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Metamaterial magnetoinductive lens performance as a function of field strength

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ABSTRACT

Metamaterials are artificial composites that exhibit exotic electromagnetic properties, as the ability of metamaterial slabs to behave like lenses with sub-wavelength resolution for the electric or the magnetic field. In previous works, the authors investigated magnetic resonance imaging (MRI) applications of metamaterial slabs that behave like lenses for the radiofrequency magnetic field. In particular, the authors investigated the ability of MRI metamaterial lenses to increase the signal-to-noise ratio (SNR) of surface coils, and to localize the field of view (FOV) of the coils, which is of interest for parallel MRI (pMRI) applications. A metamaterial lens placed between a surface coil and the tissue enhances the sensitivity of the coil. Although the metamaterial lens introduces losses which add to the losses of the tissue, the enhancement of the sensitivity can compensate these additional losses and the SNR of the coil is increased. In a previous work, an optimization procedure was followed to find a metamaterial structure with minimum losses that will maximize the SNR. This structure was termed magnetoinductive (MI) lens by the authors. The properties of surface coils in the presence of MI lenses were investigated in previous works at the proton frequency of 1.5 T systems. The different frequency dependence of the losses in both the MI lenses and the tissue encouraged us to investigate the performance of MI lenses at different frequencies. Thus, in the present work, the SNR and the pMRI ability of MI lenses are investigated as a function of field strength. A numerical analysis is carried out with an algorithm developed by the authors to predict the SNR behavior of a surface coil loaded with a MI lens at the proton frequencies of 0.5 T, 1.5 T and 3 T systems. The results show that, at 0.5 T, there is a gain in the SNR for short distances, but the SNR is highly degraded at deeper distances. However, at 1.5 T and 3 T, the MI lenses provide a gain in the SNR up to a certain penetration depth, which is deeper at 3 T, and do not degrade the SNR at deeper distances. These numerical results are checked by means of an experiment. Moreover, a second experiment developed with two-channel arrays of surface coils loaded with MI lenses shows that the pMRI ability of the lenses also improves from 1.5 T to 3 T. This improvement was quantified by means of the calculation of the GRAPPA g-factor.

1. Introduction

As is well known, imaging speed and signal-to-noise ratio (SNR) are among others the most important considerations in magnetic resonance imaging (MRI). Significant scan time reduction without the need of increased gradient performance was achievable in the last decade with the development of parallel MRI (pMRI) [1–4]. SNR improvement has been achieved, since the development of MRI, with the increase of the magnetic field strength, the optimization of receiver devices as well as the search of new technologies. In the last years, metamaterial devices [5] have been investigated as an emerging technology with possible application in MRI. Metamaterials are artificial composites which are built as periodic arrangements of resonant elements and whose electromagnetic properties can be engineered to achieve extraordinary phenomena not observed in natural materials as, for instance, negative effective permittivity and permeability simultaneously [5]. Metamaterials with negative permittivity/permeability can behave as a lens for the electric/magnetic field [5]. Moreover, metamaterials can behave as a flux guide for the electric/magnetic field if they are designed with high permittivity/permeability [5]. In the literature, several works have explored the application of metamaterials in MRI [6–18]. In these works, devices were fabricated to behave as

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flux guides or lenses for the radiofrequency (RF) magnetic field, using different types of resonant elements: the so-called swiss-rolls elements [6–10], wires [11] and capacitively-loaded metallic rings (CLRs) [12–18]. CLRs have the key advantage over other elements such as swiss rolls or wires of providing three dimensional (3D) isotropy when they are arranged in a cubic lattice, which is an essential property if the device has to image 3D sources [15]. The authors of the present work have analyzed in several papers the properties of CLR metamaterials and their ability to increase the SNR of MRI coils [12–18]. These works include the analysis of CLR metamaterial lenses with negative permeability ($\mu < 0$) to focus the RF magnetic field [12–15] and CLR metamaterials with zero/high permeability to reject/confine the RF flux [16].

A CLR metamaterial lens works placed between a surface coil and the sample and it produces an enhancement of the sensitivity of the coil, but also increases the noise in the coil due to the ohmic losses of the metallic rings of the structure. A CLR metamaterial lens will increase the SNR provided by the coil itself if the enhancement of the sensitivity of the coil is high enough to compensate the additional losses introduced in the coil by the metallic structure of the lens. The enhancement of the sensitivity is due to the focusing of the magnetic field of the coil by the lens. The magnetic field produced by the coil in the near-field region, that is, at distances from the coil less than a wavelength, can be expressed as a sum of spatial Fourier harmonics which are evanescent (in the far-field region the field would be decomposed as a sum of propagative harmonics)[5]. The key mechanism for focusing with a metamaterial lens is the amplification inside the lens of these evanescent harmonics by means of the excitation of surface waves in the slab [5], so that the lens transfers the harmonics of the source to the other side of the lens. A CLR metamaterial slab exhibits a permeability that depends on the frequency. Thus, when a coil is placed close to a CLR metamaterial lens, the lens introduces in the coil an additional impedance that depends on the frequency. An ideal homogeneous slab with $\mu = -1$ will not change the impedance of a coil placed in the proximity of this slab [22]. In the case of a real CLR metamaterial lens, at the frequency corresponding to $\mu = -1$, the additional impedance introduced in the coil by the lens shows a minimum in the real part, or resistance, and a null in the imaginary part, or reactance [22]. The authors developed a method of numerical analysis for the design of CLR metamaterial lenses [14] based on this fact, so that the parameters of the structure of the lens are set to obtain, at the desired frequency, a minimum in the resistance and a null in the reactance of the calculated impedance.

In [14] an optimal design for a CLR metamaterial lens was found that minimize the losses introduced by the lens while maintaining the enhancement of the sensitivity to increase the SNR of the coil. This design [14] was simpler than a previous one [12] and it corresponded to a pair of parallel two-dimensional arrays of CLRs (see Fig. 1). This same structure was previously studied by the authors for imaging in the microwave [19] and in the RF range [20,21] and was termed magnetoinductive (MI) lens. In [14] it was shown that the SNR provided by a coil loaded with a MI lens was higher than the SNR provided by the coil itself for short distances and that it was similar for long distances. The MI lens is anisotropic since it only interacts with fields which are perpendicular to the arrays. This is not a problem since the field produced by the coil at closer distances is mainly axial. Therefore, in the MI lens the permeability is anisotropic and it is negative only in the direction perpendicular to the two arrays of CLRs, but the procedure for the design is the same in the sense that the impedance introduced by the lens must show a minimum in the resistance and a null in the reactance [14].

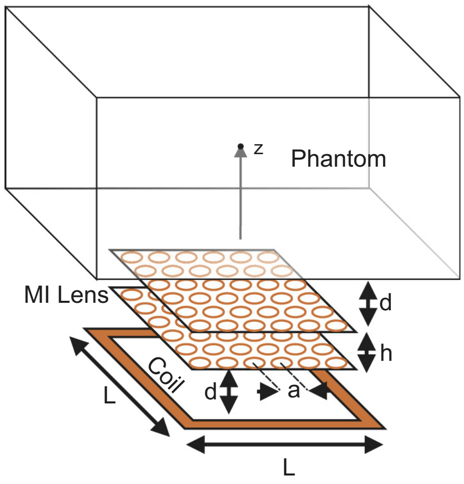

Fig. 1. Scheme of the configuration under analysis: a MI lens consisting of two parallel arrays of 6×6 rings is placed between a square coil and a phantom. The lens has an area of $9 \times 9\ \text{cm}^2$ and it is separated a distance $d = 7$ mm from the surface of the phantom. The periodicity is a = 15 mm. The square coil is $L = 12$ cm in length and it is also separated a distance $d = 7$ mm from the MI lens.

The ability of CLR metamaterials lenses to localize the field of view (FOV) of MRI coils was also investigated by the authors for pMRI applications [17,18]. As it was explained in [18], the main lobe (central lobe) of the magnetic field produced by a coil is represented by low spatial harmonics whereas the side lobes are represented by high spatial harmonics that correspond to strong spatial variations of the field. The MI lens is able to transfer the harmonics that constitute the main lobe of the magnetic field of the coil but not the side lobes [18]. Thus, the MI lens localize the FOV of the coil and remove the main source of noise correlation between adjacent coils represented the side lobes. In pMRI, image acceleration is obtained by reducing the number of phase-encoding steps and the information associated with the missed steps is provided by the spatial sensitivity pattern of a coil array [1–4]. Localization of the FOV is of great interest for pMRI applications, as is explicitly discussed in [2]. In pMRI, the SNR after the image reconstruction is decreased by the square root of the acceleration factor R as well as by an additional coil-geometry dependent factor known as g-factor [1,4]. The g-factor results in a spatially variant noise enhancement due to the noise propagation through the reconstruction method and it depends on the encoding capability of the receiver array. Thus, in [18] the authors investigated how CLR metamaterials lenses can improve the g-factor of a two-channel array.

Whereas the SNR of a surface coil increases with the field strength, it is not clear if this also holds true for a surface coil loaded with a metamaterial lens. In our research, all the previous work with metamaterial lenses was performed with devices operating at the Larmor frequency of 1.5 T systems. Therefore, it would be of interest to investigate metamaterial lenses performance at different frequencies. Sample noise in a conventional MRI experiment can be the dominant source of noise as the frequency increases [23]. This is due to the fact that the sample resistance grows with the square of the frequency, whereas the coil resistance grows with the square root of the frequency [24]. This last also applies to the metallic rings of the structure of any CLR metamaterial lens. Therefore, it is expected that in experiments with CLR metamaterial lenses, as the frequency increases, the noise coming from the sample will increase faster than the noise coming from the CLR metamaterial lenses. This suggests that the gain in the SNR provided by MI lenses will grow with the frequency provided that the enhancement of the sensitivity is still sufficient. Thus, in the present work, it is investigated, both numerically and experimentally, the ability of MI lenses to increase the SNR of surface coils at different frequencies, in particular, at the Larmor frequencies of 0.5 T, 1.5 T and 3 T systems. The numerical analysis of the