# A CRLH Zeroth-Order Resonant Antenna (ZORA) with High Near-Field Polarization Purity used as an RF Coil Element for Ultra High Field MRI

**A. Rennings**[1], **P. Schneider**[1], **S. Otto**[1], **D. Erni**[1], **C. Caloz**[2], **M. E. Ladd**[3]

[1] General and Theoretical Electrical Engineering (ATE) & High-Frequency Engineering (HFT), University of Duisburg-Essen, 47048 Duisburg, Germany; email: andre.rennings@uni-due.de

[2] Poly-Grames Research Center, École Polytechnique de Montréal, Montréal, H3T 1J4, Canada

[3] Erwin L. Hahn Institute for MRI, University of Duisburg-Essen, 45141 Essen, Germany

### Abstract

A CRLH zeroth-order resonant antenna (ZORA) with near-field performance optimized for 7 Tesla magnetic resonance imaging (MRI) is presented. Due to its zeroth-order resonance mode, occurring at the frequency where the phase constant is zero, the ZORA supports a highly uniform field, as required for MRI. Moreover, it exhibits a favorable longitudinal scalability for RF coil lengths ranging from 10 cm up to 50 cm and higher. Compared to previous implementations, the proposed ZORA uses SMD chip components placed at the back of the radiator to provide the CRLH shunt resonator elements instead of transverse stubs. As a result, the longitudinal magnetic field contributions are essentially suppressed and high transverse magnetic field purity, allowing high-resolution MRI, is achieved. As another consequence, the transverse size of the antenna is dramatically reduced, which is particularly beneficial for head or brain imaging, where undisturbed eye-contact with the patient is required in functional MRI. Furthermore the proposed ZORA features a low profile of only 2.3 mm, and could therefore be integrated behind the inner bore dielectric cover.

## 1. Introduction

Magnetic resonance imaging (MRI) is a widely used non-ionizing medical imaging technique. Radiologists use MRI to visualize the structure and functionality of the human body by providing detailed images of it in any plane [1]. The strong longitudinally polarized DC magnetic field $B_0$ aligns the nuclear spins of the hydrogen protons $^1$H of the water contained in the body, while the transversally polarized RF magnetic field $B_1$ precesses the magnetic moments around their axis of polarization (torque, $\vec{T} = \vec{m} \times \vec{B}_1$) and thereby increases the flip-angle between the spins and $B_0$. For $B_0 = 7$ T, the spectrum of the RF pulse is centered around $f = \gamma B_0/(2\pi) = 298\,$MHz, where $\gamma$ is the gyromagnetic ratio of the hydrogen protons [1].

A critical issue for high-resolution MRI is the capability to generate an extremely uniform (or homogeneous) and purely transversally polarized RF field across the field of view (FOV). The development of such RF coils is an active research topic, especially for ultra high field MRI systems with a DC field $B_0 \geq 7$ Tesla.

In [2, 3], we investigated the applicability of composite right/left-handed (CRLH) zeroth-order resonant antennas (ZORAs) [4] to provide such a uniform RF field. Due to the spatially constant current distribution of the series ZO mode ($\lambda_\mathrm{g} = 2\pi/\beta \to \infty$, where $\beta$ is the fundamental space harmonic of the periodic structure), excellent longitudinal homogeneity of the magnetic field was achieved [3]. However, this ZORA suffered from two main drawbacks: a quite large transversal dimension and unwanted longitudinal magnetic field components, both due to the transverse stubs. The proposed CRLH structure resolves these issues.

## 2. Drawbacks of the Previous ZORA

For the sake of comparison, we first consider the conventional CRLH structure, whose unit cell's equivalent circuit [4] and a common realization [2] are depicted in Figs. 1(a) and 1(b), respectively. The series elements $C_\mathrm{L}$ and $L_\mathrm{R}$

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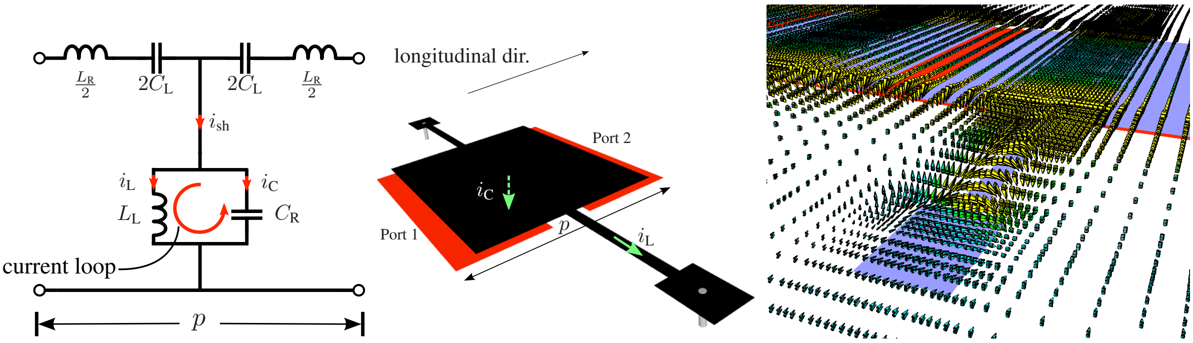
are implemented in metal-insulator-metal (MIM) technology, while the shunt element $L_\mathrm{L}$ is realized by a short-circuited stub. On the other hand, $C_\mathrm{R}$ is parasitic in nature. The two corresponding shunt currents $i_\mathrm{L}$ and $i_\mathrm{C}$ flow along the stub and below the MIM structure as conduction and displacement currents, respectively, as depicted in Fig.1(b). While the overall shunt current $i_\mathrm{sh}$ is minimized at the shunt resonance frequency, $\omega_\mathrm{sh} = 1/\sqrt{L_\mathrm{L} C_\mathrm{R}}$, this is not true for the currents $i_\mathrm{L}$ and $i_\mathrm{C}$, which are out-of-phase and build a current loop, as depicted in the equivalent circuit of Fig. 1(a). The two currents are transversally aligned, yielding an unwanted longitudinal magnetic field component. As a consequence of the non-vanishing stub current $i_\mathrm{L}$, the magnetic field exhibits longitudinal component contributions to the overall field, as depicted in Fig. 1(c).

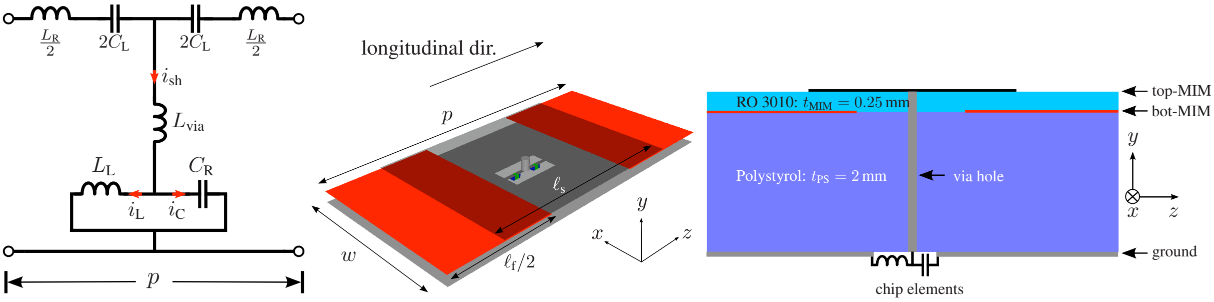


(a) Lossless T-symmetric equivalent circuit of conventional CRLH unit cell. (b) Conventional unit cell topology with side-wise stubs and MIM structure. (c) FDTD simualtion of unwanted longitudinal magnetic field component above the stubs.

Fig. 1: Conventional CRLH unit cell equivalent circuit (EC) (a) and a common realization (b) yields an unwanted longitudinal magnetic field component (c) due to non-negligible stub currents $i_\mathrm{L}$.

## 3. Proposed ZORA

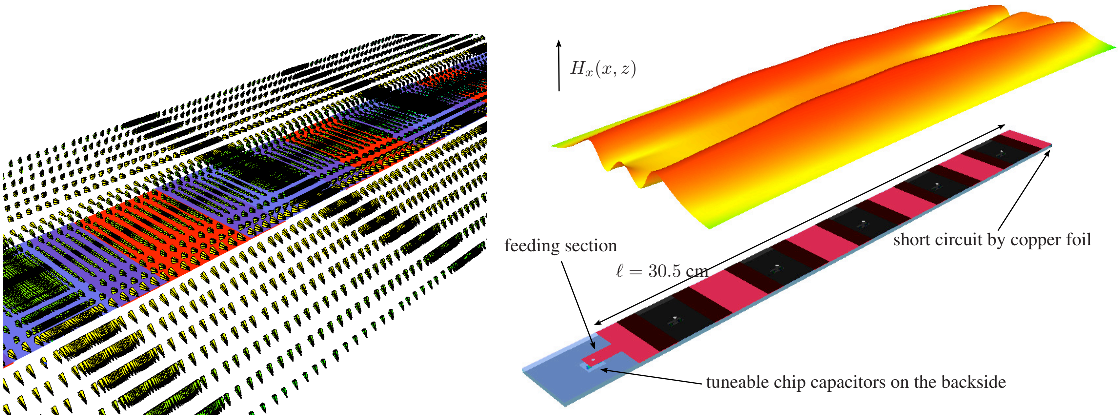
The improved CRLH unit cell for the proposed ZORA is shown in Fig. 2. The replacement of the stubs by SMD chip components for $L_\mathrm{L}$ and $C_\mathrm{R}$ in the shunt path offers more design flexibility. It is exploited to orient the currents $i_\mathrm{L}$ and $i_\mathrm{C}$ along the longitudinal direction, by placing the two chip components at the backside of the multi-layer substrate in a small area where the ground plane is cut out, as depicted in Figs. 2(b) and 2(c). One electrode of each chip element is connected to the ground plane, whereas the other electrode is connected to the top MIM plate by a simple via hole (cf. Figs. 2(b) and 2(c)). Due to the parallel-resonance of the two chip components at the operation frequency, only a small current flows through that via, i.e. all the significant currents are longitudinally oriented. This results in a perfectly polarized magnetic near-field, as shown in Fig 3(a).



(a) Extended EC (inductance $L_\mathrm{via}$) for the novel UC implementation depicted on the right. (b) Perspective view of UC w/ dimensions: $p = 61$ mm, $w = 30$ mm, $\ell_\mathrm{f}/2 = 20.5$ mm and $\ell_\mathrm{s} = 37$ mm (c) Lateral view of the UC w/ conventional MIM structure in series path but novel via-hole/chip-elements topology in shunt path.

Fig. 2: CRLH unit cell (UC) topology with high near-field polarization purity and transversally narrow shape.

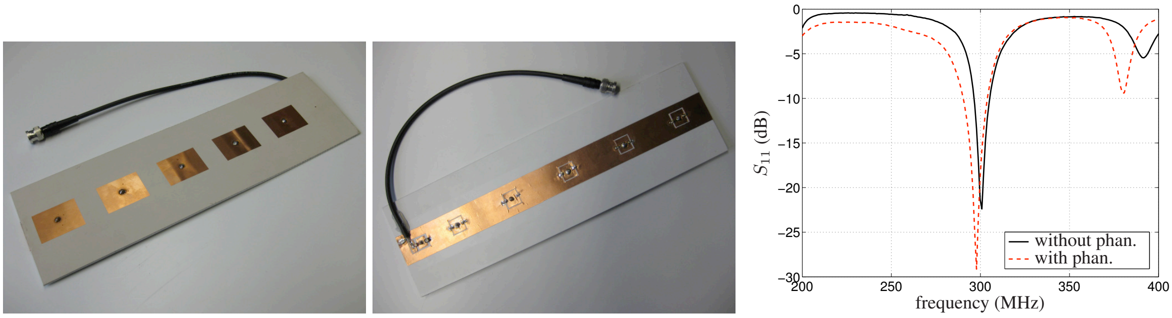
The high permittivity material Rogers RO3010 substrate with $\varepsilon_\mathrm{r} = 10.2$ allows a reduction of the width and the profile (thickness) of the MIM topology. Moreover, in order to realize a transversally narrow structure, the width of the ground plane has been kept equal to the MIM plates' width (cf. Fig 4(b)). The fabricated prototype and the corresponding measured return loss is shown in Fig. 4.



(a) Purely transversal magnetic field - the inhomog. distribution of the pyramids is due to the graded mesh used.

(b) FDTD model with root mean square (RMS over time) distribution of $H_x(x,z)$ 1 cm above the top layer.

Fig. 3: Field distribution of the magnetic vector field (a) at the transition frequency $\omega_\text{t} = \omega_\text{sh} = \omega_\text{se}$ clearly shows an improvement in terms of polarisation purity compared to the case depicted in Fig 1(c), and longitudinally a uniform RMS value for the $H_x$-distribution is obtained (b).



(a) Front view of ZORA prototype.

(b) Rear view of ZORA prototype.

(c) Measured $S_{11}$ with and without a flat phantom.

Fig. 4: Prototype of ZORA RF coil element and corresponding measured return loss with and without a flat phantom ($\varepsilon_\text{r} = 45.3,\ \sigma = 0.87$ S/m) emulating the human head at 300 MHz.

Further measurement results in terms of coupling between adjacent RF coil elements and first evaluations on the 7 T MRI tomograph ($B_1$ maps and MR images of phantoms) will be presented in our future work.

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