Comparison Between CRLH Zeroth-Order Antenna and Series-Fed Microstrip Patch Array Antenna

T. Liebig *1, A. Rennings *2, S. Otto +3, C. Caloz #4, D. Erni *5

*General and Theoretical Electrical Engineering (ATE), University of Duisburg-Essen, 47048 Duisburg, Germany
1thorsten.liebig@uni-due.de
2andre.rennings@uni-due.de
5daniel.erni@uni-due.de

+Microwave Department (HFT), University of Duisburg-Essen, 47048 Duisburg, Germany
3simon.otto@uni-due.de

#Poly-Grames Research Center, École Polytechnique de Montréal, Montréal, H3T 1J4, Québec, Canada
4christophe.caloz@polymtl.ca

***Abstract*— A metal-insulator-metal (MIM) composite right/left-handed (CRLH) series-mode zeroth-order resonant antenna (ZORA) optimized for the 24 GHz ISM band is presented and compared to a series-fed patch array (SFPA) antenna. The CRLH ZORA exhibits superior performances for relatively short lengths ($< 3\lambda_0$) whereas the SFPA may performs better, depending on the specific design, when the length is very long ($> 5\lambda_0$), so that the resonant antennas operate as leaky-wave antennas with a leakage factor proportional to the density of the radiators along the structure. To our knowledge it the first time that the leaky-wave operation of an electrically very large "resonator" has been explicitly identified. The ZORA is particularly recommended for average electrical sizes in the order of $2\lambda_0$, where it should be systematically superior to a SFPA.**

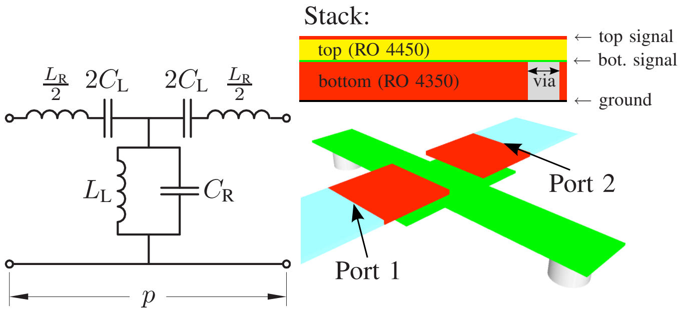
I. Introduction

Composite right/left-handed (CRLH) transmission line (TL) metamaterial theory [1] has been developed as a new concept in electromagnetics to implement novel functionality, e.g. in microwave waveguide and antenna designs. One novel antenna concept is the zeroth-order resonant antenna (ZORA) [2], [3]. This antenna operates at the transition frequency between the left-handed (LH) and the right-handed (RH) pass bands of the CRLH dispersion diagram (Fig. 2). At this frequency the parallel resonance in the shunt tank and the series resonance in the series tank of the CRLH unit cell (Fig. 1) lead to an infinite-wavelength operation (in terms of the fundamental space harmonic of the periodic structure). Therefore the size of this antenna is independent of the operation frequency allowing a simple and efficient design from small to very large antennas.

Sec. II introduces a metal-insulator-metal (MIM) CRLH unit cell, designed for the 24 GHz ISM band, and compares its dispersion diagrams obtained by circuit as well as FDTD and FEM-based full-wave simulations. In Sec. III, a conventional electrically large one-dimensional antenna consisting of a series-fed patch array is designed and compared to the ZORA. The FDTD simulation results for return loss, radiation pattern and near fields are discussed, and the two concepts (CRLH TL ZORA and conventional series array) are compared for two different antenna sizes in each case. Sec. IV deals with the particular properties of very long ZOR antennas and their operation in a leaky-wave mode, although being designed as resonator structures. Finally, conclusions are given in Sec. V.

II. MIM CRLH Structure

Fig. 1 shows the unit cell of the MIM CRLH periodic antenna structure used in this work. This configuration realizes the series capacitances (C_L, equivalent to $\mu < 0$) by MIM parallel-plate capacitors and the shunt inductances (L_L, equivalent to $\varepsilon < 0$) by stubs shorted by vias to the ground plane. The ZORA is designed to operate in its series mode, i.e. at $\omega = \omega_\mathrm{se} = 1/\sqrt{L_\mathrm{R} C_\mathrm{L}}$, where the structure is terminated by a short. Here the energy is mainly concentrated in the series elements (axis of the line). Two anti-parallel stubs are placed in each unit cell in order to minimize the cross-polarization level, since the E-field of the the series-mode ZORA is polarized along the axis of the line, perpendicularly to the direction of the stubs.



(a) EC-model (b) 3D-FDTD-model

Fig. 1. Unit cell of the MIM CRLH (periodic) antenna. (a) T-network equivalent circuit. (b) Multilayer profile and perspective view.

The antenna is implemented in a Rogers RO 4350/4450 double-layer substrate configuration [Fig. 1(b)]. The lower layer consists of a 253 μm thick RO 4350 core substrate with $\varepsilon_\mathrm{r} = 3.66$, while the upper layer consists of a 101 μm thick RO 4450 prepreg substrate with $\varepsilon_r = 3.72$. The unit cell has a length of $p = 1.7$ mm, a line width of 700 μm, a stub length of 1300 μm and a stub width of 500 μm. The LC parameters extracted at 20 GHz are L_R = 0.54 nH, L_L = 0.1 nH, C_R = 0.44 pF and C_L = 0.081 pF, yielding the dispersion diagram shown in Fig. 2.

Good agreement between the circuit model approximation and the full-wave FDTD as well as the lossless full-wave FEM results have been obtained in a broad frequency range around the transition frequency, 24 GHz, which is also the operation frequency for the zeroth-order mode. For frequencies larger than 30GHz the effective medium model gets more and more invalid due to the smaller guided wavelength at higher frequencies and thus the deviation of the circuit model from the full-wave analysis increases.

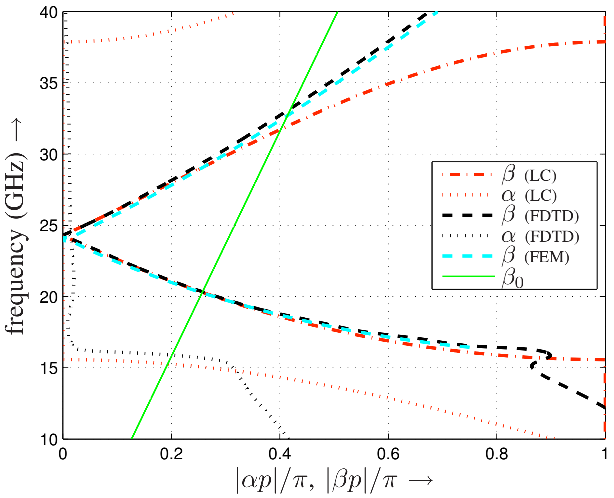


Fig. 2. Dispersion diagram for the structure of Fig. 1, comparing the circuit model (LC) and the FDTD and FEM results.

III. Comparison with a Series-Fed Patch Array

The ZOR antenna, composed of unit cells shown in Fig. 1, is now compared to a conventional series-fed patch array (SFPA) antenna. This antenna, which is schematically shown in Fig. 3, consists of half-wavelength resonant patches serially connected by microstrip lines at their edges. The phase shift induced by one unit cell consisting of a patch and a line is 2π ($\ell_{low} + \ell_{high} = \lambda_e$), so as to ensure phase uniformity between the elements of the array for broadside radiation.

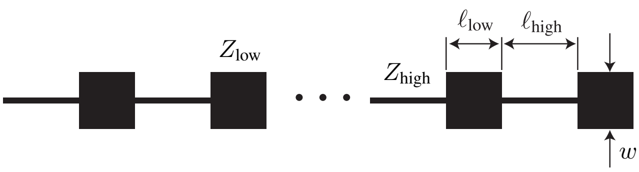


Fig. 3. Layout of the series-fed patch array antenna with the geometrical parameters $w = 3.3$ mm, $\ell_{low} = 3.1$ mm, and $\ell_{high} = 3.5$ mm.

Figure 4 depicts the magnetic field component H_y, which is perpendicular to the propagation direction, in a plane 0.1 μm above the antennas. The ZORA tends to exhibits a more uniform field distribution due to its smaller unit cell size. In contrast, in the SFPA, the magnetic field changes sign between the microstrip lines and the patches sections of the SFPA, which results in a lowered radiation efficiency compared to a single patch antenna.

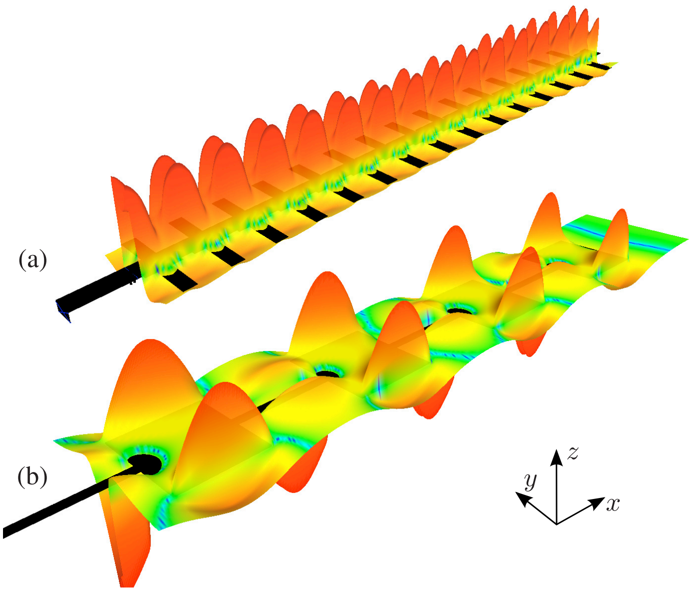


Fig. 4. $H_y(x, y)$ field distribution at 24 GHz and 0.1μm above the 15 cell ZORA (a) and a SFPA of approximately equal size size (b).

Figures 5 and 6 show the return losses and the 2D/3D radiation patterns of a 59-cell ZORA and of a 15-patch array antenna of approximately same size (25.5 mm and 27.3 mm, respectively), at 24 GHz. The two antennas exhibit relatively similar performances at the frequency of operation (24 GHz), with slightly higher efficiency and gain in the SFPA case.

More quantitative information is provided in Tab. I for two different sizes (length/$\lambda_0 \approx 2$ and length/$\lambda_0 \approx 8$) of both the ZORA and the SFPA. The following observations can be made in this table. For the short structures, the ZORA has a higher directivity and gain (+1.2 dB), with same efficiency, despite its slightly smaller size, whereas for the longer structures, the SFPA is superior in terms of both directivity and gain (+1 dB). A tentative explanation to these observations is given in the next section.

IV. Leaky-Wave Operation of a Electrically Very Long CRLH Resonant Antenna

The stronger directivity of the ZORA compared to the SFPA of same size [3] for a short size ($< 3\lambda_0$) is due to the fact that the ZORA exhibits a larger effective aperture because of the uniform zeroth-order field distribution ($\lambda_g = \infty$) and the continuous radiation along the structure, compared to the SFPA which is non-uniform and radiates only at the position of the patches. For electrically very large ZORAs, the

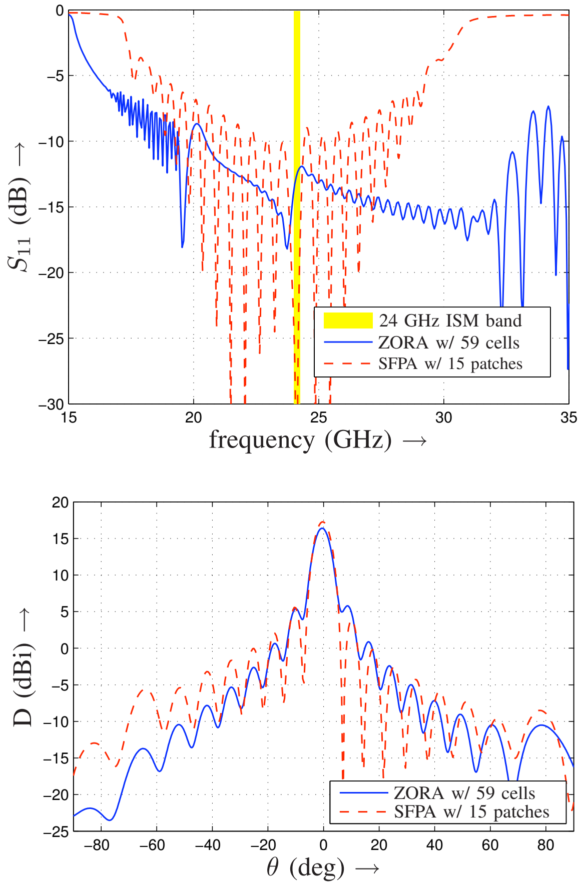


Fig. 5. Compared return losses and radiation patterns for a 59-cell ZORA and of a SFPA 15-patch array antenna of the same overall size at 24 GHz.

Parameter	ZORA (15 cells)	SFPA (short)	ZORA (59 cells)	SFPA (long)
f_0 in GHz	24.1	24.0	24.1	24.0
D in dBi	11.8	11.3	16.4	17.2
G in dB	10.5	10.1	14.5	15.5
η_{rad} in %	75%	75%	65%	68%
length in mm	25.5	27.3	100.3	100.8
length/λ_0	2.04	2.19	8.02	8.06

TABLE I
ANTENNA PARAMETERS OF TWO ZORAS WITH 15 AND 59 UNIT CELLS COMPARED TO AN SFPA OF THE SAME SIZE.

situation is different. Due to the increased spectral density of resonances (standing waves) located above the light line, most of the power injected at the input of the antenna propagates under the form of leaky-waves, which progressively loose their energy along the structure. Therefore, the standing wave picture progressively looses its meaning as the length is increased because the short or open termination at the far end becomes electrically invisible from the input of the antenna, yielding an operation condition identical to that of a leaky-wave antenna. Thus, the reason for the larger directivity of the long ($8\lambda_0$) SFPA lies in its smaller leakage factor due to

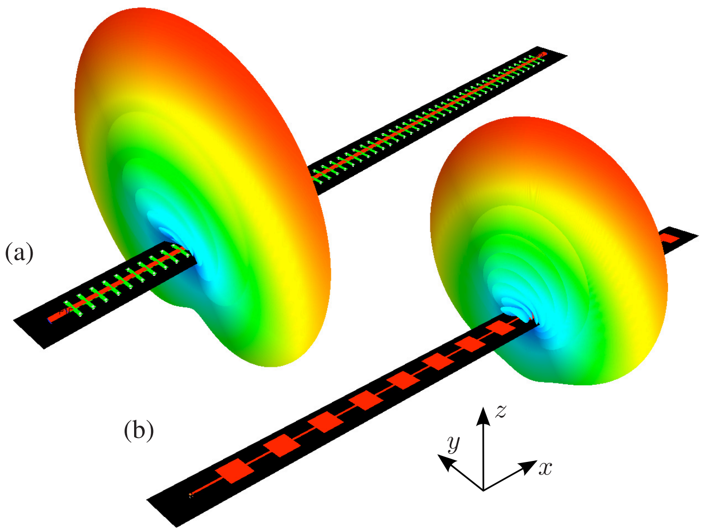


Fig. 6. 3D fan beam type radiation pattern at 24 GHz for the 59-cell ZOR antenna (a) and SFPA of similar size (b).

the smaller density of radiators per unit length, allowing a larger effective aperture, while all the power of the ZORA has leaked out before reaching the end of the structure (Fig. 7). For comparison, one SFPA cell corresponds to 4 ZORA unit cells. In order to implement even longer CRLH ZOR antennas, reducing the leakage per unit cell will be subject to further optimizations.

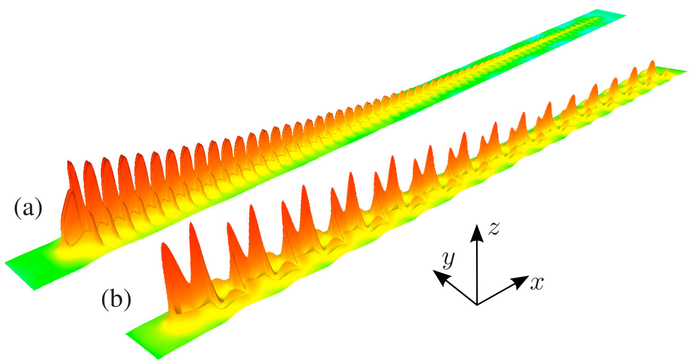


Fig. 7. $|\vec{H}|$ field distribution at 24 GHz and 0.1μm above the 59 cell ZOR-antenna (a) and SFPA of similar size (b).

V. CONCLUSIONS

A MIM CRLH series mode ZORA optimized for the 24 GHz ISM band has been presented and compared to an SFPA antenna. The CRLH ZORA exhibits superior performance for relatively short lengths ($< 3\lambda_0$), whereas the SFPA performs better, depending on the specific design, for lengths larger than $5\lambda_0$, where the resonant antenna starts to operate as a leaky-wave antenna.

The fact that the overall performances of the two 1D antennas are relatively comparable motivates further investigations and optimization of CRLH-ZORAs, especially for 2D arrays where the CRLH concept already provides a superior scheme for spatial scalability [8].

REFERENCES

[1] C. Caloz and T. Itoh, *Electromagnetic Metamaterials, Transmission Line Theory and Microwave Applications.* Hoboken, NJ: Wiley - IEEE Press, 2006.

[2] A. Rennings, T. Liebig, S. Otto, C. Caloz, and I. Wolff, "Highly directive resonator antennas based on composite right/left-handed (CRLH) transmission lines," in Proc. *2nd International ITG Conference on Antennas (INICA)*, Munich, Germany, March 2007, pp. 190–194.

[3] A. Rennings, T. Liebig, C. Caloz, and P. Waldow, "MIM CRLH series-mode zeroth-order resonant antenna (ZORA) implemented in LTCC technology," in Proc. *Asia-Pacific Microwave Conference (APMC)*, Bangkok, Thailand, Dec. 2007, CD-ROM.

[4] C. Caloz, T. Itoh, and A. Rennings, "CRLH metamaterial leaky-wave and resonant antennas," *IEEE Antennas Propagat. Magazine*, vol. 50, no.5, pp. 25-39, Oct. 2008.

[5] H. Jasik, *Antenna Engineering Handbook.* New York: McGraw-Hill, 1961.

[6] T. Metzler, "Microstrip series arrays," in *IEEE Trans. Antennas and Propagat.*, vol. AP-29, no. 1, pp. 174–178, Jan. 1981.

[7] W. Menzel, "A 40 GHz microstrip array antenna," in *IEEE MTT-S Int. Microwave Symp. Dig.*, pp. 225–226, May 1980.

[8] T. Liebig, *Entwurf und Implementierung von metamaterial-basierten Antennensystemen.* Diploma Thesis, University of Duisburg-Essen, June 2007.