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MIM CRLH Series Mode Zeroth Order Resonant Antenna (ZORA) implemented in LTCC Technology

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Abstract— **A metal-insulator-metal (MIM) composite right/left-handed (CRLH) series mode zeroth order resonant antenna (ZORA) implemented in LTCC technology is presented and demonstrated to exhibit excellent efficiency (71%) and co-to-cross polarization performances, in addition to a high gain $(10$ dB) provided by its large electrical size of $2\lambda_0$. Due to its versatile characteristics, high performances and capability to attain at low cost high directivities, conventionally available only with standard arrays, this antenna may find various applications in future.**

I. INTRODUCTION

Recentely, composite right/left-handed (CRLH) transmission line (TL) metamaterials (MTMs) have been developed as a novel paradigm in electromagnetics and have been shown to possess a vast potential for novel microwave devices with unprecedented properties [1]. In particular, CRLH TL metamaterials have lead to antennas with novel properties.

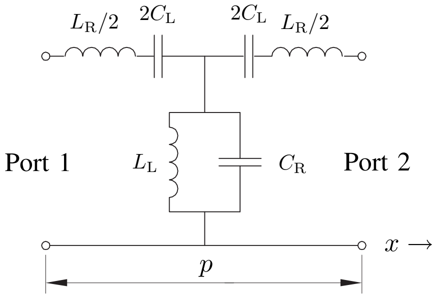
One of such antennas is the CRLH zeroth order resonant antenna (ZORA). This antenna operates at the infinite-wavelength transition frequency between the left-handed (LH) and the right-handed (RH) bands of the CRLH dispersion diagram [Fig. 1(b)], and its operation frequency is independent on the size of the structure, which allows simple and efficient designs of both small antennas for high compactness and large antennas for high directivity. A ZORA may operate either in the CRLH series mode (impedance resonance) or in the CRLH shunt mode (admittance resonance), and these two modes have distinct characteristics [1].

A series mode CRLH ZORA was presented for the first time and demonstrated to exhibit an efficiency comparable to that of a patch antenna in [2]. While the series mode ZORA of [2] was implemented with interdigital capacitors in standard PCB technology, this paper presents a series modes ZORA using superior metal-insulator-metal (MIM) capacitors [3] and integrated low-temperature cofired ceramic (LTCC) technology [4].

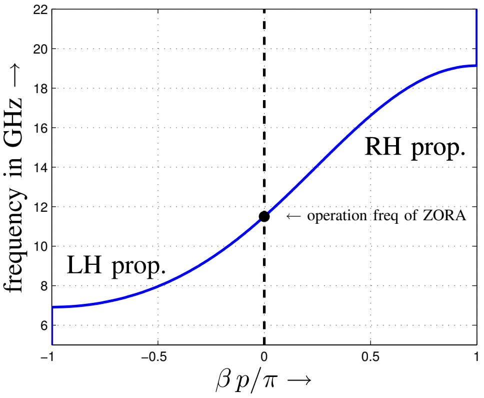
Sec. II recalls the fundamentals of CRLH TLs and explains the CRLH series mode resonance. Sec. III describes the proposed MIM LTCC CRLH structure and discusses its characteristics. Finally the antenna and its performances obtained by FDTD simulations with the software Empire XCcell are presented in Sec. IV.

II. CRLH TRANSMISSION LINE AND SERIES MODE ZEROTH ORDER RESONANCE (ZOR)

A CRLH TL is a structure obtained by cascading unit cells of the type shown in Fig. 1(a). The size p of the unit cells is much smaller than the guided wavelength ($p \ll \lambda_g$), so that the structure is "seen" by the electromagnetic wave as a uniform transmission medium. The dispersion diagram of a CRLH TL may be obtained by application of the Bloch-Floquet theorem



(a) lumped element model for real CRLH unit cell



(b) dispersion diagram for CRLH TL

Figure 1: Dispersion diagram [Eq. (2)] of the CRLH TL used for the ZOR antenna in Sec. IV. The parameters for the corresponding LC unit cell depicted in (a) are $L_R = 1.39$ nH, $C_L = 0.14$ pF, $L_L = 0.39$ nH, $C_R = 0.49$ pF and $p = 3.25$ mm.

to the unit cell of Fig. 1(a) and reads

$$\cos\left[(\beta - \mathrm{j}\alpha)\,p\right] = 1 - \frac{(\omega^2 - \omega_{\mathrm{se}}^2)(\omega^2 - \omega_{\mathrm{sh}}^2)}{2\,\omega^2\omega_{\mathrm{R}}^2}, \tag{1}$$

where $\omega_{\mathrm{se}}^2 = \frac{1}{L_{\mathrm{R}}C_{\mathrm{L}}}$, $\omega_{\mathrm{sh}}^2 = \frac{1}{L_{\mathrm{L}}C_{\mathrm{R}}}$, $\omega_{\mathrm{R}}^2 = \frac{1}{L_{\mathrm{R}}C_{\mathrm{R}}}$. Under the so-called *balanced resonances condition*, defined as $\omega_{\mathrm{se}} = \omega_{\mathrm{sh}} \equiv \omega_0$ and where maximum bandwidth is achieved, Eq. (1) may be inverted to provide the explicit frequency versus propagation constant relation

$$\omega(\beta) = \sqrt{\omega_0^2 + \omega_{\mathrm{R}}^2 \sin^2\frac{p\beta}{2}} + \omega_{\mathrm{R}}\sin\frac{p\beta}{2}, \tag{2}$$

which will be used to determine the resonance frequencies of the structure. This relation is plotted in Fig. 1(b) for a particular set of parameters given in the caption of the figure.

As any uniform TL, the CRLH structure is transformed into a resonator when it is open-ended or short-ended. Due to its limited transmission band (band-pass characteristic as depicted in Fig. 1(b)), a CRLH resonator with N unit cells and size $\ell = Np$ exhibits a finite number of $2N-1$ resonance frequencies, which are found from the dispersion curve as $\omega_n = \omega[\beta = \beta_n = n\pi/\ell = n\pi/(Np)]$ $(n \in \mathbb{Z})$ [1].

The resonance mode $n = 0$, which is called the zeroth order resonance (ZOR) mode, is particularly interesting. It corresponds to an *infinite wavelength* ($\lambda_{n=0} = 2\pi/\beta_{n=0}$) and therefore to a uniform field distribution, which is typically favorable for aperture distribution maximization (maximal directivity) and dissipative loss minimization. Moreover, the frequency of this resonance mode does not depend on the number N of the unit cells constituting the structure and a ZOR CRLH resonator is therefore straightforwardly extensible to either shorter structures (e.g. for small antennas) or to larger structures (e.g. for high-directivity antennas) [2].

A CRLH ZOR mode can be excited either by open-circuiting (with a small coupling capacitance) or by short-circuiting (with a small shunt inductance) the CRLH structure. In the former case, resonance occurs at ω_{sh} and energy is stored only in the admittance (shunt) elements; in the latter case, resonance occurs at ω_{se} and energy is stored only in the impedance (series) elements. When the structure is balanced, these two frequencies are identical, but the location of energy storage is dictated by the type of termination. The antenna presented in this paper is balanced and excited short-ending, so that its energy will be confined in the series elements.

III. DESIGN AND IMPLEMENTATION OF CRLH UNIT CELL IN LTCC TECHNOLOGY

The optimized unit cell used for the proposed LTCC ZORA is depicted in Fig. 2, which also shows the ports, as they were defined to extract the four CRLH LC parameters. In this design, the series capacitance (C_{L}) is realized under the form of a MIM parallel-plate capacitor structure [3], which has several advantages over interdigital more common realizations: i) it renders the structure more compact, due to higher capacitance per length attainable, ii) it allows much simpler design with quasi-static formulas, iii) it avoids spurious transverse resonances sometimes interfering with the operation of the CRLH structure when interdigital structures are used. The shunt inductance (L_{L}) is realized by typical stubs shorted by vias. The stub-via inductors are distributed symmetrically on both sides of the axis of the structure to ensure optimally symmetric radiation patterns. The structure is implemented in LTCC technology. LTCC is well-known to provide an efficient solution for versatile and low-cost compact multilayer circuits. The LTCC technology used is that available at IMST corporation [4]. Here A6-M substrates with $\varepsilon_r = 5.9$ and $\tan\delta = 2 \times 10^{-3}$ from the company Ferro with tape thicknesses of 127 μm and 254 μm before co-firing and 95 μm and 190 μm after co-firing have been used, respectively, which corresponds to a perpendicular firing shrinkage of around 25%, while the in-plane firing shrinkage is of around 14%. The vias in Fig. 2 are consituted of stacked vias across the different LTCC layers, which include via pads to ensure proper contacts.

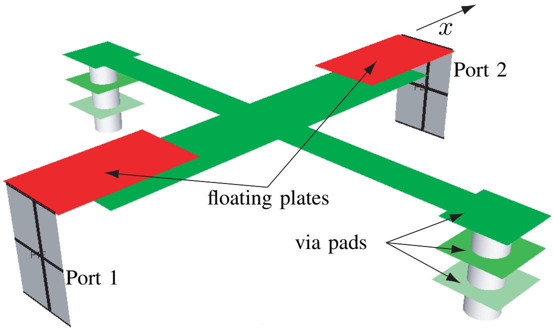


Figure 2: CRLH unit cell in LTCC technology: The series C_{L} is implemented as MIM (metal-insulator-metal) capacitance and the shunt inductance L_{L} as short-circuited stub. The LTCC substrate Ferro A6-M with heights of $h_1 = 95$ μm (between the MIM plates) and $h_2 = 3 \times 190\mu$m (between lower MIM plate and ground), $\varepsilon_r = 5.9$ and $\tan\delta = 2.0 \times 10^{-3}$ has been used. The extracted parameters of the depicted unit cell with a length $p = 3.25$ mm are given in the caption of Fig. 1.

The design parameters for the CRLH unit cell shown in Fig. 2 are as follows: unit cell length: $p = 3.25$ mm; width of MIM caps: $w_{\mathrm{MIM}} = 0.5$ mm; MIM gap: $g_{\mathrm{MIM}} = 0.6$ mm; length of floating patches: $\ell_{\mathrm{float}} = 1.8$ mm; width of stubs: $w_{\mathrm{stubs}} = 0.25$ mm; length of stubs: $\ell_{\mathrm{stubs}} = 1.2$ mm; width of via pads: $w_{\mathrm{pads}} = 0.4$ mm. The corresponding extracted LC parameters are given in the caption of Fig. 2, yielding a series – shunt resonance frequency of $f_{\mathrm{se}} = f_{\mathrm{sh}} = f_0 = 11.50$ GHz.

IV. ANTENNA DESIGN AND RESULTS

Figs. 3, 4 and 5 depict the complete proposed antenna. This antenna was chosen to include 16 cells, which corresponds to the large size of $2\lambda_0$ for high directivity [2]. A quarter wavelength transformer is used to match the 40 Ω input impedance of the ZORA to 50 Ω (Fig. 4), while the structure is terminated by a via short-circuit for excitation of the CRLH series ZOR mode (Fig. 5). Figs. 6 and 7 show the input impedance and return loss of the antenna, respectively. These

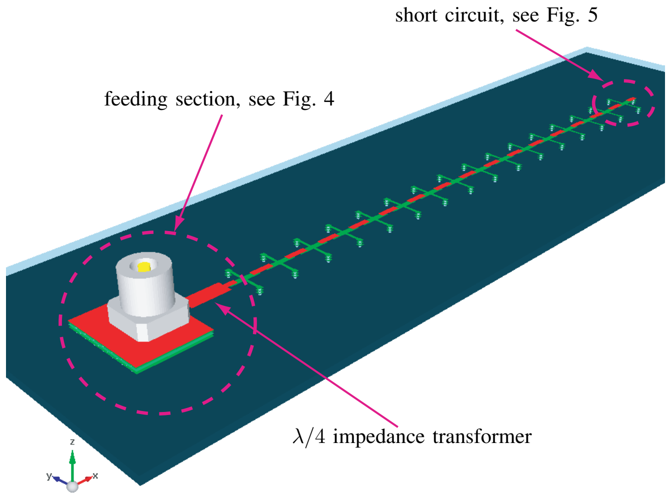


Figure 3: Series mode ZORA in LTCC technology consisting of 16 unit cells.

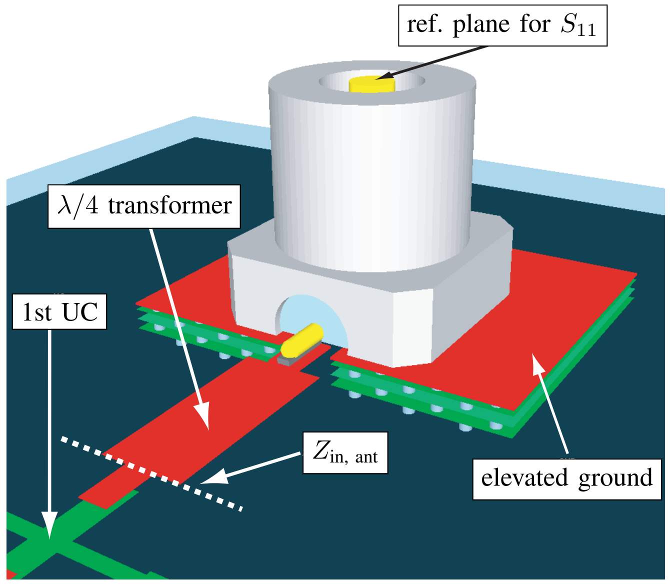


Figure 4: Zoomed view onto the simulation model for the SMP connector and the quarter-wavelength impedance transformer.

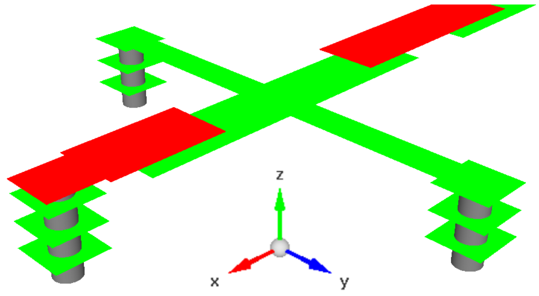


Figure 5: Zoomed view onto the short circuit connected to the last unit cell of the CRLH TL.

graphs show both the ZO ($n = 0$) resonance at $f_0 = 11.51$ GHz and the two half-wavelength ($n = \pm 1$) modes at $f_{-1} = 11.03$ GHz and $f_{+1} = 12.14$ GHz [5]. The input quarter-wavelength transformer was optimized for matching to the desired ZOR mode.

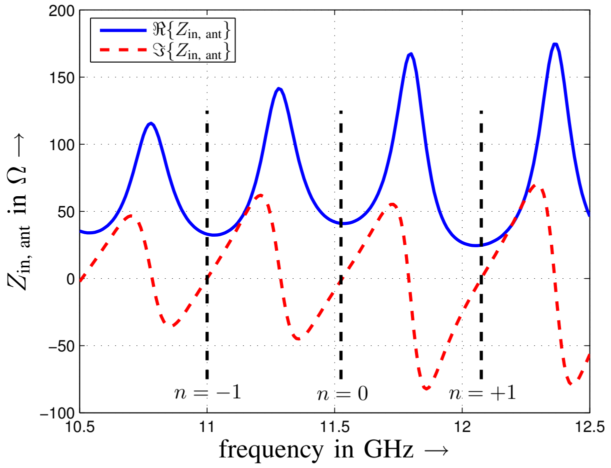


Figure 6: Complex input impedance $Z_{\text{in, ant}}$ at the first CRLH unit cell (see Fig. 4) of the ZORA.

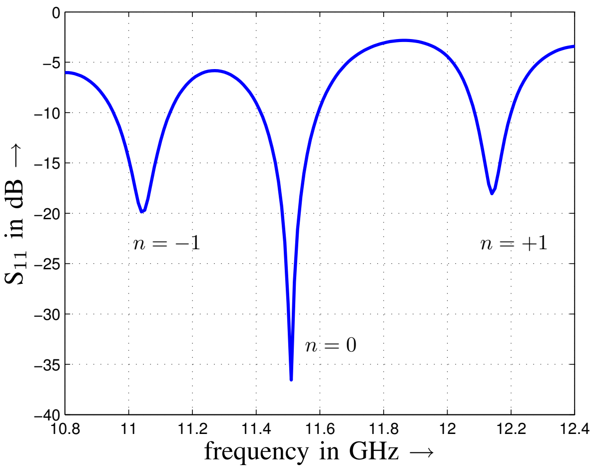


Figure 7: FDTD-simulated return loss of ZORA.

Fig. 8 shows the ZOR current distribution along the structure, which is seen to be uniform and mostly concentrated, as expected, along the series elements of the CRLH structure, while very little current exist on the stubs. In addition, Fig. 8 shows the 3D broadside radiation pattern of the antenna, which exhibits a fan beam pattern due to the large and narrow effective apertures along the directions x and y, respectively. As indicated by the vectorial currents, the polarization of this antenna is longitudinal (x-direction).

The 2D co- and cross-radiation patterns are shown in Figs. 9(a) and 9(b), respectively. The cross-polarization is extremely small for all angles in the E-plane ($x - z$) due to the highly symmetric current distribution (large dominance of longitudinal over very symmetric transverse currents), but it is much larger in the H-plane ($y-z$) off broadside due to small currents traveling along the stubs (still less than -15 dB).

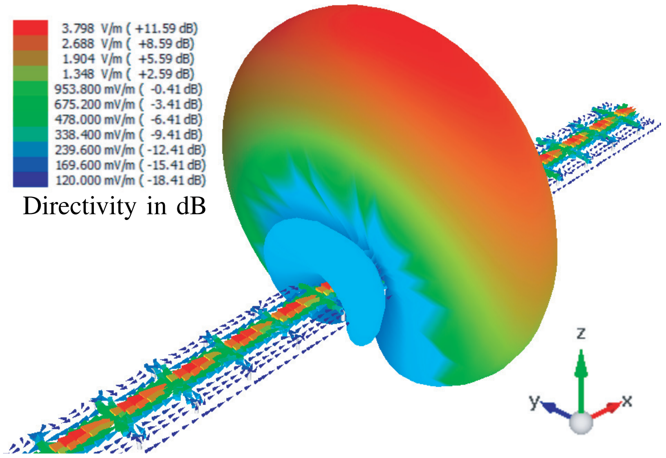


Figure 8: Vectorial current distribution indicating the spatially constant series current and 3D radiation pattern indicating the fan-beam characteristic of the proposed LTCC-ZORA.

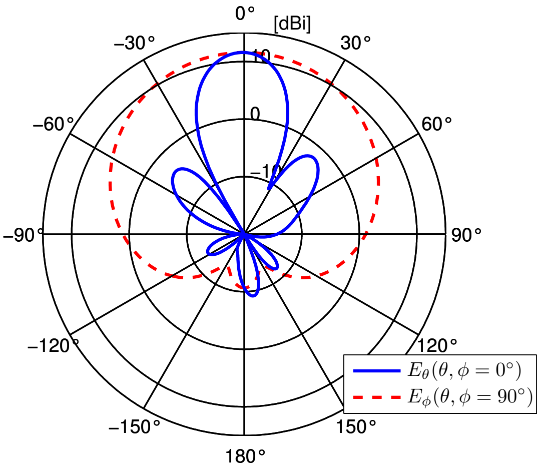
Finally, Tab. I summarizes the integral parameter of the ZORA. The antenna features a high gain of 10.1 dB due to its large electrical size of $2\,\lambda_0$ and the good efficiency (comparable to that of a patch antenna on the same substrate) of 71%. Moreover, it achieves an excellent broadside co-to-cross polarization discrimination due to the highly symmetric current distribution with respect to the x-axes.

Parameter	FDTD-Simulation
f_{LC} in GHz [Eq. 1]	11.50
f_{FDTD} in GHz	11.51
length/λ_0	2.0
D in dBi	11.6
G in dB	10.1
η_{rad} in %	71%
Co-2-X in dB @ $\theta = 0°$	> 80
HBW (E-/H-plane) in deg.	24/90

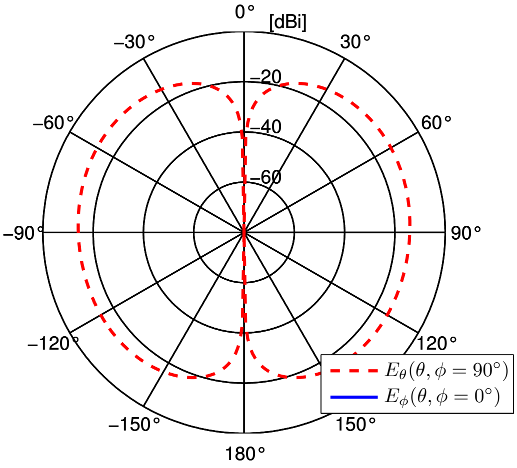
Table I: Integral Parameters of LTCC-ZORA obtained by FDTD Simulation.

V. CONCLUSION

A MIM CRLH series mode zeroth order resonator antenna (ZORA) implemented in LTCC technology has been presented and demonstrated to exhibit excellent efficiency and co-to-cross polarization performances, in addition to a high directivity provided by its large electrical size. Due to its versatile characteristics, high performances and capability to attain at a low cost (without any corporate feeding network) high directivities, conventionally available only with standard arrays, this antenna may find various applications in future. Only FDTD results have been presented here; the antenna is currently under fabrication.



(a) co-polarisation



(b) cross-polarisation

Figure 9: FDTD-simulated co-/cross-polarization as a function of θ for the E- ($\phi = 0°$, solid blue line) and H-plane ($\phi = 90°$, dashed red line) cut. $E_\phi(\theta, \phi = 0°)$ is not shown because it is extremely small due to perfect symmetry of the structure.

ACKNOWLEDGMENT

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