Design and Characteristics of a metamaterial transmit/receive coil element for 7 Tesla MRI

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Abstract— **In this work the usage of a composite right/left-handed (CRLH) metamaterial transmission line resonator as a transmit/receive coil for 7 Tesla magnetic resonance imaging (MRI) is investigated. On the basis of zeroth-order resonant antennas (ZORAs) a zeroth-order resonant coil (ZORC) was designed. Due to a constant current distribution along the element, a homogenous magnetic field is achieved in a larger area compared to a conventional microstrip transmission line (MTL) element. Numerical and experimental results are presented.**

Keywords— **metamaterial, CRLH, MRI, ZORA, ZORC**

I. INTRODUCTION

Ultra-high field magnetic resonance imaging (3.0 Tesla and above) promises better signal-to-noise ratio compared to lower strengths of the DC magnetic field. A challenging issue, especially for 7 Tesla and more, is the homogeneity of the RF magnetic field. This RF field can be excited and detected by birdcage resonators as well as by arrays of coils for the use with parallel transmit and receive techniques.

Microstrip transmission line (MTL) resonators are often used as basic elements for such transmit/receive arrays (e.g. [1]). In contrast to a conventional MTL in this work studies of a composite right/left handed (CRLH) metamaterial transmission line resonator [2], with respect to the usage as a transmit/receive coil, are presented. According to CRLH zeroth-order resonant antennas (ZORAs) [3] a zeroth-order resonant coil (ZORC) [4] was designed for the usage at 7 Tesla, corresponding to a frequency of 297.2 MHz. The zeroth-order resonance provides an infinite wavelength. Therefore a constant current distribution along the element can be realized utilizing the series mode resonance.

II. DESIGN OF THE ZORC ELEMENT

The ZORC element is a periodic structure and consists of cascaded CRLH metamaterial unit cells. The equivalent circuit of one unit cell is shown in Fig. 1. The ZORC element is implemented in a double-layer substrate assembly (Fig. 2), realizing the discrete elements of the equivalent circuit as distributed elements.

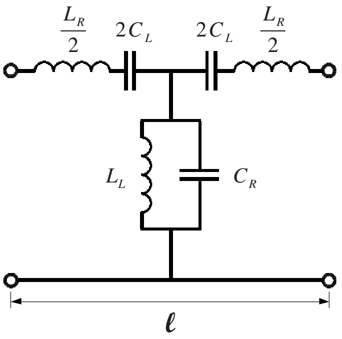

Fig. 1 Equivalent circuit of a T-symmetric CRLH unit cell

A. Layout of a single CRLH unit cell

The layout of one unit cell is depicted in Fig. 2. The series inductances L_R and the shunt capacitance C_R arise both parasitic from the whole unit cell topology, whereas the other elements of the corresponding equivalent circuit are explicitly realized. The series capacitances C_L are implemented as metal-insulator-metal (MIM) capacitors, and the shunt inductance L_L is realized by a stub, shorted by a via to the ground metallization. The top metallization is separated from the bottom metallization by a $t_{Rogers} = 250\ \mu m$ thick Rogers 3010 substrate ($\varepsilon_r = 10.2$, $\tan(\delta) = 0.0035$). The overlapping areas of these two metallization layers compose the MIM capacitors. A $t_{Poly} = 2$ mm thick Polystyrol ($\varepsilon_r = 2.7$, $\tan(\delta) = 0.0003$) substrate layer is positioned between the bottom and ground metallization. The unit cell is $l = 61.1$ mm long, and the MIM capacitors are $w = 30$ mm wide. The stubs are 22.5 mm long and 1.5 mm wide. This design was optimized to realize the series mode zeroth-order resonance [3] with the resonant frequency $f_{se} = 1/\sqrt{L_R \cdot C_L}/(2\pi) = 297.2\ \text{MHz}$.

O. Dössel and W.C. Schlegel (Eds.): WC 2009, IFMBE Proceedings 25/II, pp. 173–176, 2009.
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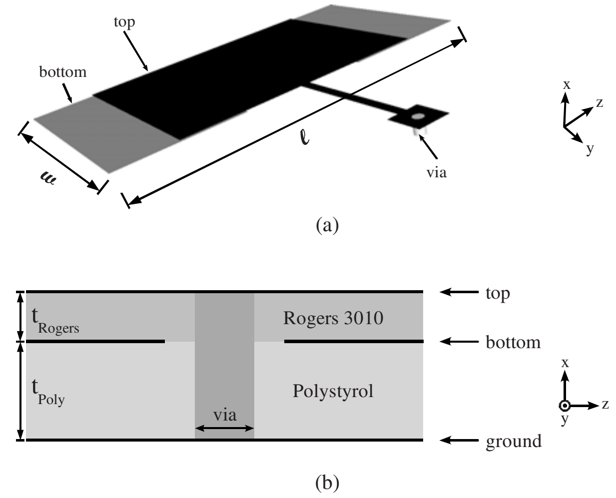


(a)

(b)

Fig. 2 Layout of the unit cell, showing a perspective view of the top and bottom metallization (a) and the multilayer stack (b)

B. Composition of the complete ZORC element

The complete ZORC element (Fig. 3) is 250 mm long and 100 mm wide. It consists of 4 unit cells, but as the zeroth-order resonance is independent of the number of unit cells, the ZORC element could be easily extended. At one end the element is terminated by a short to the ground metallization. This enforces the required series mode zeroth-order resonance. At the other end of the ZORC element a feeding network is positioned on the backside of the element to match the purely resistive and very small input impedance to 50 Ω.

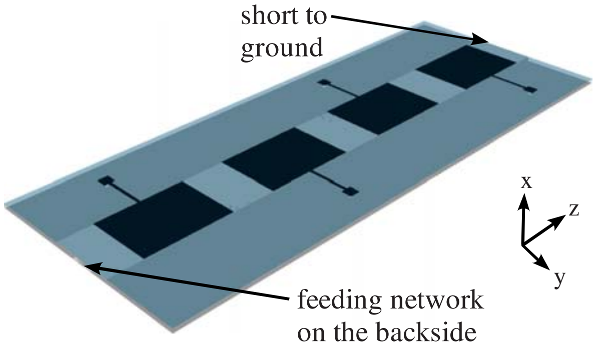


Fig. 3 Model of the ZORC element

III. CHARACTERIZATION OF THE ZORC ELEMENT

A. Simulation setup

The characteristics of the ZORC element are compared to a conventional MTL coil element, similar to the one in [5]. This MTL element has the same substrate configuration as the presented ZORC element, and a 30 mm wide strip line on the top metallization. All simulations were done using the commercially available software package EMPIRE^{TM}. A flat phantom ($\varepsilon_r = 43.4$, $\sigma = 0.8$ 1/Ω/m) was positioned in x-direction 20 mm above the elements. To determine the mutual coupling, two elements with a gap of 5 mm were investigated for each case.

B. Numerical Results

The penetration depth is the distance at which the magnetic field falls to the 1/e of the field at the surface of the phantom. The distribution of the magnetic field along the perpendicular x-direction is shown in Fig. 4. Both elements show a similar characteristic in the distribution of the magnetic field, and the calculated penetration depth into the phantom is about 22 mm for both elements.

In Fig. 5 (a) and (b) respectively, the magnetic field along the longitudinal, and the transverse direction, 30 mm above the element (10 mm inside the phantom) is shown. In both directions the field of the MTL element is more concentrated around the center of the element ($y = 0$ mm, $z = 125$ mm) than the field of the ZORC element. Therefore, the ZORC element can be used to examine a larger field of view, while the size of the element is the same as the MTL element.

The homogeneous magnetic field along the longitudinal z-direction results from the constant current distribution of the series mode zeroth-order resonance. The simulated current density in the top metallization layer is shown in

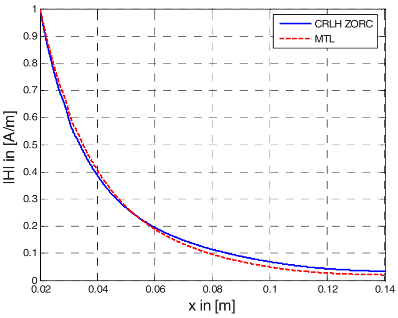
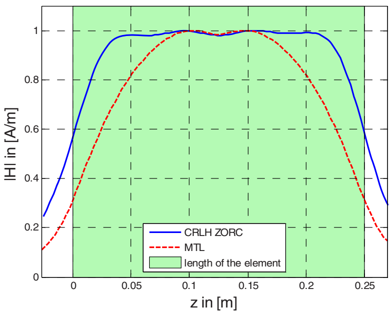
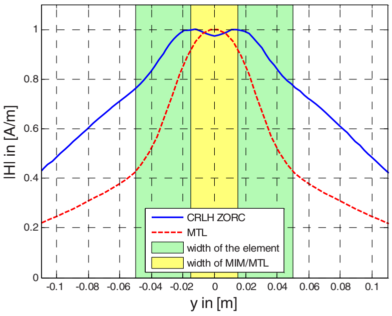


Fig. 4 Normalized magnetic field perpendicular to the element (along the x-axis). Starting from 20 mm above the element, where the phantom is positioned



(a) Along the longitudinal z-axis



(b) Along the transversal y-axis

Fig. 5 Normalized magnetic fields 30 mm above the element (10 mm inside the phantom)

Fig. 6. At the positions along the longitudinal z-direction, where this distribution shows the discontinuities, the current is guided in the bottom metallization. Apart from these discontinuities, the current distribution is nearly constant along the element.

Another parameter for the characterization of a coil element to be used for a transmit/receive array is the mutual coupling of neighboring elements. The smaller the coupling between the elements the better results can be produced. The ZORC element produces a homogeneous magnetic field in a larger area compared to the conventional MTL element. Although showing a significant larger field strength adjacent to the element (Fig. 5 (b)), where the second element is positioned, the mutual coupling between two elements increases only slightly to – 13 dB for the ZORC element, compared to – 14 dB for the MTL element.

C. Experimental Results

A first prototype of the ZORC element was build and is shown in Fig. 7. Since the used materials are not transparent, only the top metallization and a part of the feeding cable are visible. First measurements of the magnetic field were done 20 mm above the ZORC element without a phantom.

These results are depicted in Fig. 8 (a), whereas in Fig. 8 (b) the numerical result for the same setup is shown. Good agreement is observed between measured and simulated values.

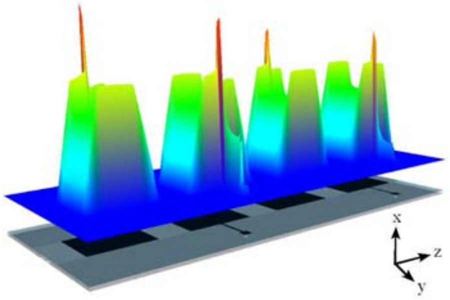


Fig. 6 Simulated current density distribution in the top metallization layer

IV. CONCLUSIONS

A CRLH metamaterial coil element for the usage at 7 Tesla ultra-high field MRI was designed and numerically investigated with respect to near-field characteristics and the mutual coupling of two neighboring elements. Compared to a conventional MTL element, the ZORC element produces a homogeneous magnetic field in a larger area and offers therefore the possibility to investigate a larger field of view with the same physical size of a single element. A prototype of the presented ZORC element was build and first measurements were done. Detailed experimental investigations will follow.

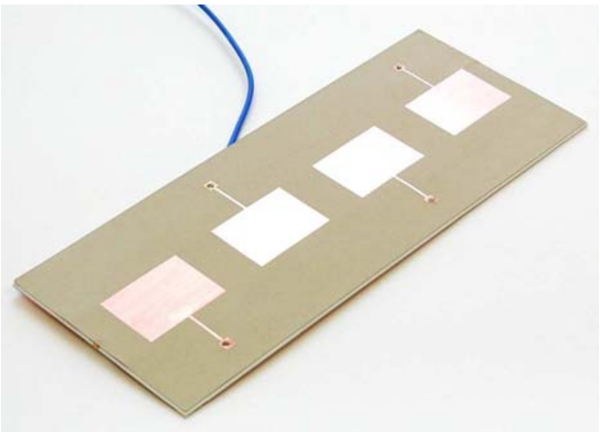
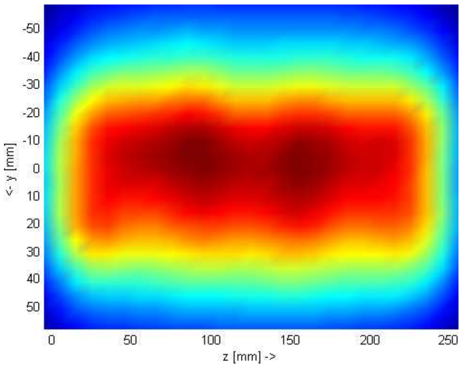
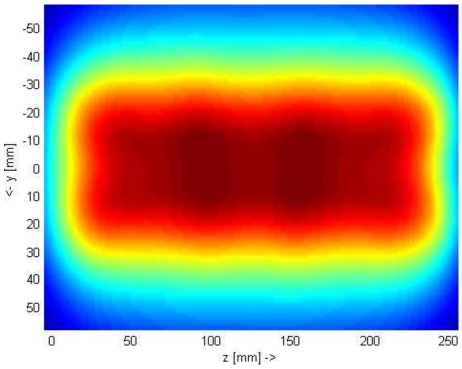


Fig. 7 Prototype of the ZORC element



(a) Measured field



(b) Simulated field

Fig. 8 Absolute magnetic fields in air, 20 mm above the element and normalized to each maximum value

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