Experimental demonstration of a $\mu=-1$ metamaterial lens for magnetic resonance imaging

Manuel J. Freire,[a] Ricardo Marques, and Lukas Jelinek
Departamento de Electronica y Electromagnetismo, Facultad de Fisica, Universidad de Sevilla, Avda. Reina Mercedes s/n, E 41012 Sevilla, Spain

(Received 30 August 2008; accepted 18 November 2008; published online 9 December 2008)

In this work a $\mu=-1$ metamaterial (MM) lens for magnetic resonance imaging (MRI) is demonstrated. MRI uses surface coils to detect the radio frequency (rf) energy absorbed and emitted by the nuclear spins in the imaged object. The proposed MM lens manipulates the rf field detected by these surface coils so that the coil sensitivity and spatial localization are substantially improved. Beyond this specific application, we feel that the reported results are the experimental confirmation of a new concept for the manipulation of rf field in MRI, which paves the way to many other interesting applications. © *2008 American Institute of Physics*. [DOI: 10.1063/1.3043725]

After the demonstration of the ability of a slab of an ideal negative refractive index metamaterial (MM) with $\varepsilon=-1$ and $\mu=-1$ to obtain subdiffraction images,[1] the issue of optical subwavelength imaging through the direct manipulation of the electromagnetic field has attracted a lot of attention. This effect has been shown in the optical frequency range,[2] in the microwave range,[3,4] and in the radio frequency (rf) range[5,6] by using different devices. However, the ability to image objects smaller than the wavelength is not a recent concept. It is something well known since long in magnetic resonance imaging (MRI), where imaged objects are very small as compared to the wavelength of the rf fields used to obtain the image. As it is well known, the generation of images in MRI is based on the detection of spatial variations in the phase and frequency of the rf energy absorbed and emitted by the nuclear spins of the imaged object.[7] These spatial variations are induced by some static magnetic field gradients, and the image is built from signals measured by a receiving coil that has no information about the relative location of the emitting magnetic dipoles. Conventional MRI involves many repeated measurements and then signal processing (inverse Fourier transforming) before obtaining an image of a single slice of tissue. Therefore, conventional subwavelength MRI is based on signal processing and does not involve any optical means such as focusing or collimation. At this point a question arises in a natural way: would it be possible to combine both signal processing and optical means so that the ability of MM devices to directly obtain subwavelength images could be used to improve conventional MRI? The application of microstructured MM in MRI was already explored to some extension by Wiltshire *et al.*[8] In Ref. 8 a magnetic flux guide with high permeability was used to guide the rf flux to a remote coil. This work clearly showed the compatibility of microstructured MMs with conventional MRI machines, as well as their potential usefulness in the frame of this technology, thus encouraging our search for a rf lens with application in MRI.

In a recent work[9] some of the authors proposed to use a subdiffraction MM lens to improve the images obtained by surface coils in MRI. Surface MRI coils are usually placed just on the skin of the patient and are used to obtain images of tissues in the proximity of the coil. Due to its higher sensitivity, surface coils provide a signal-to-noise ratio (SNR) much larger than that obtained with whole-volume coils or body coils. However, whereas the sensitivity of body coils is uniform, the sensitivity of surface coils, as well as the SNR, decreases rapidly with the distance from the coil. Due to Lorentz reciprocity, the sensitivity of a coil is directly proportional to the intensity of the magnetic field created by the coil inside the body of the patient for a standard value of the current on the coil.[10] Figure 1(a) shows a typical plot of the sensitivity (i.e., the normalized magnetic field intensity)

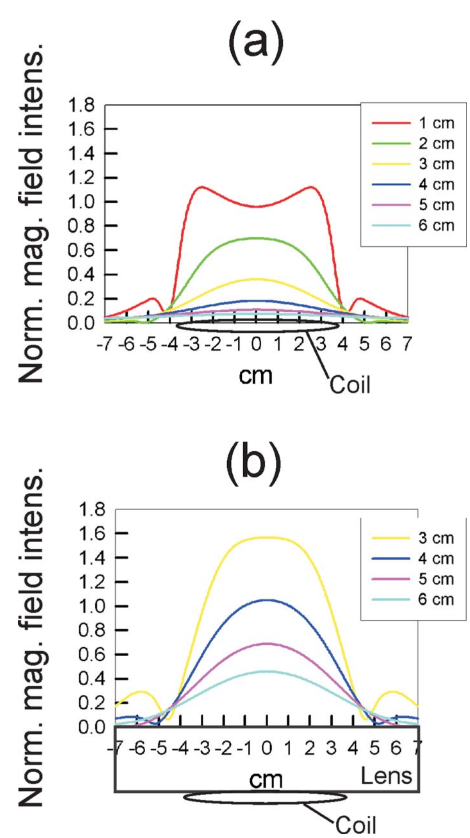

FIG. 1. (Color online) Calculation of the normalized magnetic field intensity (sensitivity) for different distances in centimeter of (a) a standard surface coil of 3 in. in diameter and (b) of the same coil placed on the lens. Units are arbitrary.

[a]Electronic mail: freire@us.es.

of a circular coil placed on the skin of the patient. As can be seen, this sensitivity decays with the distance from the coil, making the coil useless for obtaining images of tissues located at distances into the body deeper than the coil dimensions, typically. Let us now imagine that an ideal MM lens of thickness d is placed between the coil and the skin of the patient. An ideal MM lens of thickness d has the ability of focusing the electromagnetic field, translating the field distribution on the plane of the coil to another plane at a distance $2d$ from the coil, and vice versa.[1] Therefore, this configuration would increase the coil sensitivity, making it possible to obtain images of deeper tissues. Before going further with the design, we must consider that rf fields used for MRI have an associated wavelength much higher than the dimensions of any practical coil. Therefore, we are in the realm of the quasimagnetostatics, and a slab of a microstructured MM with $\mu=-1$ should be enough for manufacturing the lens. Figure 1(b) shows the sensitivity of a coil in the presence of such a lens with $\mu\approx-1$ [actually, the permeability of this MM lens corresponds to that computed according to Eq. (13) of Ref. 11 for the lens manufactured for this work]. As it can be seen, the theory predicts a substantial increase in the coil sensitivity and SNR inside the body of the patient. It is worth mentioning here that the same effect would appear if the lens is placed not directly on the coil but at some distance from it. In this case the only difference will be that the coil sensitivity in the space between the coil and the lens will not be affected by the presence of the lens.

For the practical implementation of the aforementioned ideas, the ideal $\mu=-1$ lens was mimicked by a slab consisting of a three-dimensional (3D) array of copper metallic rings loaded with nonmagnetic capacitors. Capacitively loaded rings (CLRs) were previously proposed by Schelkunoff and Friis[12] in order to design artificial media with strong magnetic response. In our case they were placed in a simple cubic lattice in order to obtain an isotropic artificial medium with $\mu=-1$. The magnetic permeability of this medium was computed from Eq. (13) of Ref. 11 as a function of the periodicity, the ring resistance, the ring self-inductance, and the frequency of resonance. The fabricated MM lens was a two unit cell thick slab of this artificial medium. A sketch of the proposed lens is shown in Fig. 2(a). Before proceeding with the description of the experiments, some additional words will be devoted to the modeling of the lens. It is apparent that a slab made of only two layers of unit cells can hardly be considered as a continuous medium. Therefore, the detailed description of this structure deserves a deeper discussion. Actually, the authors have recently developed a homogenization procedure for thin slabs made of resonant metallic rings.[13,14] A conclusion of this analysis was that for the specific configuration proposed in this report, the continuous medium approach gives a good description of the behavior of the lens. Only a small shift in the frequency of operation of the lens with regard to the continuous medium model was detected. This conclusion was confirmed by additional electromagnetic simulations made by using the commercial software package CST MICROWAVE STUDIO. Additional design corrections were necessary as a consequence of the finite size of the capacitors, which was not taken into account by the models. Finally, the lens was manufactured for operation in a MRI system of 1.5 T (i.e., for a frequency of operation of 63.85 MHz). Figure 2(b) shows a sketch of a CLR of the lens whose dimensions and design parameters are external radius

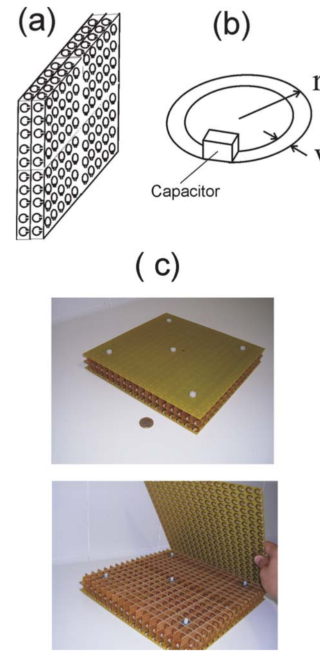

FIG. 2. (Color online) (a) Sketch of the lens: a 3D array of CLRs. (b) Sketch of a CLR with dimensions. Parameters of the fabricated CLRs: w=2.17 mm, r=6.02 mm, self-inductance of 13.45 nH, capacitance of $470\pm1\%$ pF, resonance frequency of 63.28 MHz, and quality factor of Q=115. (c) Photographs of the fabricated lens consisting of a 3D array of $18\times18\times2$ cubic cells with a periodicity of 15 mm. The total number of CLRs is 2196. The height and width of the lens are both 27 cm and the thickness is 3 cm.

of the rings $r=6.02$ mm, ring width $w=2.17$ mm, ring self-inductance of 13.45 nH, and ring capacitance of $470\pm1\%$ pF, which gives a resonance frequency of 63.28 MHz and a quality factor of 115. Finally, Fig. 2(c) shows two photographs of the final device consisting of a 3D array of $18\times18\times2$ cubic cells with a periodicity of 15 mm and a total number of CLRs of 2196. The dimensions of the lens are $27\times27\times3$ cm^3. The capacitors were low-loss nonmagnetic capacitors of the series ATC100B specially designed by the company American Technical Ceramics Corp. (NY, USA) for MRI applications and manufactured with low tolerance for our application. The rings were photoetched on a FR4 substrate by the company Circuitronica S. L. (Seville, Spain) and the capacitors were inserted by the company Silicium S. L. (Seville, Spain).

The fabricated lens was tested in a General Electric Signa 1.5T MRI machine using a standard 3 in. circular surface coil 1.5T model M1085GA manufactured by ETL for General Electric. In the experiment, one of the authors was lying on the MRI machine and the coil was placed beside one of his knees. In our study, axial images (i.e., images of a plane normal to the bore of the magnet) of type T1 were acquired using a standard spin-echo sequence typical of T1 acquisitions. The repetition time between signals was 220 ms and the echo time was 10 ms. The field of view was 34×34 cm^2 with a 256×192 data matrix. Two acquisitions with averaging were used in all cases. Figure 3(a) shows an axial image of the knees without the lens so that both knees are touching. In this figure, the knee on the right of the image is closer to the coil and is clearly visible, whereas the knee on the left is hardly visible, as it is expected from the fact that the sensitivity of the coil drops off rapidly with distance. Figure 3(b) shows also an axial image of both knees with the

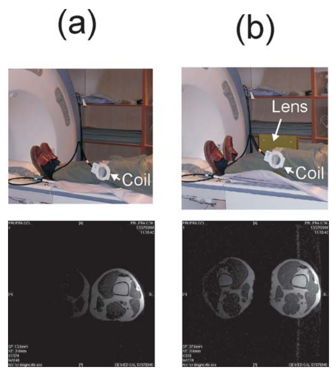

FIG. 3. (Color online) Axial T1 image of the knees of one of the authors (a) without the lens and (b) with the lens between the knees. It must be noted that the magnetic resonance images are inverted with respect to the photographs, and that this is inherent to the MRI acquisition process.

lens being placed between them (with this configuration it is not necessary to retune the coil, and a direct comparison with the previous image is possible using the same coil). In spite of the fact that the distance between the coil and the knee on the left of the image is larger than in the absence of the lens, this knee is now more visible due to the presence of the lens. This makes apparent that the lens increases the sensitivity of the coil. We feel that this is a completely new result that relies on the specific design of the lens, which mimics a $\mu=-1$ medium. We also feel that this result introduces a new concept in MRI, showing that a $\mu=-1$ MM lens can be applied in the frame of conventional MRI technology in order to improve the sensitivity of surface coils.

Up to now we have shown that MM lenses can be useful in MRI technology due to their ability of focusing the rf magnetic field lines of force. Specifically, we have shown that MM lenses can be applied to improve the sensitivity of surface coils, thus resulting in an improvement in image quality, reduction in acquisition time, and/or increase in spatial localization. Since MM lenses can translate the field distribution in a plane behind the lens to another "equivalent" plane in front of the lens, they can be also useful for obtaining images of deeper tissues. We feel that the reported results provide a sufficient "proof of concept" for the reported effect. Other MM lens configurations different from the manufactured CLR lens, as that proposed in Ref. 15, could be also useful for this application. Regarding further applications of this new concept, we feel that it may also find application in *parallel imaging* MRI technology,[16] as suggested in Ref. 15. MRI parallel imaging techniques use several surface coils and take advantage of the spatial localization of the images detected by each coil[17] to reduce acquisition time. The spatial localization of the images detected by the different coils would be substantially increased if the coils were placed on the equivalent plane of the imaged slice of tissue. In the limit, this technique could make possible to avoid the phase encoding process following the technique reported in Ref. 18, thus opening the way to real time image acquisition of deep tissues.

This work has been supported by the Spanish Ministerio de Educación y Ciencia under Project No. TEC2007-68013-C02-01/TCM and by the Spanish Junta de Andalucía under Project No. P06-TIC-01368. We want to thank Dr. Francisco Moya, Dr. Eduardo Gil, and Borja Mohedano from PET Cartuja Medical Center (Seville) for providing the MRI facilities used in this work and for their advice.

[1]J. B. Pendry, Phys. Rev. Lett. **85**, 3966 (2000).
[2]N. Fang, H. Lee, C. Sun, and X. Zhang, Science **308**, 534 (2005).
[3]A. Grbic and G. Eleftheriades, Phys. Rev. Lett. **92**, 117403 (2004).
[4]M. J. Freire and R. Marques, Appl. Phys. Lett. **86**, 182505 (2005).
[5]M. C. K. Wiltshire, J. B. Pendry, and J. V. Hajnal, J. Phys.: Condens. Matter **18**, L315 (2006).
[6]M. J. Freire and R. Marques, J. Appl. Phys. **100**, 063105 (2006).
[7]P. C. Lauterbur, Nature (London) **242**, 190 (1973).
[8]M. C. K. Wiltshire, J. B. Pendry, I. R. Young, D. J. Larkman, D. J. Gilderdale, and J. V. Hajnal, Science **291**, 849 (2001).
[9]M. J. Freire and R. Marques, Proceedings of the Second International Congress on Advanced Electromagnetic Materials in Microwaves and Optics, Pamplona, Spain, 21–26 September 2008 (unpublished), pp. 639–640.
[10]E. K. Insko, M. A. Elliott, J. C. Schotland, and J. S. Leigh, J. Magn. Reson. **131**, 111 (1998).
[11]J. D. Baena, L. Jelinek, R. Marques, and M. G. Silveirinha, Phys. Rev. A **78**, 013842 (2008).
[12]S. A. Schelkunoff and H. T. Friis, *Antennas Theory and Practice* (Wiley, New York, 1952).
[13]L. Jelinek and R. Marques, Proceedings of the Second International Congress on Advanced Electromagnetic Materials in Microwaves and Optics, Pamplona, Spain, 21–26 September 2008 (unpublished), pp. 629–631.
[14]L. Jelinek, R. Marques, and M. J. Freire, "Accurate modeling of split ring metamaterial lenses for magnetic resonance imaging applications," J. Appl. Phys. (submitted).
[15]M. J. Freire and R. Marques, J. Appl. Phys. **103**, 013115 (2008).
[16]K. P. Pruessmann, M. Weiger, M. B. Scheidegger, and P. Boesiger, Magn. Reson. Med. **42**, 952 (1999).
[17]M. A. Griswold, P. M. Jakob, M. Nittka, J. W. Goldfarb, and A. Haase, Magn. Reson. Med. **44**, 602 (2000).
[18]M. P. McDougall and S. M. Wright, Magn. Reson. Med. **54**, 386 (2005).