Journal of Magnetic Resonance 286 (2018) 78–81

Contents lists available at ScienceDirect

Journal of Magnetic Resonance

journal homepage: www.elsevier.com/locate/jmr

Experimental investigation of a metasurface resonator for *in vivo* imaging at 1.5 T

Alena V. Shchelokova [a], Alexey P. Slobozhanyuk [a,b], Paul de Bruin [c], Irena Zivkovic [c], Efthymios Kallos [d], Pavel A. Belov [a], Andrew Webb [c,*]

[a] Department of Nanophotonics and Metamaterials, ITMO University, Saint Petersburg, Russian Federation
[b] Nonlinear Physics Center, Australian National University, Canberra, ACT 2601, Australia
[c] C.J. Gorter Center for High Field MRI, Department of Radiology, Leiden University, Medical Center, Leiden, The Netherlands
[d] MediWise | Medical Wireless Sensing Ltd, Queen Mary Bio Enterprise, London, UK

ARTICLE INFO

Article history:
Received 17 September 2017
Revised 18 November 2017
Accepted 21 November 2017
Available online 22 November 2017

Keywords:
Metasurface
Transmit efficiency
Specific absorption rate
Implant

ABSTRACT

In this work, we experimentally demonstrate an increase in the local transmit efficiency of a 1.5 T MRI scanner by using a metasurface formed by an array of brass wires embedded in a high permittivity low loss medium. Placement of such a structure inside the scanner results in strong coupling of the radiofrequency field produced by the body coil with the lowest frequency electromagnetic eigenmode of the metasurface. This leads to spatial redistribution of the near fields with enhancement of the local magnetic field and an increase in the transmit efficiency per square root maximum specific absorption rate in the region-of-interest. We have investigated this structure *in vivo* and achieved a factor of 3.3 enhancement in the local radiofrequency transmit efficiency.

1. Introduction

Nazarian et al. [1] have reported that the likelihood of a patient with an implanted medical device requiring an MRI scan is more than 75%. Clinical scans performed either at 1.5 T or 3 T normally use the body coil for radiofrequency (RF) transmission, meaning that RF is deposited in all parts of the body, not only in the region-of-interest. The presence of medical implants often results in scans with low specific absorption rate (SAR) being prescribed, which reduces the diagnostic quality of the images. In many cases a patient who would be scanned at 3 T in the absence of an implant is moved to a 1.5 T system since the power deposited in the patient is lower: again this process is accompanied by lower image quality.

In many cases the imaging region-of-interest is different from the area in which the medical device is implanted, or in which electrical leads to the medical device are located. In these cases the SAR issues can potentially be overcome if a local transmit coil rather than the body coil could be used. However, with a few exceptions (e.g. head and knee) there are very few local transmit coils which are produced commercially, and many sites do not have even those which are commercially available. To address this issue Yu et al. [2] proposed an elegant approach in which high permittivity materials [3,4] could be placed around the imaging region-of-interest in order to concentrate the local transmit field produced by the body coil, resulting in a reduction in the required power transmitted by the body coil for a given image contrast, and an associated reduction in global and local SAR [2]. The authors showed electromagnetic simulations at 3 T which suggested that judicious placement of such materials could result in a reduction of the SAR averaged over 1 g of tissue next to a pacemaker lead by almost 75%. This approach could potentially be extended to 1.5 T, although one would require materials with much higher permittivity values.

A potential alternative approach is to use metamaterial-like structures [5,6]. Some approaches to shaping the local magnetic fields using metamaterials for MRI have already been discussed in the literature [7–13]. For example, metamaterials made from split-ring resonators can be employed as matching devices between a patient and the receive coils and for local transmit efficiency improvement [9]. However, these types of structures are very complicated to construct and fine-tune. Recently, a simple two-dimensional structured metasurface has been proposed [11]. Results in phantoms showed that this artificial structure could effectively increase the local RF magnetic field at 1.5 T. However, in this original work, the geometry was not practical in requiring the sample to be placed in a high dielectric material and no

* Corresponding author at: C.J. Gorter Center for High Field MRI, Department of Radiology, Leiden University Medical Center, Albinusdreef 2, 2333 ZA Leiden, The Netherlands.

E-mail address: a.webb@lumc.nl (A. Webb).

https://doi.org/10.1016/j.jmr.2017.11.013
1090-7807/

detailed consideration of SAR was covered, which is a key element in translating its use to human scanning. In this current work we extend the principles developed for the original metasurface [11] and show the first human MRI scans at 1.5 T. An increase in the transmit field efficiency of up to a factor of 3.3 has been achieved, with a reduction in global SAR by the equivalent amount.

2. Methods

2.1. Electromagnetic simulations

For comparison between simulation and experimental results, a numerical model of the metasurface was developed in commercially available software (CST Microwave Studio 2016). A 16 rung high-pass birdcage coil (inner diameter 68 cm; length 104 cm) was used, loaded with the virtual voxel human model "Gustav" (from the CST voxel family) with a mesh resolution $2.08 \times 2.08 \times 2\ mm^3$. The B_1^+ field and SAR were calculated using the time domain solver. For phantom simulations the following parameters were used: $\varepsilon = 80 + 0.2i$ – low loss phantom, $\varepsilon = 80 + 168.5i$ – phantom with losses approximating those of the body; length 16 cm, width 6 cm and height 3 cm. The phantom was placed on top of the metasurface. Simulated effects of loading were evaluated using a model incorporating an untuned 4 cm diameter conducting loop placed directly below the center of the metasurface.

2.2. Experimental setup

All MR images were acquired on a Philips Ingenia 1.5 T system (Leiden University Medical Center, Leiden, The Netherlands). Volunteer experiments were approved by the local medical ethics committee. As described previously [11], the metasurface was assembled from an array of 14 × 2 brass wires with length $L = 37.2$ cm, radius $r = 0.1$ cm, and period $a = 1$ cm which was placed in thin hollow 3D-printed ABS plastic holders and embedded in a watertight and mechanically robust box made of 0.5 cm thick acrylic sheet of dimensions $42.2 \times 18.2 \times 5.7\ cm^3$ filled with water ($\varepsilon = 80 + 0.2i$ at room temperature). The resonant frequency of the metasurface eigenmode characterized by the highest penetration depth was measured using a pick-up loop and vector network analyzer both outside and inside the magnet: minimal detuning was measured inside the bore. *In vivo* images were acquired using two multislice low tip angle T_1-weighted gradient echo sequences: (1) used for acquiring slices which cover both wrists (and abdomen), tip angle = 10^0, TR = 216 ms, TE = 3 ms, acquisition matrix = 280 × 280, field-of-view = $560 \times 560\ mm^2$, acquisition time = 93 s; (2) used for zoomed imaging of one wrist placed above the metasurface: tip angle = 10^0, TR = 616.3 ms, TE = 18 ms, acquisition matrix = 120 × 120, field-of-view = $120 \times 120\ mm^2$, acquisition time = 101 s. The transmit efficiency (B_1^+ per square root input power) was calculated using a single image acquired using the larger field-of-view obtained with the body coil in transmit and receive mode and the metasurface placed underneath one wrist of the volunteer, while the other wrist was located on top of a sandbag. The signal intensities in each wrist are proportional to the product of the transmit and receive sensitivities, which are essentially identical at 1.5 T. In a second experiment, the metasurface performance was evaluated under more realistic scanning conditions using the body coil to transmit and a small (10 cm diameter) surface coil for receive. One surface coil was placed in an identical position above each wrist, with the metasurface placed below the right wrist. The signal-to-noise ratio (SNR) enhancement was measured as the ratio between the average value of the signal in the right wrist divided by that in the left.

3. Results

3.1. Electromagnetic simulations

Electromagnetic simulations of the metasurface are shown in Fig. 1. The metasurface supports a set of eigenmodes in the frequency range of the first Fabry-Perot regime. These eigenmodes are the result of the splitting of the original resonance frequency into several bands associated with the high coupling between the resonant wires, which are spaced apart by much less than one wavelength [14–16]. Each eigenmode can be characterized by its penetration depth and for all eigenmodes the magnetic field is concentrated in the central part of the metasurface while the electric field is maximum at its ends. In the current design, the metasurface was tuned to the eigenmode that has the highest penetration depth [11]. Fig. 1(c) shows that for this eigenmode of the metasurface the highest magnetic field is localized in the center of the metasurface (blue curve), and the electric field is confined near the ends of the wires (red curve). Compared to the setup described previously [11] the wires are placed much closer to the top part of the box to maximize the coupling with the subject who is positioned directly on top of the structure. Fig. 1(b) shows approximately a 300 kHz downward shift in frequency when a load with realistic loss is placed directly on top.

Fig. 2 shows the simulated B_1^+ maps for the human voxel model inside a birdcage body coil without (a) and with (b) the metasurface placed under the wrist. All simulations were normalized to 1 W accepted power. Comparing Fig. 2(a) and (b) the metasurface significantly enhances the B_1^+ field due to the coupling of the excitation field with the lowest frequency metasurface eigenmode: the increase of the B_1^+ in the imaging region-of-interest is a factor of 3.6. Of course, as with all surface elements, the magnetic field decreases with distance from the metasurface [Fig. 2(b)].

Fig. 2(c) and (d) shows the corresponding numerical SAR simulations without (c) and with (d) the metasurface. It should be noted that, in order to accommodate the metasurface, the body model is offset approximately 5 cm in the left–right direction, and this accounts for the asymmetry in the SAR maps. For 1 W accepted power for the cases without and with the metasurface, the maximum SAR values are 0.15 and 0.13 W/kg, respectively. There is a slight spatial redistribution of the SAR within the wrist below the metasurface.

3.2. In vivo results

Fig. 3 shows photographs of the *in vivo* setup and the metasurface. Volunteers were placed such that the wrist was positioned above the center of the metasurface while the other wrist was placed on top of an equivalently-sized sandbag. As mentioned above, the volunteer was offset slightly in the left–right direction to accommodate the metasurface.

As described in the methods section, images of the wrist were acquired with and without the metasurface using the body coil in both transmit and receive mode. The average increase in SNR was a factor of 11, corresponding to an increase in transmit efficiency of a factor of 3.3, slightly less than that obtained from electromagnetic simulations. Fig. 4 shows low tip angle gradient echo scans of the human wrist using the more realistic situation of body coil transmit and surface coil receive. An SNR improvement of a factor of 4.4 was measured in the wrist placed above the metasurface compared to the other wrist. Since this SNR increase is slightly higher than that of the transmit efficiency, one can conclude that the receive sensitivity of the surface coil is also improved due to the presence of the metasurface eigenmode, despite the presence