab is $6 \times 6 \times 1$ unit cells and the periodicity is 15 mm. The slab has been fabricated with rings of 12 mm in diameter and 1.87 mm of strip width, and 470 pF non-magnetic capacitors were used to tune the loops. A pair of crossed diodes in parallel with the capacitors provides the nonlinear response which is different for strong or weak fields.

can be automatically switched to show $\mu \simeq 1$ under the strong field of excitation and $\mu = 0$ under the weak field coming from tissue. This can be accomplished in the practical implementation of the slabs by inserting nonlinear elements in the split rings that allow to switch between different responses under strong or weak fields. In particular, a pair of crossed diodes inserted in each ring (see Fig. 1.c) can help to switch off them under the strong excitation field. Under the strong excitation field, the high electromotive force induced in the capacitively-loaded rings makes the diodes to drive and then the capacitors are short-circuited, so that the capacitively-loaded rings behave like simple closed metallic loops with a value of μ which is close to that of the air. Once the sample is excited, the tissue reradiates a weak field which is unable to drive the diodes, so that the rings behave like resonant circuits. Following the homogenization procedure previously reported by some of the authors [11], a three-dimensional array of resonant rings can be designed to show $\mu = 0$ at the desired frequency. The frequency of resonance has been chosen so that from the homogenization model the system has $\mu = 0$ at the working frequency of 63.6 MHz. This frequency corresponds to the Larmor frequency of the 1.5T Siemens Avanto MRI system sited in the Department of Experimental Physics 5 (Biophysics) of the University of Würzburg (Germany), where the experiment reported in this work was done. Since the capacitance of each split-ring is fixed, the frequency of resonance was fitted by adjusting the dimensions of the rings. A small correction to the value predicted by the homogenization model was necessary due to the parasitic reactance of the diodes. Thus, a split-ring slab of $6 \times 6 \times 1$ unit cells (see Fig. 1.c) with a periodicity of 15 mm was designed to exhibit $\mu = 0$ at the frequency of 63.6 MHz. The fabricated split-rings have 12 mm in diameter and 1.87 mm of strip width. Each split-ring in the array contains a $470 \pm 1\%$ pF non-magnetic capacitor (*American Technical Ceramics Corp.*, NY, USA) for resonance at a specific frequency below 63.6 MHz, and a pair of crossed diodes (*Microsemi Corp.*, CA, USA) in parallel with the capacitor in order to switch off the slab in transmission.

3. Results

The fabricated device was tested in an experiment where a 90 mm in length receive-only loop coil was used as detector and a $12 \times 12 \times 18$ cm^3 phantom, filled with a hydroxyethyl cellulose solution doped with 1.5 g/l $CuSO_4$, was used as load. The loop was tuned to 63.63 MHz and matched to 50Ω in the presence of the slabs and the phantom. It was actively decoupled by a tuned trap circuit including a PIN diode in transmission. The active decoupling for the loop was -25dB with and without the metamaterial slabs. All the experiments were performed in the 1.5 T system mentioned above. In the experiment, the metamaterial slab is perpendicular to the loop and it is positioned at one side of the phantom (see Fig. 2.a), so that the magnetic flux is rejected by the slab and then confined inside the phantom. This will increase the signal coming from this region of the phantom.

SNR maps were calculated from a series of phantom measurements [12] with the $\mu = 0$ slab and compared with the situation where the slab was removed. In Fig. 2.a, the calculated SNR maps are shown for both the presence and the absence of the $\mu = 0$ slab, and profiles along the white dashed line are compared in Fig. 2.b. The comparison between these profiles show that the signal increases up to 64% in the side of the phantom where the $\mu = 0$ slab is placed. In the experiments, an artifact appeared in the phantoms surface due to the discrete nature of the split-ring structure, but it was easily removed by taking the slab 1 cm far from the surface of the phantom.

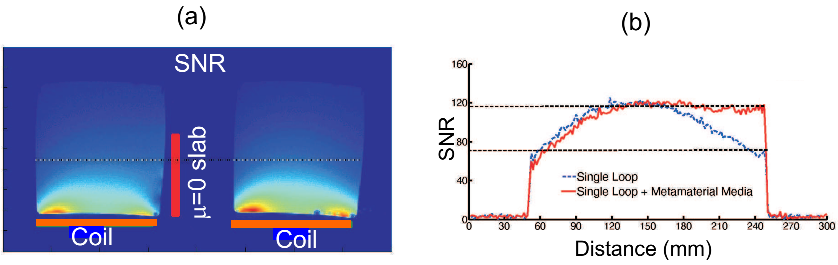

Fig. 2: (a): SNR map for the experiment with the $\mu = 0$ slab in an axial plane. (b) Profile of the SNR along the white line in the map. The SNR is given in arbitrary units.

4. Conclusion

This work demonstrates how split-ring metamaterial slabs designed with zero permeability can help to increase the SNR in certain configurations. The SNR gain can be improved with a smart design of the configuration, making a suitable choice of the size of both the coil and the sample. $\mu = 0$ slabs surrounding the sample could improve the SNR in the borders of the sample and thus the SNR will be homogenized in the field of view of the coil. The metamaterial slab could be useful in limited channel systems or as complement of an array.

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