Directive Antennas based on Zeroth-Order Resonant CRLH Metamaterials implemented in Multilayer-Technology

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Abstract

Series and shunt mode directive composite right/left-handed (CRLH) zeroth-order resonant antennas (ZORAs) implemented in multilayer-technology (LTCC) are demonstrated experimentally.

1. Introduction

Composite right/left-handed (CRLH) metamaterial structures [1] can build both leaky-wave and resonant antennas [2]. Zeroth-order resonant antennas (ZORAs) operating at $\beta = 0$ can provide high-directivity and high-efficiency due to the smooth infinite-wavelength aperture distribution [2]. Depending on the termination of the CRLH structure, two different ZORAs are possible - the series and the shunt mode version. In [3] only FDTD-results of the series-mode type were given. These antennas can be made electrically very long, as their resonance frequency is not related to their physical size. Both here presented ZORAs are about $2\lambda_0$ in length, limited only by the maximal possible LTCC substrate length of 66 mm that can be fabricated in our facilities.

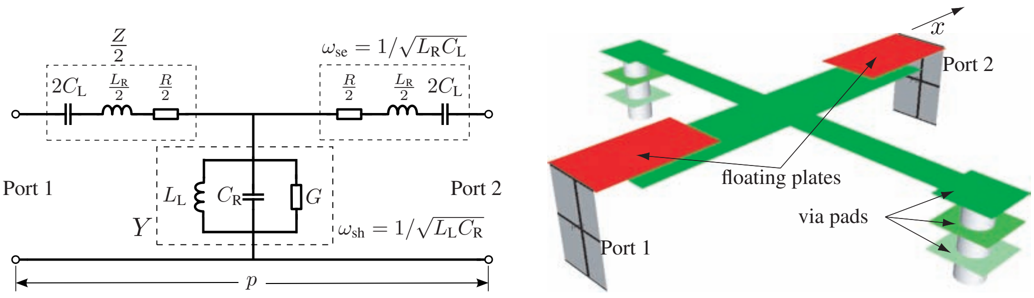

Fig. 1: ZORA unit cell. (a) T-network equivalent circuit. (b) Perspective view. LTCC parameters: substrate Ferro A6-M with heights of $h_1 = 95\ \mu$m (between the MIM plates) and $h_2 = 3 \times 190\mu$m (between lower MIM plate and ground), $\varepsilon_r = 5.9$ and $\tan\delta = 2.0 \times 10^{-3}$. Extracted circuit parameters: $L_\mathrm{R} = 1.26$ nH, $C_\mathrm{L} = 0.154$ pF, $L_\mathrm{L} = 0.290$ nH, $C_\mathrm{R} = 0.664$ pF, $R = 2.47\,\Omega$, $G = 0.153\,$mS with $p = 3.25$ mm.

2. CRLH Metamaterial implemented in Multilayer-Technology

Fig. 1 shows the CRLH unit cell of the proposed periodic ZORA. For the general (un-balanced and lossy) case its dispersion and attenuation diagram reads

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

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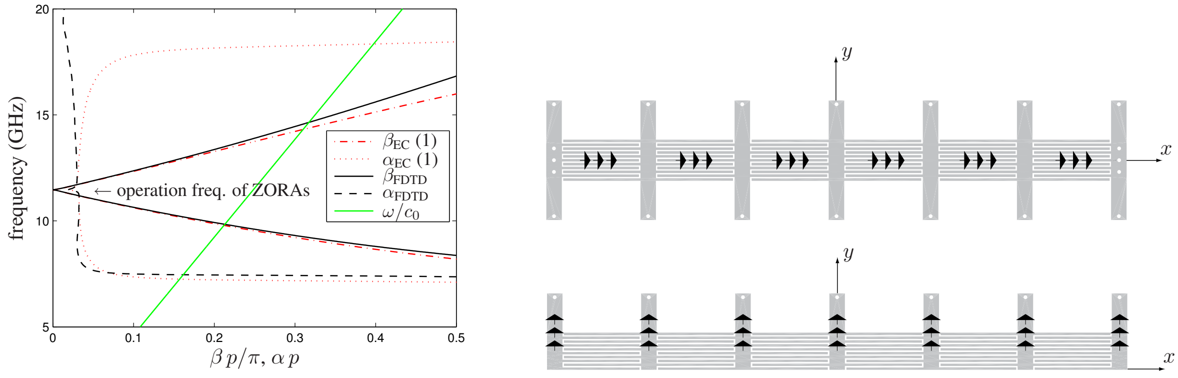
where $\omega_R^2 = 1/(L_R C_R), \omega_{se}^2 = 1/(L_R C_L), \omega_{sh}^2 = 1/(L_L C_R), Q_{se} = \omega L_R/R, Q_{sh} = \omega C_R/G$, and is plotted in Fig. 2(a) for the parameters given in the caption of Fig. 1.



(a) (b)

Fig. 2: Dispersion and attenuation diagram based on full-wave (FDTD) and equivalent-circuit [EC, Eq. (1)] results (a) and schematic current distributions for the series and shunt mode ZOR operations (b).

The CRLH structure is transformed into a resonator when it is open-ended or short-ended. A CRLH resonator with N unit cells and size $\ell = Np$ exhibits $2N - 1$ resonance frequencies, which are found from the dispersion curve as $\omega_n = \omega[\beta_n = n\pi/\ell = n\pi/(Np)]$ $(n \in \mathbb{Z})$ [1]. The resonance mode $n = 0$ is called the zeroth order resonance (ZOR) mode and corresponds to an *infinite wavelength* $(\lambda_{n=0} = 2\pi/\beta_{n=0})$. It may be excited either by open-circuiting or by short-circuiting the structure, to yield resonances at $\omega_{se} = 1/\sqrt{L_L C_R}$ and $\omega_{sh} = 1/\sqrt{L_R C_L}$, respectively, with current and energy concentration in the corresponding elements, as depicted in Fig. 2(b).

3. Series-Mode and Shunt-Mode ZORAs

Fig. 3 shows the series-mode ZORA, which is terminated by a via short circuit and excited through a low-impedance quarter-wavelength transformer, and the corresponding radiation patterns and performances are given in Fig. 4.

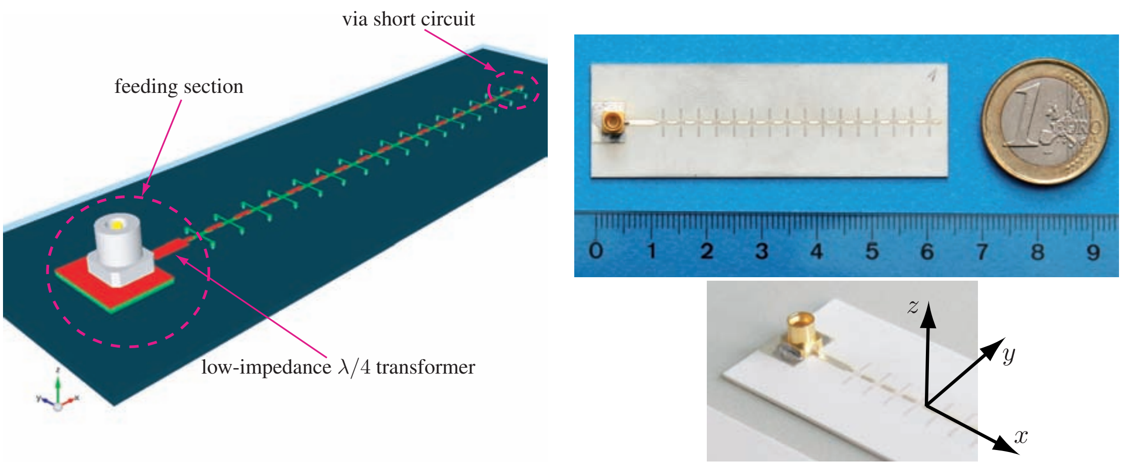


Fig. 3: Series-mode ZORA implemented in LTCC technology consisting of 16 unit cells and operating at ω_{se}.

Fig. 5 shows the shunt-mode ZORA, which is terminated by an open circuit and excited through a high-impedance quarter-wavelength transformer, and the corresponding radiation patterns and performances are given in Fig. 6.

The series-mode ZORA exhibits a higher efficiency and co-to-cross polarization discrimination compared to the shunt-mode ZORA because the latter suffers of normal-to-ground currents (in z-direction) through the vias short circuiting the stubs.

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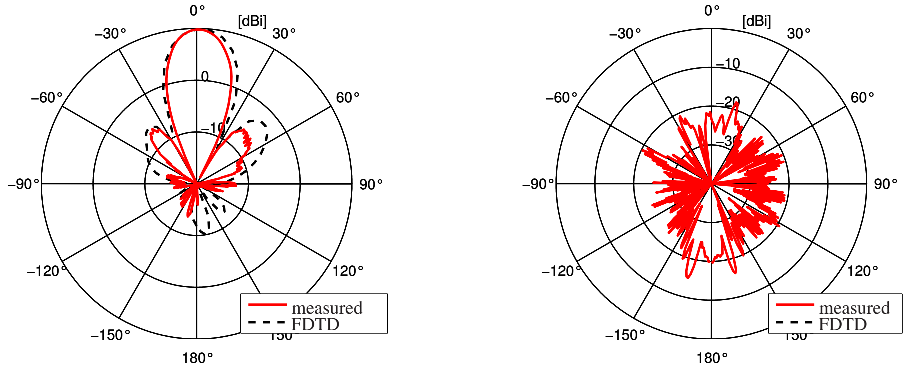


(a) co-pol. $E_\theta(\theta, \phi = 0°)$ (b) cross-pol. $E_\phi(\theta, \phi = 0°)$

Fig. 4: Radiation pattern for the series-mode ZORA of Fig. 3 (gain $G = 10$ dB, efficiency $\eta = 71\%$).

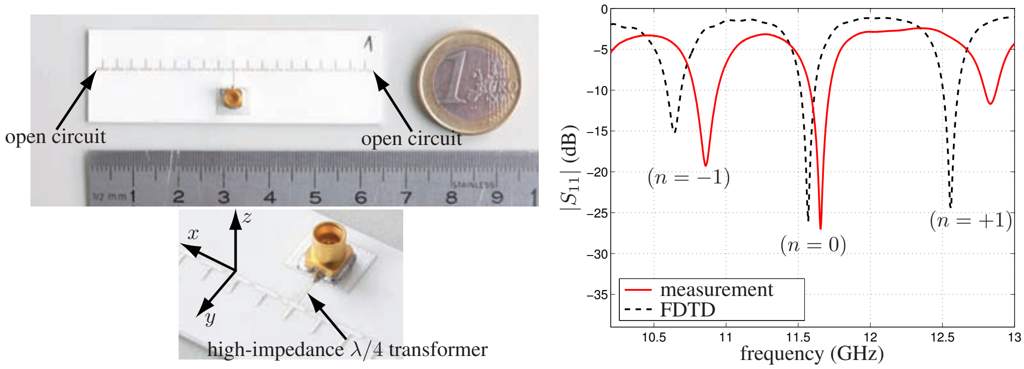
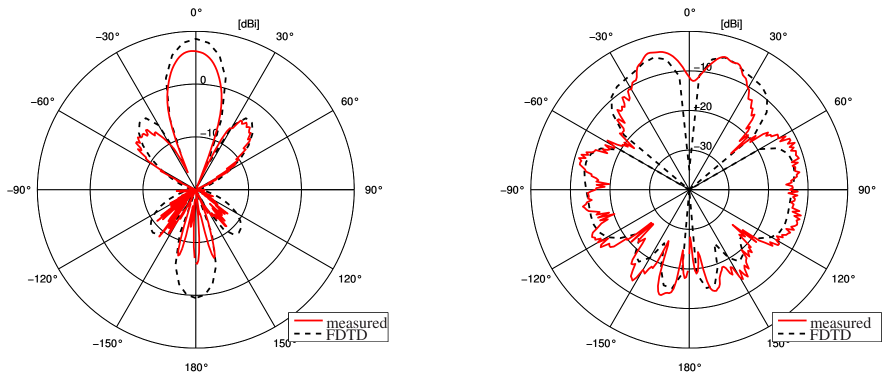


Fig. 5: Shunt-mode ZORA consisting of 19 unit cells and operating at ω_{sh} together with its return loss behavior.



(a) co-pol. $E_\phi(\theta, \phi = 0°)$ (b) cross-pol. $E_\theta(\theta, \phi = 0°)$

Fig. 6: Radiation pattern for the shunt-mode ZORA of Fig. 5 (gain $G = 9$ dB, efficiency $\eta = 63\%$).

References

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