Magnetoinductive lenses for reduction of correlated noise in parallel magnetic resonance imaging

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Abstract

In this work, it is shown the application of split-ring magnetoinductive (MI) lenses in parallel magnetic resonance imaging (MRI). MI lenses provide high localization of MRI coil sensitivities and higher signal-to-noise-ratio in comparison with split-ring $\mu = -1$ lenses. This conclusion is supported by both numerical and experimental results.

1. Introduction

Metamaterials have a narrow band response due to the resonant nature of the elements that constitute the periodic structure (see [1] and references therein). This constitutes one of the most severe limitations for applications. In Magnetic Resonance Imaging (MRI), MR images are acquired by measuring radiofrequency magnetic fields in the MHz range inside a relatively narrow bandwidth of a few tens of kilohertz. Therefore, the narrow band response of metamaterials is not a problem for MRI. Thus, MRI constitutes a promising field of application for metamaterials. One of the most striking properties of metamaterials is the ability of a metamaterial slab with relative permittivity ε and relative permeability μ, both equal to -1, to behave as a super-lens with sub-wavelength resolution [2]. In the case of MRI applications, since the frequency of operation is sufficiently low, metamaterials are in the realm of the quasi-magnetostatics, and a metamaterial slab with $\mu = -1$ can behave as a super-lens [2]. In previous works, some of the authors showed that a three-dimensional (3D) array of capacitively-loaded rings can behave as an effective homogeneous medium with $\mu = -1$ and also explored both theoretically and experimentally the ability of this structure to behave as a super-lens for MRI [3]–[7]. The long acquisition time is the main drawback of MRI in comparison with computerized tomography, and time reduction without degrading the signal-to-noise ratio (SNR) is the main aim of research in the MRI comunity. Image acceleration in MRI is achieved by means of techniques known in general as parallel MRI (pMRI) [8]. pMRI works by taking advantage of the spatially sensitive information inherent in a receiving array of multiple surface coils in order to partially replace time-consuming spatial encoding. Overlapping of the field of view (FOV) of adjacent coils in the array degrades the SNR of the image due to the noise correlation existing between the coils [8]. In a previous work, the authors experimentally shown [6] that a $\mu = -1$ slab consisting of a 3D array of capacitively-loaded rings can help to discriminate the fields produced by the coils at deeper distances inside the patient body, so that this device could be advantageously used in pMRI techniques in order to obtain improved localization of coil sensitivities. Although the reported device [6] actually improved the localization of the FOV, the authors also realized that the SNR was degraded in the full FOV by the presence of the lens due to the additional ohmic losses of the device [6]. Therefore, in order to achieve a practical application in pMRI, reduction of these losses is required. In the present work, capacitively-loaded ring lenses with different structures have been investigated in order to look for a device providing higher SNR. This research was carried out by means of a computational tool developed by the authors for the calculation of the SNR provided by MRI coils in the presence of capacitively-loaded ring structures and a conducting phantom resembling human tissue [7]. Using this method, several structures have been numerically and experimentally analyzed and an optimum structure has been found.

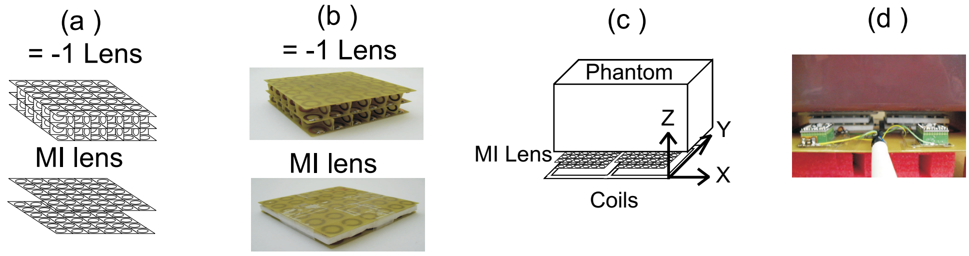

Fig. 1: (a): Sketch of a 3D $\mu = -1$ lens with two unit cells in depth and a MI lens, both of them with an area of 6×6 unit cells. (b): Photographs of the real devices sketched in (a). (c): Sketch of the configuration under analysis and consisting of two lenses placed between a two-channel array of coils and a phantom. (d): Photograph of the real configuration with MI lenses.

2. Analysis

The configuration under analysis is shown in Fig.1. It consists of a two-channel coil array of squared coils with a metamaterial structure placed between these coils and a phantom. In a previous work [6], a similar configuration was analyzed where the metamaterial lens had a larger area than the array. In the present research, we have found that the noise coming from the metamaterial structure is reduced significantly if the metamaterial lens is divided into two smaller lenses, each one of them with an area smaller than the area of each coil (see Fig. 1.c). The distance between the coils, the lenses and the phantom can be optimized using the previously reported method [7] in order to get higher SNR. In our analysis, $\mu = -1$ lenses corresponding to 3D arrays of two and one unit cells in depth were studied. A second type of lens proposed in the past by the authors [9]-[11] and termed magnetoinductive (MI) lens was also studied. The MI lens consists of a pair of parallel 2D arrays of rings. The principle of operation of the MI lens is different from the $\mu = -1$ lens. In the MI lens, the operating frequency does not correspond to an effective value of permeability but to a frequency between two resonances [11] which are similar to plasmons in negative permittivity devices [2]. Moreover, whereas the $\mu = -1$ lens is isotropic, 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 MRI coils at closer distances is mainly axial. In our analysis, it was found that the MI lens provides the higher SNR. This is because the ohmic losses are lower in the MI lens in comparison with the $\mu = -1$ lens, due to the removal of unnecessary rings. Thus, two MI-lenses with 6×6 rings were designed and fabricated to operate at 63.63 MHz for experiments in a 1.5 T clinical MRI scanner. Each ring is 4.935 mm in radius and have 2.17 mm of strip width and contains a 470 pF non-magnetic capacitor. The two arrays in the MI lens are separated by a distance of 11 mm, and the distance between the coils and the lenses and between the lenses and the phantom was 6 mm. Two receive-only arrays with two 12x12 cm^2 elements were built. One array was combined with the MI-lenses. The elements in both arrays are decoupled using a shared conductor with a decoupling capacitor. Each element in both configurations was tuned to 63.63 MHz and matched to 50 Ω in presence of an agar–phantom. The elements in the coil arrays were also actively decoupled by a tuned trap circuit tuned to 63.63MHz including a PIN diode in transmission. MR images were acquired in the 1.5 T whole body system (Symphony, Magnetom, Siemens, Germany) sited at the University Hospital Virgen Macarena (Seville, Spain)

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3. Results and discussion

The decoupling between elements achieved in both coil array configurations was better than -24 dB. The active decoupling by the traps has been found to be better than -30dB. In order to investigate the SNR performance of the coil arrays, quantitative pixel per pixel SNR maps were calculated from a series of identical phantom images for both setups using a gradient-echo sequence (parameters: TR/TE: 300 ms/10 ms, FOV: 380×380 mm^2, Matrix: 256×256, slice thickness=5 mm). Figure 2 shows a comparison of the calculated SNR-maps. The results if Fig. 2 make apparent the ability of the MI lenses to localize the FOV of the individual elements in the coil array. Moreover, for short distances, the SNR provided by the lenses is even higher than in absence of the lenses. This is a clear improvement in comparison with the experimental results previously reported by the authors [6]. In addition, in order to investigate the parallel imaging capabilities of the MI lenses with the GRAPPA method [12], the noise correlation matrix between the elements in the coil arrays was calculated from measured data. It was found that the noise correlation between elements was reduced from 0.115 to 0.025 with the MI lenses. Therefore, it can be concluded that the MI lenses can improve the parallel imaging capabilities of a coil array.

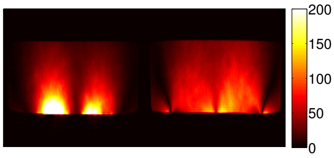

Fig. 2: SNR maps of an agar phantom for a two-channel array of coils with (left) and without (right) MI lenses.

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