Magneto-active Metamaterials for 1.5T MRI: An Intelligent Approach to Boost the Signal-to-Noise Ratio of a Scan

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***Abstract* — Magnetic metamaterials can improve the performance of conventional MRI systems by boosting the magnetic fields in the region-of-interest under scan. However, these reported metamaterials amplify the electromagnetic fields during both RF transmission and reception during MRI scans. The amplification of RF fields by metamaterials during the transmission phase of MRI could lead to potential hazards for patients such as tissue heating, high specific absorption rate, *etc.* Thus, a magneto-active metamaterial is proposed for the 1.5T MRI that can selectively boost the received signals from the patient's body without affecting the transmitted signals during a scan. The magneto-active metamaterial could provide an intelligent way to enhance the MRI scanned images (boosts the SNR by 2.5 times), keeping patients' safety in mind by minimizing potential scan threats.**

Keywords* — *magneto-active metamaterials, signal-to-noise ratio, intelligent scanning, magnetic resonance imaging

I. INTRODUCTION

Magnetic metamaterials constitute periodically arranged unit cells made of conventional materials (dielectrics or metals) that can show peculiar electromagnetic properties not exhibited by these conventional materials [1]. These magnetic metamaterials can enhance and localize the magnetic fields in the region of interest at a target frequency, enabling its application in commercial MRI systems that also operate on narrow bandwidth RF signals [1]. Numerous magnetic metamaterial designs have been reported for boosting the RF magnetic fields and signal-to-noise ratio (SNR) of 1.5T MRI [2]. However, these electromagnetic field boosting structures interact during both RF transmission (Tx) phase as well as reception (Rx) phase inside the MRI scanners. This interaction or enhancement of electromagnetic signals during the Tx phases by metamaterials leads to a higher transmission of RF power inside the human body parts undergoing scan, which might result in safety threats for patients such as tissue heating, high specific absorption rate (SAR), *etc.* [2,3]. In addition, the modification of signals in the RF Tx phases could create artifacts, suboptimal imaging, and difficulties in the clinical adoption of the reported metamaterials.

Therefore, a magneto-active metamaterial is demonstrated in this manuscript which could resolve the aforementioned limitations by selectively enhancing the RF signals mainly during the Rx phases and staying nearly non-interactive during the Tx phases of RF signals inside an MRI scanner. The proposed metamaterial opens an intelligent approach to scanning and provides a ~2.5 times enhancement in the SNR while assuring minimal scanning hazards for patients during the clinical routine.

II. DESIGN, RESULTS, AND DISCUSSION

For designing the unit cell, a flexible FR4 substrate (of thickness 0.2 mm) is sandwiched between two layers of copper spirals (each of 0.035 mm thickness). The unit cell of magneto-active metamaterial loaded with two capacitors (C_1 & C_2 of 2.9 pF) and an MRI-compatible PIN diode (MA45471) is demonstrated in Fig.1(a) [4]. An 8×8 array of unit cells is placed on a saline water-filled phantom under an RF coil excitation, as shown in Fig. 2(b) [2]. The resonance frequency (f_0) of the metamaterial depends on the equivalent inductance (L) and capacitance (C) of the structure *i.e.* $f_0 = 1/2\pi\sqrt{LC}$ which changes during the Tx phase under high RF

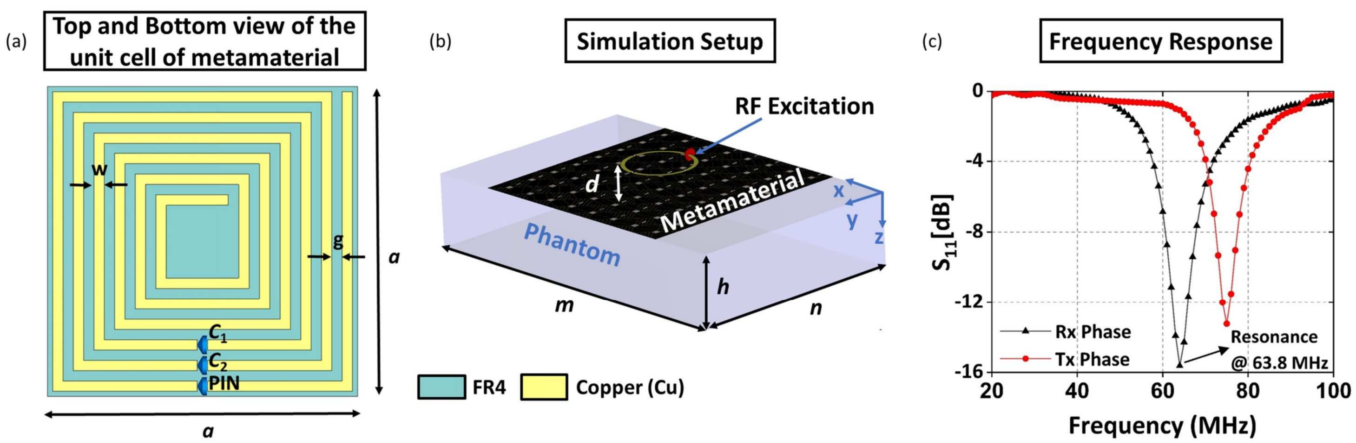

Fig. 1. (a) Unit cell of the magneto-active metamaterial loaded with two capacitors (C_1 & C_2 of value 2.9 pF) and a PIN diode (MA45471) as a switch [4]. The dimension parameters are a = 30 mm, w = 1 mm & g = 1 mm. (b) Simulation setup of the metamaterial on a saline water-filled phantom (m = 380 mm, n = 240 mm & h = 100 mm) with an RF excitation (placed at an optimized distance of d = 25 mm). (c) Frequency response of the magneto-active metamaterial during Tx and Rx phases of RF signals (simulation parameters mimics the MRI scanner Tx and Rx phases).

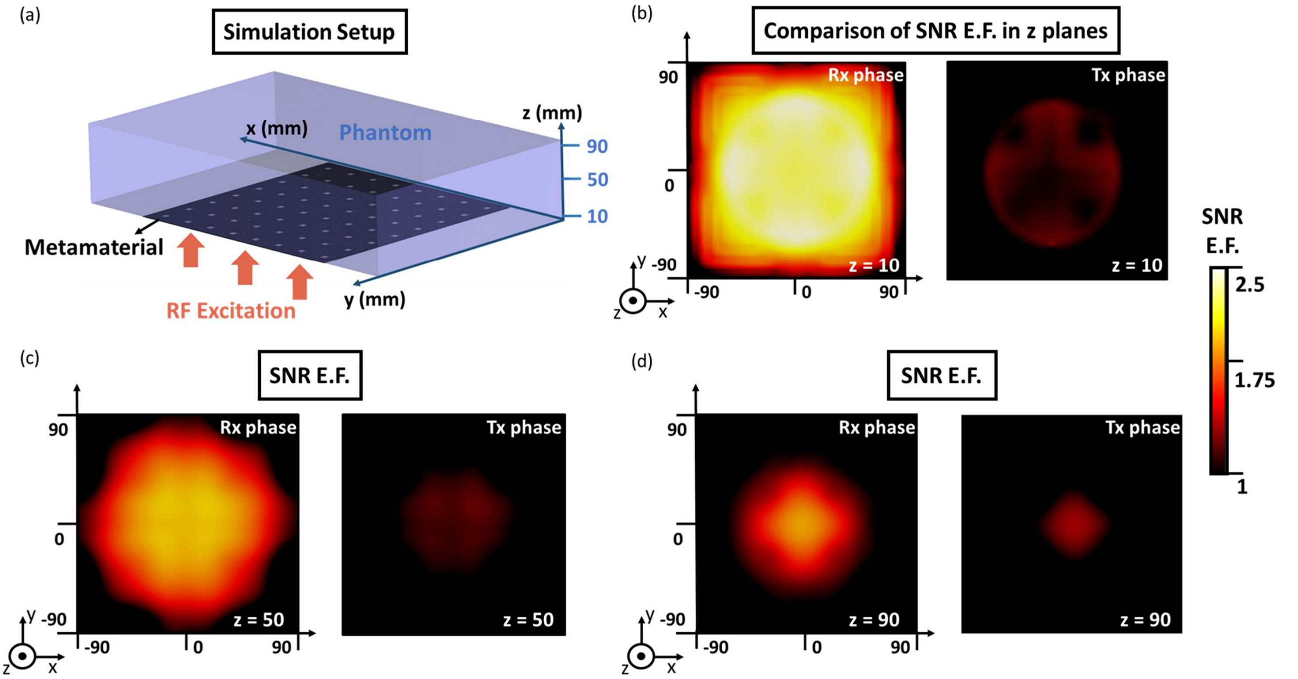

Fig. 2. (a) Simulation setup of the metamaterial. Comparison of SNR enhancement factor (E.F.) on various planes along z-axes of (b) 10 mm, (c) 50 mm and (d) 90 mm inside the phantom. The maximum attained value of SNR E.F. is ~2.5 at z = 10 mm plane during the Rx phase. The value of SNR E.F. remains ~1 along all the z-planes during the Tx phase inside the phantom.

signal due to the presence of PIN diode [4]. In simulation, the MA45471 PIN diode is considered as a parallel RC network for a small signal *i.e.* the Rx phase and a short circuit for a high RF signal *i.e.* the Tx phase of MRI scanning [4]. Numerical simulations demonstrate that the metamaterial behaves as a resonant tank circuit during the Rx phase and detune during the Tx phase, as shown in Fig. 1(c). Therefore, the metamaterial boosts the received magnetic field which translates to a high SNR during the Rx phase and behaves close to a non-interacting element for RF signals during RF transmission. The SNR is proportional to the received RF magnetic field B_1^- divided by the square root of the accepted power P_{abs} for 1A current fed to the coil [1].

$$\text{SNR} \propto \frac{B_1^-}{\sqrt{P_{\text{abs}}}} \tag{1}$$

To analyze the boost in the performance using the metamaterial (MM), the SNR enhancement factor (E.F.) can be calculated as [1]:

$$\text{SNR Enhancement Factor} = \frac{\text{SNR}_{\text{with\_MM}}}{\text{SNR}_{\text{without\_MM}}} \tag{2}$$

The simulated SNR E.F. is compared along three different planes inside the phantom along z-axes of 10 mm, 50 mm, and 90 mm, as shown in Fig. 2. The SNR E.F. attains a maximum value of 2.5 along z = 10 mm plane *i.e.* close to the metamaterial (Fig. 2(b)) during Rx phase which remains around 1.75 at the center throughout the phantom as depicted at plane z = 90 mm (Fig. 2(d)). During Tx phase, the value of SNR E.F. remains ~1 along all three z-planes inside the phantom. The proposed magneto-active metamaterial with the simulation findings could pave the way for smart and improved MRI scanning, while minimizing all potential risks for patients besides offering flexible manufacturing benefits.

III. Conclusion

An intelligent approach is demonstrated here to increase 1.5T MRI imaging quality (in terms of SNR) by selectively boosting the magnetic field during the reception phase of the RF signals inside MRI scanner using a magneto-active metamaterial. The designed magneto-active metamaterial turns itself "on" to boost the RF signal emissions from the patient's body parts under scan *i.e.* SNR by 2.5 times and stays "off" during the phase of high-energy RF signal transmission from the scanners. Therefore, this self-switching capability of the metamaterial will be beneficial in high-quality MRI scanning of patients without the risk of creating any unwanted artifacts or tissue heating as compared to conventional passive metamaterials.

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