Design and characterization of metamaterial-based zeroth-order resonance antennas for 3T MRI

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Abstract – Balanced composite right-left-handed (CRLH) metamaterial transmission lines (TL) operating at their zeroth-order resonance frequency are capable to create constant current distributions alongside them, which is directly associated to the emergence of a uniform RF magnetic field [1]. Such structures are therefore well suited for coil design in high-field magnetic resonance imaging (MRI). Based on the design of the zeroth-order resonance antenna (ZORA) for 7T MRI presented in [2], the geometry of the unit cell (UC) has been extracted and analyzed using EMPIRE XPU's [3] discrete gradient optimizer, whose ZOR frequency lies at 128 MHz, namely the operating frequency for 3T MRI. Prior to optimization, the original topology of the UC has been modified by adding a layer of FR4 while increasing the length of the UC [4]. This ensures that the effective homogeneity condition [1] is still fulfilled. During optimization, the selected geometry parameters are varied, and the scattering parameters are then simulated and compared to a set of predefined specifications. Considering the symmetry and reciprocity of the UC, the following conditions were set for this optimization:

$$|S_{22}| < -20\,\text{dB} \qquad \forall\, f \in [126\,\text{MHz}, 130\,\text{MHz}] \qquad (1)$$
$$|S_{21}| > -0.1\,\text{dB} \qquad \forall\, f \in [126\,\text{MHz}, 130\,\text{MHz}] \qquad (2)$$
$$\arg\{S_{21}\} = 0 \qquad \forall\, f \in [126\,\text{MHz}, 130\,\text{MHz}] \qquad (3)$$

Conditions (1) and (2) ensure that most of the power is transmitted from one port to the other, while minimizing reflections. Condition (3) establishes a zero crossing of the transmission phase in the given range. To simplify the design and to properly balance the unit cell, an inductor has been added connecting top and bottom copper layers. In the fabricated UC the inductor was later substituted by a lumped air coil or a short-circuited coaxial stub line [2]. Fig. 1 illustrates the final design of the UC.

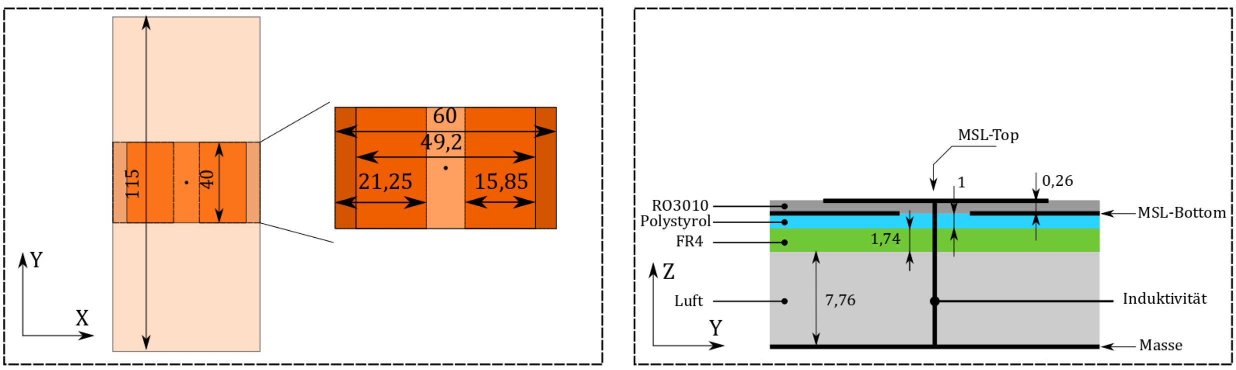

Fig. 1: (left) Top view and (right) side view of the designed UC; all the measures are given in mm.

Extracting the dispersion diagram from the simulated S-parameters, the zeroth-order resonance frequency can be determined by finding the zero of the transmission phase [1]. This can be further evaluated by analyzing the Bloch impedance of the UC (cf. Fig. 3), which yields a frequency-balanced structure with a flat frequency response for its real part (i.e. a closed bandgap) [1]. The

ZORA has been setup by concatenating six unit cells and short-circuiting e.g. the terminal on one side in order to favor the series resonance with a predominantly longitudinal current flow as the operating state of the 36 cm long ZORA coil element. For validation purposes the latter has been loaded with a phantom filled with body tissue simulating liquid (BTSL) that is positioned 20 mm above the ZORA. The nearly uniform magnetic field distribution inside the phantom on a virtual plane 10 mm above its lower boundary is shown in Fig. 2. Further analyses show that the BTSL phantom's proximity does not significantly affect the resonance frequency, whilst the quality factor increases with increasing phantom distance, as shown in Fig. 3. Since ZORAs are scalable, it is possible to design differently sized antennas with similar longitudinally uniform magnetic field distributions, rendering this coil element highly suitable for various high-field MRI applications.

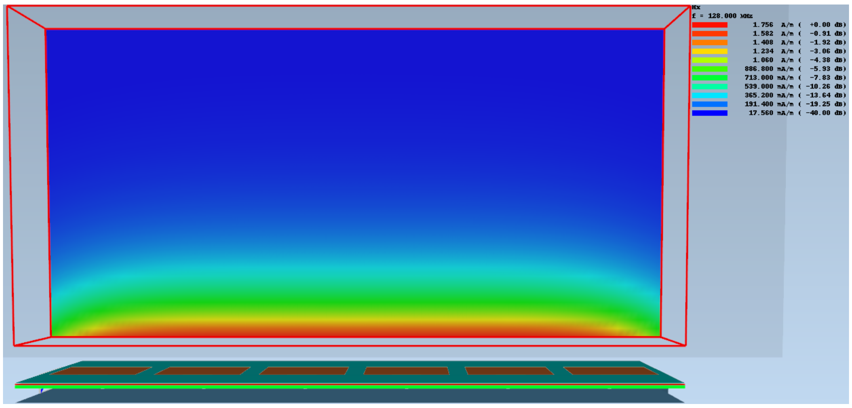

Fig. 2: Virtually uniform distribution of the transversal y-component of the magnetic field 10 mm inside the BTSL phantom.

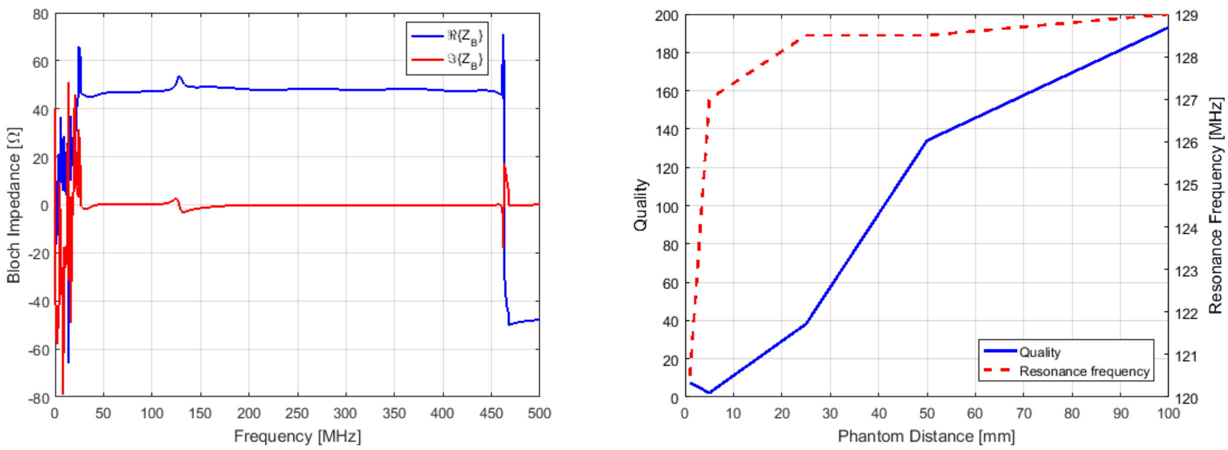

Fig. 3: Spectral response of (left) the Bloch impedance, and (right) the quality factor together with the resonance frequency as a function of the distance between the ZORA coil element and the overlying BTSL phantom.

When using the Bloch impedance of the UC or an approximate resistor instead of the short-circuited termination, the CRLH-TL starts operating as a leaky wave antenna (LWA). As indicated in Fig. 3 its Bloch impedance stays nearly constant over a wide frequency range, aiming thus at ultra-broad-band coil designs for e.g. multi-nuclei MRI, which is now intensely investigated in our lab.

References

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