

Nonlinear split-ring metamaterial slabs for magnetic resonance imaging

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This work analyzes the ability of split-ring metamaterial slabs with zero/high permeability to reject/confine the radiofrequency magnetic field in magnetic resonance imaging systems. Split-ring slabs are designed and fabricated to work in a 1.5 T system. Nonlinear elements consisting of pairs of crossed diodes are inserted in the split-rings, so that the slab permeability can be switched between a value close to unity when interacting with the strong field of the transmitting coil, and zero or high values when interacting with the weak field produced by protons in tissue. Experiments are shown where these slabs locally increase the signal-to-noise-ratio. © 2011 American Institute of Physics. [doi:10.1063/1.3574916]

Application of metamaterials in magnetic resonance imaging (MRI) has been previously explored in several works making use of devices based on swiss-rolls,¹⁻⁵ wires,⁶ and capacitively-loaded split rings.⁷⁻⁹ Most of these works have explored the subwavelength imaging ability of metamaterials with negative permeability (μ). 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 Although metamaterials can be engineered to tailor whatever value of μ at the desired frequency, 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 ($\mu=0$) or high permeability ($\mu\rightarrow\infty$) at the operating frequency. $\mu=0$ and $\mu\rightarrow\infty$ slabs can reject and confine, respectively, the radiofrequency (rf) magnetic field, as sketched in Fig. 1. These properties can help to locally increase the signal-to-noise-ratio (SNR) of surface coils in certain configurations which have been experimentally investigated in this work.

Typical MRI acquisition consists of the excitation of tissue with a strong and uniform rf field generated by a transmitting body coil, and then the detection of the weak field generated by hydrogen nuclei in tissue by means of surface coils. The split-ring device previously reported by the authors consisted of a $\mu=-1$ slab,⁷⁻⁹ which does not distort the uniform excitation field. However, $\mu=0$ and $\mu\rightarrow\infty$ slabs can actually distort this field. Therefore, it is necessary to implement these slabs as nonlinear slabs which can be automatically switched to show $\mu\approx 1$ under the strong field of excitation and $\mu=0$ and $\mu\rightarrow\infty$ 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 split-ring can help to switch off them

under the strong excitation field. Following the homogenization procedure previously reported by some of the authors,¹⁰ two split-ring slabs of $6\times 6\times 1$ unit cells with a periodicity of 15 mm were designed to exhibit $\mu=0$ and $\mu\rightarrow\infty$ at the frequency of 63.6 MHz. This frequency corresponds to the Larmor frequency of the 1.5 T Siemens Avanto MRI system sited in the Department of Experimental Physics 5 (Biophysics) of the University of Würzburg (Germany), where the experiments reported in this work were done. The fabricated split-rings have 12 mm in diameter and 1.87 mm of strip width for the $\mu=0$ slab, 11.8 mm in diameter, and 1.7 mm of strip width for the $\mu\rightarrow\infty$ slab. Each split-ring in the array contains a $470\pm 1\%$ pF nonmagnetic 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 (see Fig. 2) in order to switch off the slab in transmission. Under the strong excitation field, the high electromotive force induced in the rings makes the diodes to drive and then the capacitors are short-circuited, so that the split-rings behave like simple closed metallic rings. Following the mentioned homogenization procedure,¹⁰ the calculated permeability for this system of simple metallic loops is $\mu=0.85$, a value which is closed to the value of the permeability of 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. The frequency of resonance has been chosen so that from the homogenization model¹⁰ the system has $\mu=0$ and $\mu=\infty$ at the working frequency of 63.6 MHz. Since the capacitance of each split-ring is fixed, the frequency of resonance was fitted by adjusting the dimensions

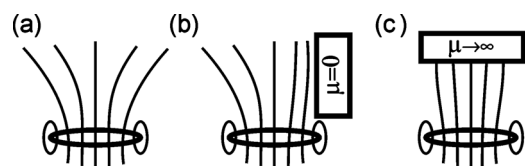


FIG. 1. Sketch of the magnetic field lines for (a) a single coil, (b) a $\mu=0$ slab perpendicular to the coil, and (c) a $\mu\rightarrow\infty$ slab placed parallel to the coil.

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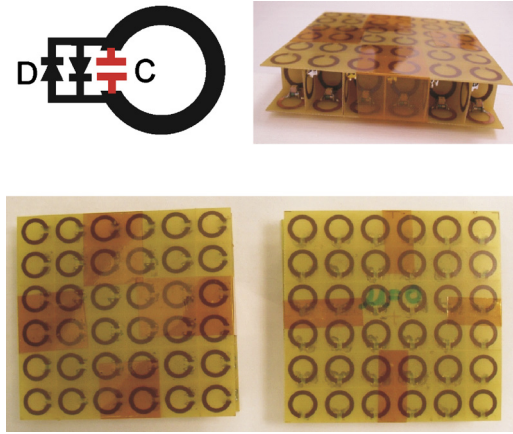


FIG. 2. (Color online) Sketch of the constituent element and photographs of the slabs. The slabs are $6 \times 6 \times 1$ unit cells and the periodicity is 15 mm. The $\mu=0$ slab has been fabricated with rings of 12 mm in diameter and 1.87 mm of strip width, and the $\mu \rightarrow \infty$ slab has been fabricated with 11.8 mm in diameter and 1.7 mm of strip width. For both cases, 470 pF 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.

of the rings. A small correction to the value predicted by the homogenization model was necessary due to the parasitic reactance of the diodes.

For the experiments, a 90 mm in length receive-only loop coil was used and a $12 \times 12 \times 18$ cm³ phantom, filled with a hydroxyethyl cellulose solution doped with 1.5 g/l CuSO₄, was used as a load for the experiments. The loop was tuned to 63.63 MHz and matched to 50 Ω in the presence of the slabs and the phantom. It was actively de-

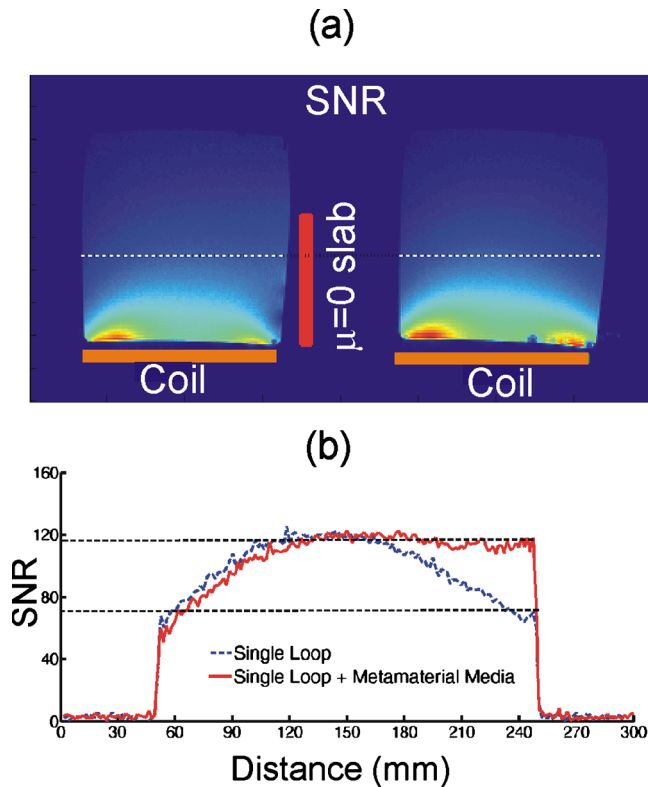


FIG. 3. (Color online) (a) SNR map for the experiment with the $\mu=0$ slab in an axial plane. (b) Profile of the SNR along the white line in the map. The SNR is given in arbitrary units.

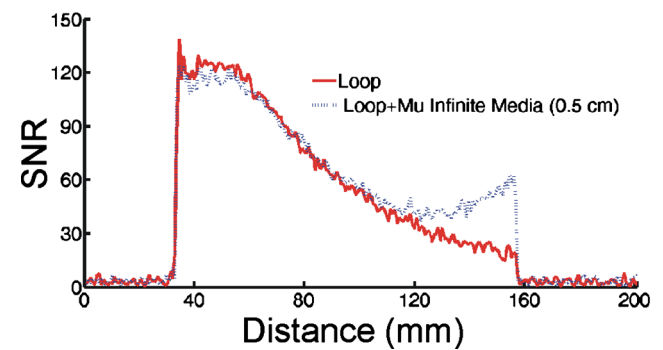
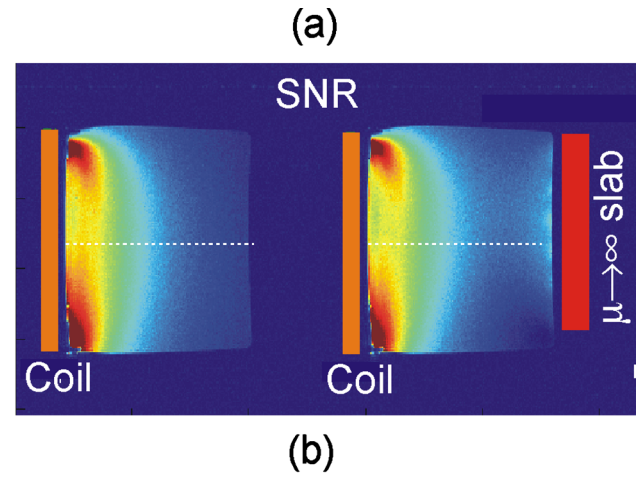


FIG. 4. (Color online) (a) SNR map of the experiment with the $\mu \rightarrow \infty$ slab in an axial plane. (b) Profile of the SNR along the white line in the map. The SNR is given in arbitrary units.

coupled by a tuned trap circuit including a PIN diode in transmission. The active decoupling for the loop was -25 dB with and without the metamaterial slabs. All the experiments were performed in the 1.5 T system mentioned above. In the $\mu=0$ experiment, the metamaterial slab is perpendicular to the loop and it is positioned at one side of the phantom [see Fig. 3(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. In the $\mu=\infty$ experiment, the metamaterial slab is placed parallel to the loop in the opposite side of the phantom [see Fig. 4(a)] in order to guide the flux lines through the phantom.

SNR maps were calculated from a series of phantom measurements¹¹ for both the $\mu=0$ and the $\mu=\infty$ slabs and compared with the situation where the slabs were removed. In Fig. 3(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. 3(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. The calculated SNR maps for the $\mu=\infty$ slab are shown in Fig. 4(a), and the corresponding profiles in Fig. 4(b). The signal presents an increment of up to 200% with the presence of the slab. In the experiments, an artifact appeared in the phantom's 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.

This work demonstrates how split-ring metamaterial slabs designed with specific permeability values can increase

the SNR in different 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. In the $\mu=\infty$ experiment, although the SNR gain could not be comparable to that provided by another coil positioned in the same position as the slab, the metamaterial slab could be useful in limited channel systems or as complement of an array.

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