Highly Directive Resonator Antennas based on Composite Right/Left-Handed (CRLH) Transmission Lines

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***Abstract*— A composite right/left-handed (CRLH) series mode zeroth order resonator antenna (ZORA) and a CRLH half-wavelength antenna (HWA) with tunable directivity are presented and demonstrated to exhibit substantially higher directivity than a conventional patch antenna in the case of a 2.4 GHz (WLAN) design. Due to the special dispersion relation of a CRLH transmission line (TL), the length of CRLH TL resonators can be enlarged while keeping their resonance frequency constant, which yields enhanced directivity. The ZORA has been shown to have a higher efficiency ($\eta_{\text{ZORA}} > 70\%$) than the CRLH HWA ($\eta_{\text{HWA}} \approx 40\%$), comparable to that of a patch antenna, as a result of the perfectly uniform current distribution in the zeroth order mode. In particular, the ZORA due to its versatile characteristics and high performance, is expected to find wide applications in the future.**

I. INTRODUCTION

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

This paper presents two high-directivity CRLH TL antennas, a zeroth order resonator antenna (ZORA) and a half-wavelength antenna (HWA). The former is a novel configuration based on the zeroth order series mode of a short-circuited CRLH TL, while the latter is an optimized version of the HWA introduced in [2]. The operation frequency of the HWA has been chosen close to the one of the ZORA, in order to allow a meaningful comparison between the two types of antennas. The design and optimization of the two antennas have been carried out with the method of moments (MoM) tool Ansoft Designer and the finite-difference time-domain (FDTD) software Empire XCcell.

Sec. II describes the operation and design principles of CRLH TL resonators and corresponding directive antennas. The series mode ZORA and the HWA (with different unit cell for similar operation frequency as the ZORA) are presented in Secs. III and IV, respectively. Next Sec. V compares the series mode ZORA, the HWA and a conventional patch antenna. Conclusions are given in Sec. VI.

II. CRLH TL RESONATORS AND DIRECTIVE ANTENNAS

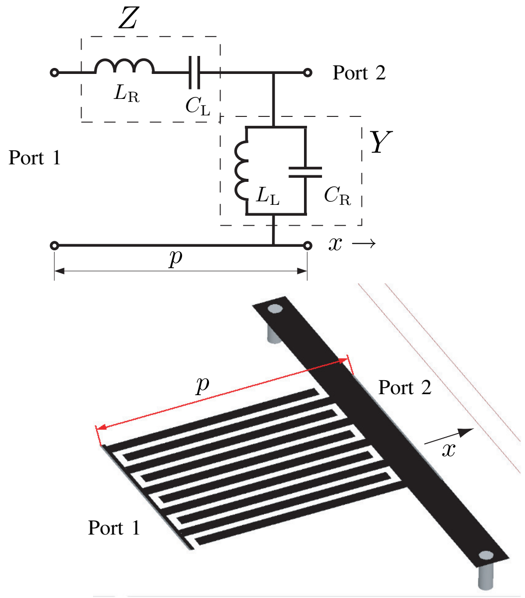

Figure 1: Typical CRLH microstrip unit cell topology along with its circuit model. The series C is implemented as interdigital capacitance and the shunt inductance as short-circuited stub. The substrate Rogers RO 4003 with height $h = 1.52$ mm, $\varepsilon_r = 3.38$ and $\tan\delta = 2.7 \times 10^{-3}$ has been used in all of the structures of this paper.

The CRLH TL is a periodic structure composed of cascaded unit cells. Fig. 1 shows a typical interdigital/shorted-stub microstrip CRLH unit cell topology along with its lumped circuit model. Such a TL exhibits the dispersion/attenuation relation [1]

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

where $\omega_{\text{se}}^2 = \frac{1}{L_{\text{R}}C_{\text{L}}}$, $\omega_{\text{sh}}^2 = \frac{1}{L_{\text{L}}C_{\text{R}}}$, $\omega_{\text{R}}^2 = \frac{1}{L_{\text{R}}C_{\text{R}}}$. Under the so-called *balanced condition*, $\omega_{\text{se}} = \omega_{\text{sh}} \equiv \omega_0$, the function $\omega(\beta)$ can be derived from the general relation (1) as

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

and is plotted in Fig. 2 for a particular set of parameters. Due to the fact that the size p of the unit cell is strongly sub-wavelength, in the frequency range of operation ($p/\lambda_{\text{g}} \ll 1$), CRLH structures behave as an uniform transmission media. Therefore all of the concepts of uniform traveling-wave and resonant-type structures can be transposed to such metamaterial structures, while they offer in addition unique properties

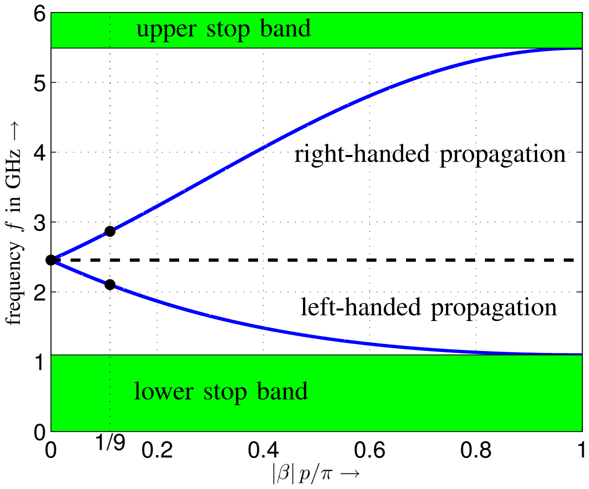

Figure 2: Dispersion diagram [Eq. (2)] of the CRLH TL used for the ZOR antenna in Sec. III. The parameters for the corresponding unit cell are $L_\mathrm{R} = 1.89$ nH, $C_\mathrm{L} = 2.20$ pF, $L_\mathrm{L} = 1.53$ nH, $C_\mathrm{R} = 2.78$ pF and $p = 11.3$ mm.

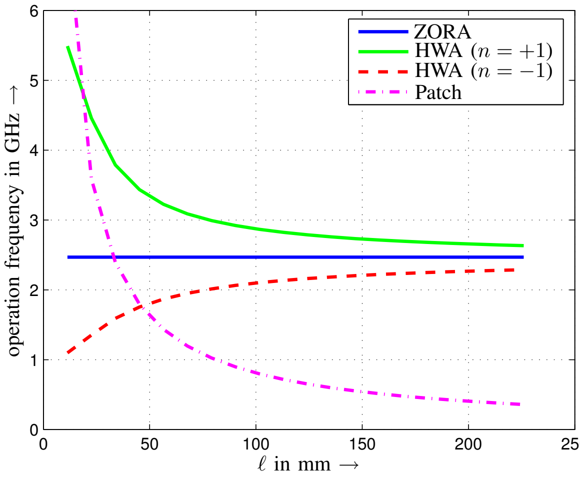

Figure 3: Operation frequency for a ZORA $(n = 0)$ [Eq. (3)], a HWA $(n = \pm 1)$ [Eq. (4)], and a conventional patch antenna [Eq. (5)] as a function of the resonator length ℓ.

not available in conventional systems. Like any TL, a 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. 2), a CRLH resonator of N unit cells and size $\ell = Np$ exhibits $2N - 1$ resonance frequencies [1]. These frequencies are determined from the dispersion diagram by the condition $\ell = n\lambda_\mathrm{g}/2$, or equivalently, $\beta_n = n\pi/\ell = n\pi/(Np)$, with the CRLH particularity that n can be both positive and negative, and even zero.

For the half-wavelenght operation the $(n = \pm 1)$ resonances in an open-ended TL configuration are used. For these boundary conditions a sinusoidal current distribution with a vanishing amplitude at the ends of the TL is established, yielding a broadside radiation. Two zeroth order modes $(n = 0)$ are possible for a CRLH TL resonator [1]. If the TL is short-circuited at both ends the so-called series mode with a uniform series current can be excited easily. This mode is used for the ZORA since it radiates with maximal directivity in broadside direction [3] due to the uniform effective aperture and shows also better co-to-cross-polarisation discrimination than the other zeroth order resonance – the shunt mode.

From Eq. 2, the ZORA and HWA resonance frequencies are given by

$$\omega_\mathrm{ZORA} = \omega_\mathrm{se} = \frac{1}{\sqrt{L_\mathrm{R} C_\mathrm{L}}} \neq F(\ell), \tag{3}$$

$$\omega_\mathrm{HWA} = \omega_{\pm 1}(\ell) = \sqrt{\omega_0^2 + \omega_\mathrm{R}^2 \sin^2 \frac{\pi p}{2\ell}} \pm \omega_\mathrm{R} \sin \frac{\pi p}{2\ell}, \tag{4}$$

respectively, where it is seen that the ZORA resonance, in contrast to the HWA resonance, does not depend on the length of the structure. In comparison, the resonance frequency of a conventional patch antenna is given by the well-known inversely proportional relation between resonance frequency and resonator length.

$$\omega_\mathrm{PATCH}(\ell) = \frac{\pi c_0}{\ell\sqrt{\varepsilon_\mathrm{r,\,eff}}} \propto \frac{1}{\ell} \tag{5}$$

The resonance frequencies for the cases of Eqs. (3) – (5) are plotted in Fig. 3.

It is well-known that the directivity D of an antenna is proportional to its effective aperture A_e as $D = 4\pi A_\mathrm{e}/\lambda_0^2$, where λ_0 is the free-space wavelength [3]. According to Fig. 3, it is then possible to *enhance the directivity* of a resonant CRLH antenna by *increasing its physical length ℓ (or number of cells N) while keeping its operation frequency constant.* In the case of a HWA, this operation only necessitates a slight adjustment of the unit cell parameters. In the case of a ZORA, it is achieved automatically by just increasing the number of cells, which is particularly convenient in terms of design simplicity and may be exploited advantageously in reconfigurable systems with tunable gain.

Such a directivity enhancement operation is possible neither with a conventional patch antenna nor with a leaky-wave antenna (LWA). In the former case, this is because increasing the size of the structure inevitably results into decreasing its resonance frequency [Eq. (5)]. In the latter case, the structure length cannot be effectively increased beyond the point where all of the energy has been leaked out. Additionally, a LWA is usually less efficient than a resonant antenna, due to the load at the end on the line used for matching. Finally, although high directivities can be easily attained by arrays, the proposed antennas exhibit the advantage of requiring no feeding network. The overall design is therefore easier and the ZORA is probably more efficient, due to the fact that no losses are dissipated in complex feeding networks. These aspects will be examined in detail in a later report.

III. CRLH SERIES MODE ZEROTH ORDER RESONANTOR ANTENNA (ZORA)

Fig. 4 shows a ZORA unit cell with its optimized layout parameters, while Figs. 5 and 6 show the corresponding simulated current distribution and radiation pattern. The symmetrical distribution of the stubs in this design allows a high co-to-cross polarization discrimination [4]. The current corresponding to the series mode excitation is longitudinal (along the x-axis of the line), which results into longitudinal (linear) polarization ($E \parallel x$) and broadside radiation. Due to the zeroth mode operation ($n = 0, \lambda_{\rm g} = \infty$), the current distribution is perfectly uniform (i.e. equi-phase and equi-magnitude), which results into maximized directivity [3].

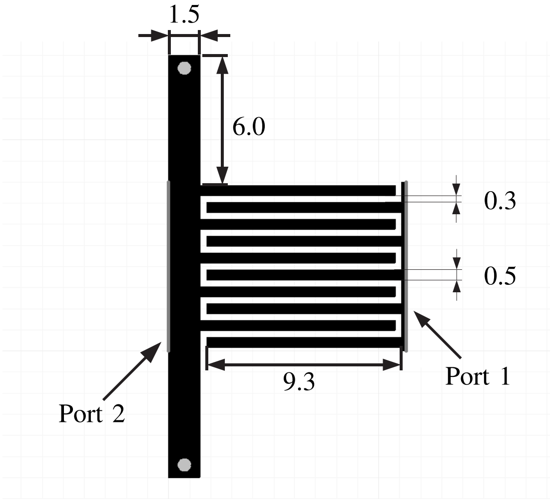

Figure 4: Optimized unit cell with layout parameters in mm for the series mode ZORA operating at 2.42 GHz (parameters corresponding to the dispersion diagram of Fig. 2).

The ZORA prototype is shown in Fig. 7. An interdigital capacitance together with a short 50Ω line is used to transform the needed short circuit (in practice it is around 3Ω) at the input of the structure to a 50Ω level, where a coaxial probe is connected (Fig. 7). Three vias in parallel are forming the short circuit at the output of the ZORA.

The measured and full-wave simulated return loss behavior and radiation patterns of this ZORA prototype are shown in Figs. 8 to 12.

IV. CRLH HALF-WAVELENGTH ANTENNA (HWA)

In the case of the CRLH HWA, we will consider only simulation results as this antenna (with another design) was already demonstrated experimentally in [2].

The structure of the HWA is identical to that of the ZORA. Only the excitation changes. Whereas the ZORA was excited by a short-ended mechanism, the HWA has to be excited by an open-ended mechanism; in addition, whereas the ZORA could be excited at any location, including at its end as done in the previous section), the HWA can be excited only at the specific point along the structure where 50 Ω matching is achieved. It should be noted that the parameters of this HWA have been modified from those of the ZORA of the previous section, in order to exhibit a close resonance frequency for comparison in the next section.

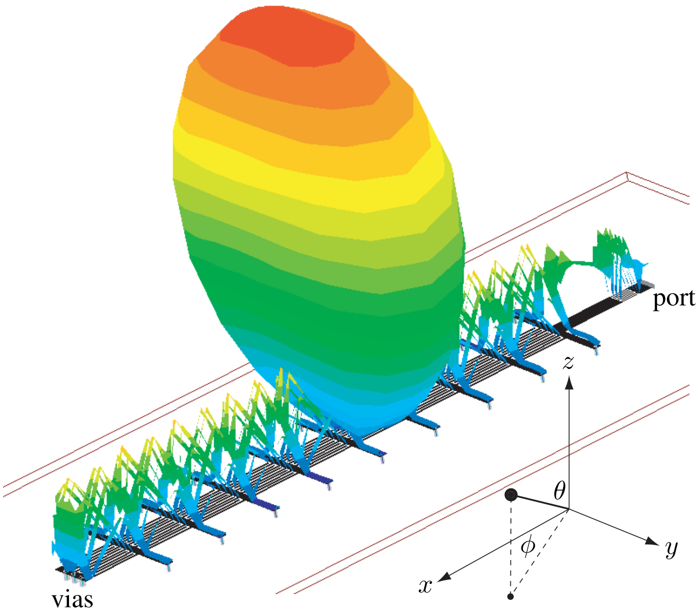

Figure 5: Scalar current distribution and linear 3D radiation pattern at 2.42 GHz for a 9-cell CRLH series mode ZORA with the unit cell shown in Fig. 4.

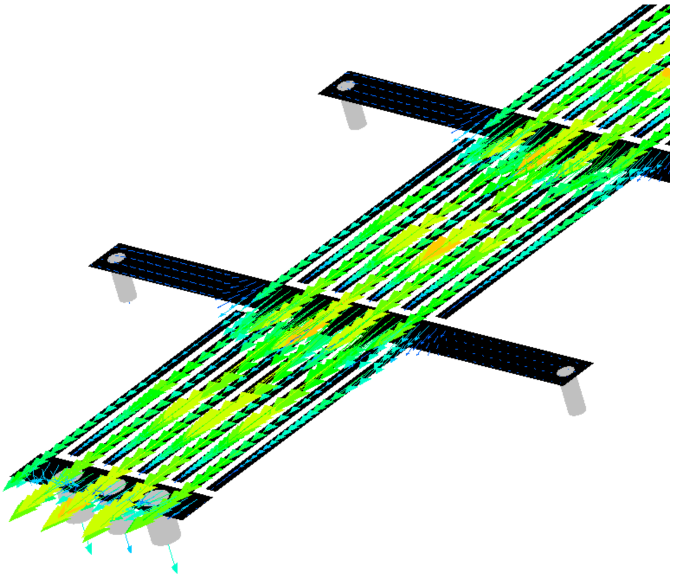

Figure 6: Vectorial current distribution for the same case as in Fig. 5.

The simulated current and radiation patterns of the CRLH HWA are shown in Fig. 13. The half-wavelength quasi-sinusoidal current distribution ($\ell = \lambda_{\rm g}/2 \Rightarrow |\beta|p/\pi = 1/N = 1/9$) with series current almost vanishing at both ends (the shunt currents have a maximum there) of the structure is

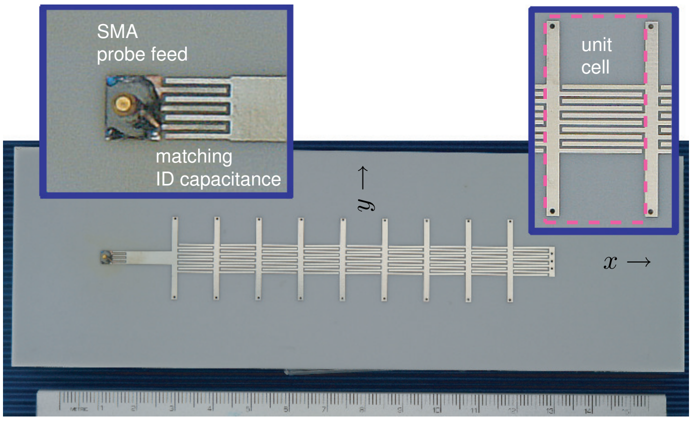

Figure 7: Series mode ZORA prototype fed via a matching network (interdigital capacitor connected to a 50Ω line) in order to transform the low input impedance of the antenna. The upper left inset shows a zoomed view of probe feeding along with the matching network while the upper right inset shows a zoom on the unit cell of the prototype.

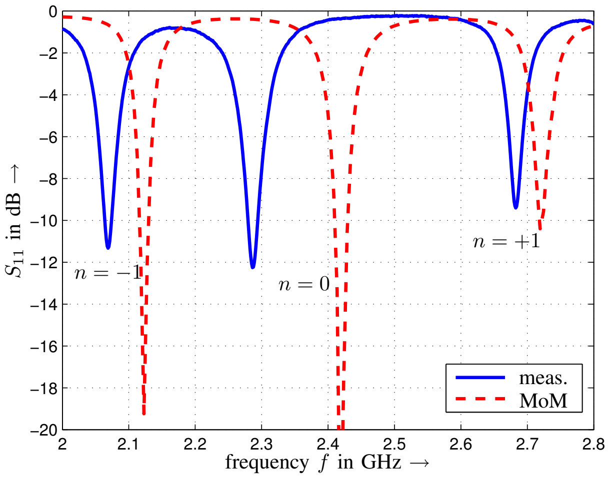

Figure 8: Return loss for the series mode ZORA ($n = 0$) of Fig. 7. The adjacent resonances for $n = \pm 1$ are not used here, since they yield a non-broadside radiation.

clearly visible in this graph. This antenna is similar to a patch antenna in terms of excitation offsetting, polarization (also longitudinal along the line) and broadside radiation pattern, with the fundamental difference stated above that the CRLH HWA can be directivity-enhanced.

As can be seen in the dispersion diagram in Fig. 2, a CRLH structure exhibits in fact *two* frequencies satisfying the condition $\ell = |\lambda_g|/2$, which correspond to $n = \pm 1$. These frequencies are given in Eq. (4). The CRLH TL is thus inherently dual-band, but only the resonance $\omega_{m=+1}$ will be considered here for comparision with the ZORA and a patch antenna in the next section.

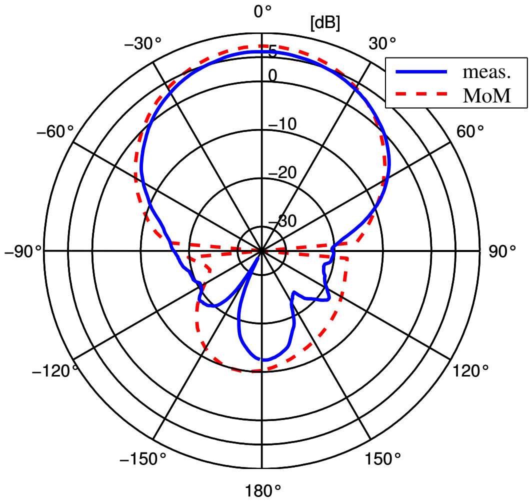

Figure 9: Co-polarized accepted-gain $E_\theta(\theta, \phi = 0°)$ in the E-plane (xz) of the ZORA in Fig. 7.

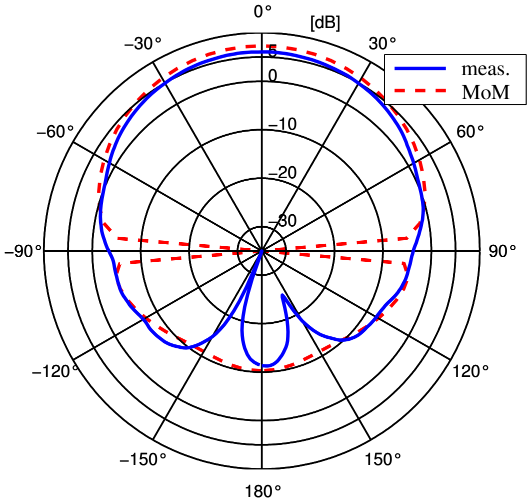

Figure 10: Co-polarized accepted-gain $E_\phi(\theta, \phi = 90°)$ in the H-plane (yz) of the ZORA in Fig. 7.

V. COMPARISON OF THE SERIES MODE ZORA, THE HWA AND A CONVENTIONAL PATCH ANTENNA

The most fundamental antenna parameters – efficiency, gain, directivity, electrical aperture length – for a CRLH series mode ZORA, a CRLH HWA and a conventional patch antenna operating at a similar frequency are given in Tab. I. The results in this table confirm the above prediction of directivity enhancement in CRLH ZORA and HWA. In addition, they reveal that the CRLH ZORA may attain an efficiency comparable to that of a conventional patch antenna. This is due to the perfectly uniform current distribution (see Figs. 5 and 6) along the structure leading to maximized current dipole moment and minimal dissipation. In contrast, the efficiency of the CRLH HWA is lower, due to the fact that its current

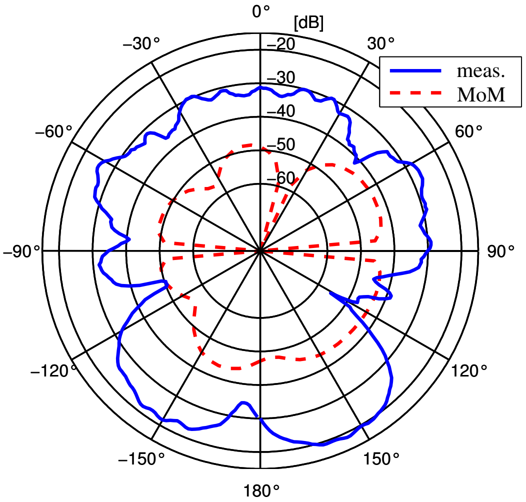

Figure 11: Cross-polarized accepted-gain $E_\phi(\theta, \phi = 0°)$ for in the E-plane (xz) of the ZORA in Fig. 7.

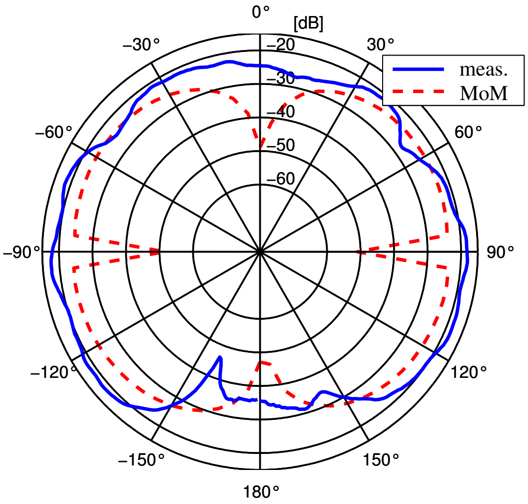

Figure 12: Cross-polarized accepted-gain $E_\theta(\theta, \phi = 90°)$ in the H-plane (yz) of the ZORA in Fig. 7.

density is less uniform and perturbed, due to small spurious transverse resonances occuring in these interdigital capacitors. In a MIM version [5] which is currently developed these spurious transversal resonances occur at higher frequencies. Therefore an undisturbed current distribution together with a higher efficiency is expected for the half-wavelenght operation frequency.

VI. Conclusion

A CRLH series mode zeroth order resonator antenna (ZORA) and a CRLH half-wavelength antenna (HWA) with tunable directivity have been presented and demonstrated to exhibit substantially higher directivity than a conventional patch antenna for a given 2.4 GHz (WLAN) design. The ZORA achieves a higher efficiency ($\eta_{\text{ZORA}} > 70\%$) than the CRLH HWA ($\eta_{\text{HWA}} \approx 40\%$), comparable to that of the patch antenna, as a result of its perfectly uniform current distribution. Especially the series mode ZORA, due to its versatile characteristics and high performance, is expected to find wide applications in the future.

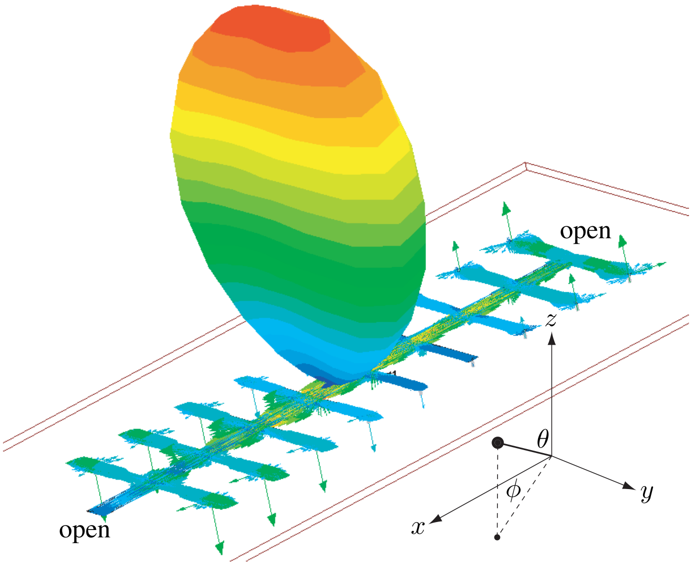

Figure 13: Vectorial current distribution and (linear) 3D radiation pattern at 2.23 GHz for 9-cell CRLH HWA with a similar electrical length as the CRLH ZORA of Fig. 5.

Type	CRLH ZORA	CRLH HWA	Patch
f_{res} in GHz	2.42	2.23	2.42
length in mm	102	118	33
length/λ_0	0.83	0.88	0.27
D in dB	8.8	9.6	6.3
η_{rad} in %	72	39	76
G_{acc} in dB	7.4	5.5	5.1

Table I: Full-wave simulated parameters of the CRLH series mode ZORA, a CRLH HWA and a conventional patch antenna.

Acknowledgment

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