MetaBeam: Multi-layer CRLH Antennas for 24 GHz Sensor Applications Based on Low Cost PCBs

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Abstract—**We investigate the feasibility of CRLH zeroth-order resonant (ZOR) antennas for the 24 GHz ISM band on Rogers RO4350/4450 multi-layer low-cost technology. This technology is used for the first time to implement metal-insulator-metal (MIM) CRLH antennas with its fine metallization features. The fabricated antennas may find applications in the field of automotive or industrial sensors, since the RO4350/4450 laminates are approved for this purpose. The presented return loss and radiation pattern measurements of several prototypes with different length varying from nearly one up to several free space wavelengths indicate that the proposed low-cost implementation is reliable in terms of fabrication and material parameter tolerances.**

Index Terms—**CRLH, zeroth-order resonant antenna, low-cost multi-layer PCB, 24 GHz ISM band, automotive and industrial sensor.**

I. INTRODUCTION

Metamaterial-based design procedures offer enhanced possibilities for the development of electromagnetic structures and devices [1 - 3]. Especially in the field of antennas, where the control of the effective radiating aperture plays an important role, a lot of research has been carried out. The one-dimensional transmission line metamaterial, namely the composite right/left-handed (CRLH) meta-line [1], has paved the way for a lot of innovative antennas [4]. The non-zero dispersion origin (frequency-offset) in the CRLH meta-line dispersion diagram ($\beta = 0 \,@\, \omega \equiv \omega_0 \neq 0$) is the key for several novel antenna concepts, like quasi-uniform leaky-wave antennas scanning through broadside or zeroth-order resonant antennas (ZORAs) operating in the infinite wavelength regime.

So far, related publications about the leaky-wave and zeroth-order resonant CRLH antennas provide only proof of principle prototypes with an operation frequency mostly in the lower GHz range (< 10 GHz) to avoid technological and measurement challenges / problems [4].

Here we present our initial results of an ongoing project called “MetaBeam” that is carried out in the framework of the innovation competition Transfer.NRW [5]. Within this science-to-business pre-seed activity the gap between the aforementioned proof of concept studies and prototypes mature enough for serial production shall be closed. In our case, the fields of application are low cost automotive radar antennas and industrial sensors operating in the 24 GHz ISM band with its edge frequencies of 24.0 GHz and 24.25 GHz. A multi-layer printed circuit board (PCB) technology approved for automotive applications (UL flammability rating 94-VO) and suitable for the operation frequency around 24 GHz is the Rogers RO4350 (core) and RO4450 (prepreg) stack-up. Compared to other multi-layer technologies, like high- / low-temperature co-fired ceramics (HTCC / LTCC) or other specialized PCB processings (e.g. lamination of Rogers RT/duroid substrates with DuPont FEP fluorocarbon bonding film), the RO4350/4450 ML approach is considered to be low-cost.

The results presented in this paper are based on a first fabricated PCB batch, where among other antennas and transmission lines, three different ZORAs composed of five, ten and fifteen unit cells have been realized. For finetuning purposes a key geometry has been varied by ± 50 microns. For reproducibility investigations each identical antenna layout was fabricated twice for comparison.

The paper is organized as follows. In Section II the geometry and the PCB stack-up of the CRLH structures are specified. In Sec. III the measurement results in terms of reflection coefficient, input impedance and radiation pattern for the 5-cell and 10-cell ZORA are presented and discussed. Finally, conclusions are given in Section IV.

II. CRLH ANTENNAS FABRICATED ON LOW COST MULTI-LAYER PRINTED CIRCUIT BOARDS (PCBS)

Fig. 1 shows the equivalent circuit model [1, 4] and the layout in perspective and side view of the CRLH antenna unit cell. The series elements C_L and L_R are implemented in metal-insulator-metal (MIM) technology, while the shunt element L_L is realized by a short-circuited stub. On the other hand, C_R is parasitic in nature. In addition to the two MIM metal layers we have a third bottom metal layer – the ground plane. The Rogers RO4350/4450 multilayer (ML) PCB technology yields the best compromise between fabrication cost and losses, since it is a standardized ML technology and the used core (RO4350 with $\varepsilon_\mathrm{r} = 3.66$, $\tan\delta = 4.0 \cdot 10^{-3}$) and prepreg substrates (RO4450 with $\varepsilon_\mathrm{r} = 3.72$, $\tan\delta = 4.0 \cdot 10^{-3}$) are suitable for devices operating up to 30 GHz. Furthermore, these substrate materials are approved for automotive applications – another required property. The proposed RO4350/4450 stack for these antennas is depicted in Fig. 1c. It encompasses a top and bottom core substrate with thicknesses of 168 µm and 250 µm, respectively, and a 100 µm thick prepreg film in between. The lateral dimensions of the unit cell topology are summarized as following: width of the MIM structure = 700 µm, length of the overall floating plate (depicted in red) = 1900 µm, length of the non-floating plate (depicted in green; connected to the stubs) = 1250 µm, stub length = 1200 µm, stub width = 470 µm and via hole diameter = 300 µm. For optimization purposes the given stub length of 1.2 mm has been varied by ± 50 µm.

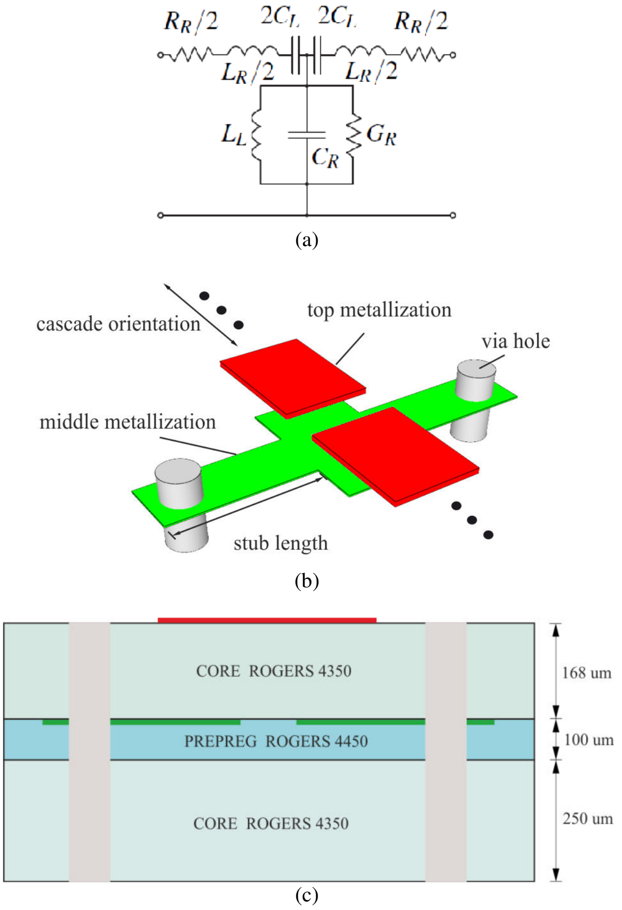


Fig. 1: CRLH unit cell: equivalent circuit model with the three elements L_R, C_L, R_R for the series resonator and the elements C_R, L_L, G_R for the shunt resonator (a), perspective (b) and side (c) view of the proposed CRLH layout.

The CRLH unit cell of Fig. 1 has been cascaded to build up ZOR-antennas with a length of 5, 10 and 15 cells. The output port of the last unit cell of each antenna is connected to a short circuit, which is realized by an approximately 180° long microstrip line connected to a via hole. Thus the three short-circuited CRLH antennas operate in the series mode where mainly the series elements are excited [4]. For this ZOR operation the Q-factor of the shunt resonator of the unit cell should be significantly higher than the corresponding value of the series resonator, due to a large radiation resistance R_R (cf. Fig. 1a). In this case the radiation resistance contribution of each unit cells' series resonator add-up depending on the number of cells of the specific antenna under test. In other words, a longer antenna exhibits a higher input resistance at the zeroth-order operation frequency than a shorter one. This statement is only true for a limited antenna length or correspondingly number of unit cells. For electrically long antennas the input impedance converges to the Bloch impedance of the periodic structure [6]. Thus the proposed CRLH unit cell for the 24 GHz ISM band has been designed for a Bloch impedance close to 50 Ω. In this case no further input impedance transformation to the feeding 50 Ω RF system is necessary – at least for the longer antennas with an extent of several free space wavelength. The input port of the first unit cell of each antenna is simply connected to a 50 Ω microstrip line, which is excited by using an end launch connector (2.92 mm series, Southwest Microwave) suitable for the corresponding ML substrate height of 620 microns.

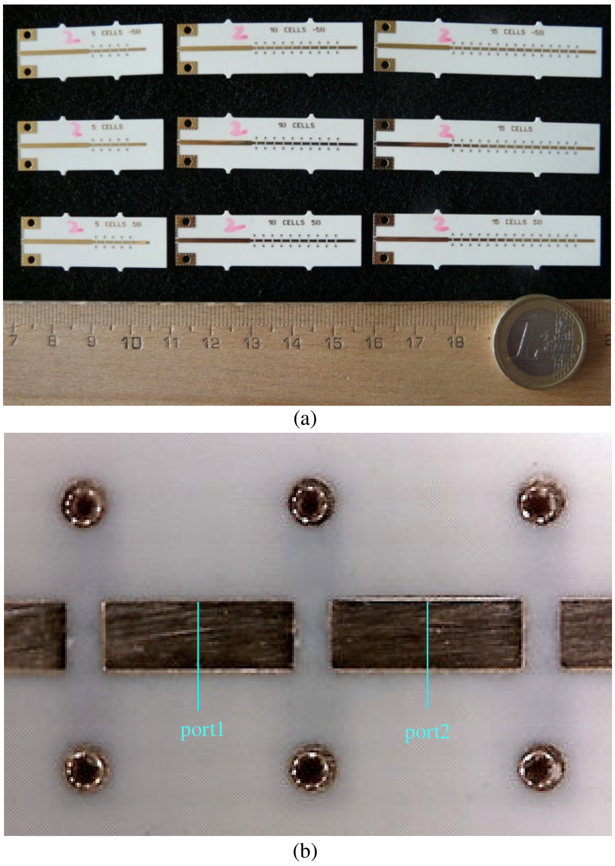


Fig. 2: CRLH ZOR prototypes: Overall nine different prototypes are depicted in (a) with different length (from left to right: 5, 10 and 15 unit cells) and with slightly different stub-length (from top to bottom: original 1.2 mm and the ± 50 µm versions). The lengths of the 5, 10, 15-cell structures correspond to 0.9 λ_0, 1.8 λ_0 and 2.7 λ_0, respectively. (b) Photo of a CRLH unit cell under the microscope. The unit cell length measures p = 2.25 mm which corresponds to only 18% of λ_0.

Altogether 18 ZOR antennas have been build – these one-ports vary in terms of longitudinal extent (five, ten and fifteen unit cells), in terms of stub-length (original 1200 µm and the ± 50 µm versions) and in terms of location on the overall PCB (two groups consisting of nine antennas located on the left and right half of the PCB). In Fig. 2(a) one of these groups with overall nine antennas is shown. The antennas are fed at the left edge of the PCB by using the end launch connectors. The via hole used for short-circuiting the meta-line is located at the right end of each antenna. In Fig. 2(b) a zoomed view with three unit cells of one of the antenna prototypes is shown. The floating plates on the top layer are directly visible, whereas for the non-floating plates on the intermediate layer (cf. Fig. 1b) only a shaded outline is visible through the 168 µm thick upper core substrate.

III. SCATTERING-PARAMETERS AND RADIATION PATTERN RESULTS AND DISCUSSION

A TRL calibration technique has been used so to measure the scattering parameters in the microstrip environment with the reference planes located at the outer unit cell ports. The Bloch impedance Z_B of a periodic CRLH structure is a sensitive measure for resonance frequency balancing [1, 4] of the meta-line (resonance frequency of the series resonator equals the one of the shunt resonator; cf. Fig. 1a). The measured reflection coefficient S_{11} of an electrically very long 60-cell CRLH meta-line terminated with a load is used to get an accurate approximation for Z_B via the well-known conversion formula

$$Z_{in} = \frac{1 + S_{11}}{1 - S_{11}} Z_0 , \qquad (1)$$

with the reference impedance Z_0 = 50 Ω. Since the insertion loss for the 60-cell meta-line was extreme low ($|S_{21}| < -40$ dB) this approximation is considered to be very good. The Bloch impedance for the different stub lengths is plotted in Fig. 3. It indicates the case with optimum frequency balancing [7] for the –50 µm stub version, where the real part exhibits a nearly symmetric characteristic with respect to the zeroth-order operation frequency at 24 GHz.

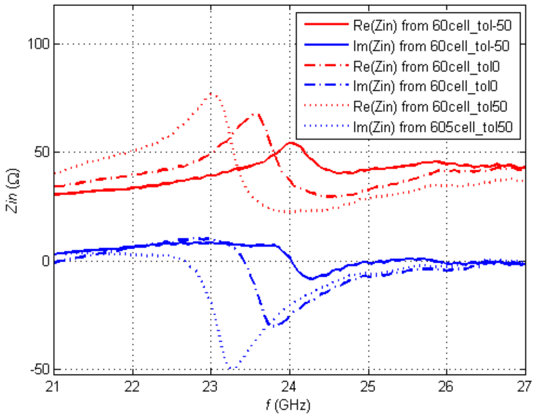
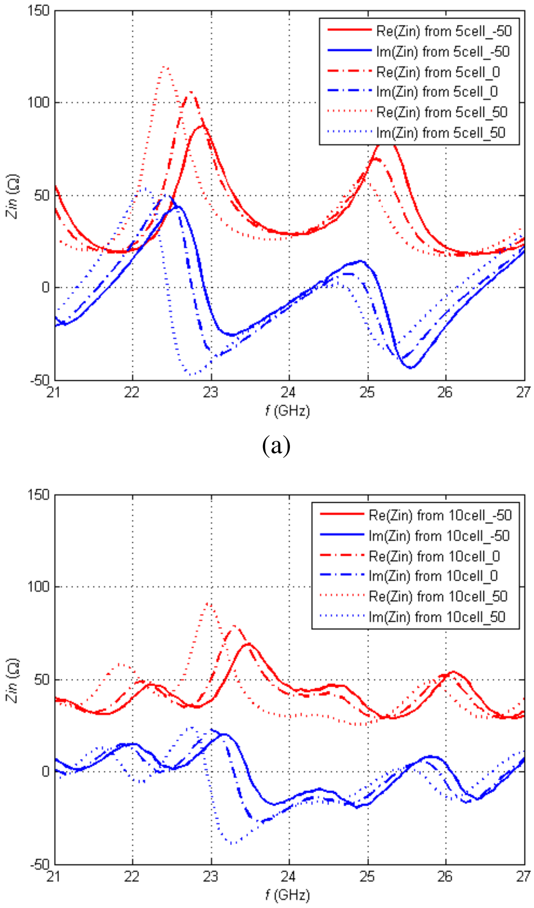


Fig. 3: Bloch impedance Z_B which corresponds to the measured input impedance Z_{in} of an electrically long 60-cell CRLH meta-line terminated by a load for three different stub length cases.

In a similar manner (1) is used to compute Z_{in} for the short-circuited 5- and 10-cell ZOR antenna structures. The results for the different stub lengths are given in Fig. 4. The frequency selective characteristic for the two antennas (5-cell vs. 10-cell) differ significantly. The electrically short 5-cell ZORA exhibits a standing wave behavior with a highly frequency selective input impedance. Around the zeroth-order operation at 24 GHz a series resonator characteristic (SRC) can be observed. The SRC is not strongly affected by the stub length variation. Still we can observe a minor offset for the imaginary part, potentially caused by an imperfect short-circuit at the output port of the 5-cell-ZORA. For the optimal stub length version the parallel resonator characteristic (PRC) for the two quarter-wavelength distributions with high impedance anti-resonance condition occur in a symmetrical manner at 22.8 GHz and 25.2 GHz, respectively (cf. Fig. 4a). This is another indication for a frequency balanced CRLH meta-line as has been shown in [7].



(a)

(b)

Fig. 4: Input impedance Z_{in} calculated from the measured reflection coefficient S_{11} of the five-cell-ZORA (a) and the ten-cell-ZORA (b) both for three different stub length cases.

The input impedance behavior is different for the 10-cell-ZORA. Here Z_{in} exhibits a diluted characteristic due to the mixed standing / traveling wave operation. The longer extent of the antenna causes the real part of the input impedance at the zeroth-order operation to be larger (nearly doubled) than for the 5-cell ZORA – this value converges actually to the Bloch impedance, which is slightly larger than 50 Ω at 24 GHz (cf. Fig. 3).

In both antenna cases a broadband matching has been achieved as depicted in Fig. 5. A local maxima located at 24 GHz is surrounded by two minima yielding a broadband matching with at least 10 dB return loss for the 5-cell ZORA and at least 15 dB for the 10-cell ZORA, respectively.

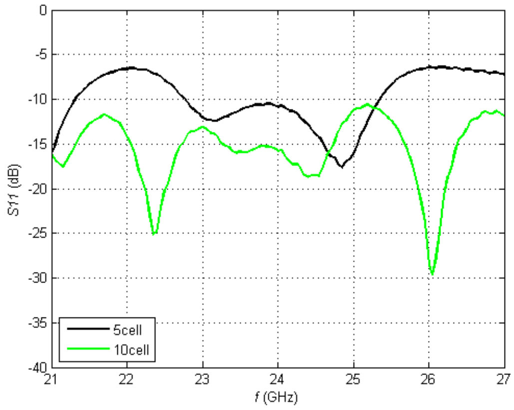
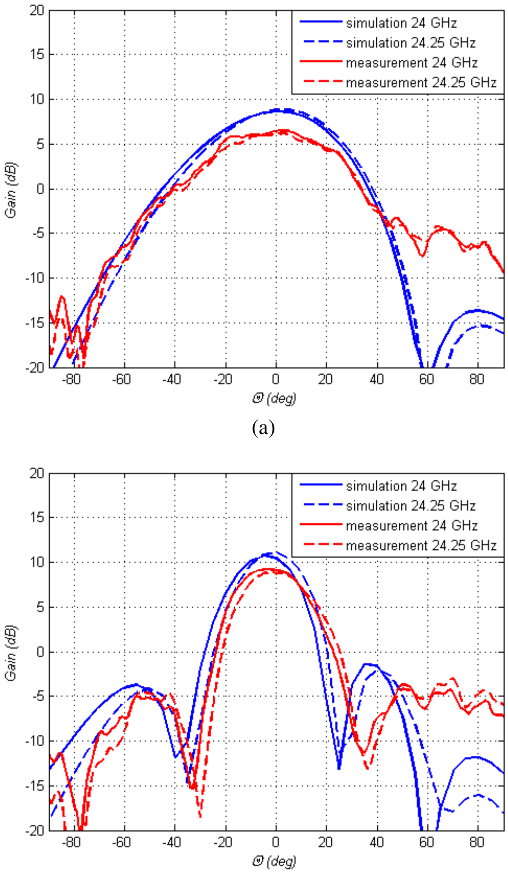


Fig. 5: Measured reflection coefficient S_{11} of the five- and the ten-cell-ZORA for the optimal stub length version (– 50 µm).

Finally, the E-plane radiation patterns of the five-cell and the ten-cell ZORA, both for the optimal stub length versions (– 50 µm), have been measured. The two sub-plots are depicted in Fig. 6 together with the corresponding simulation results obtained by the FDTD software EMPIRE XCcel (IMST GmbH, Kamp-Lintfort, Germany).



(a)

(b)

Fig. 6: E-plane radiation patterns of the five-cell (a) and the ten-cell (b) ZORA both for the optimal stub length versions (– 50 µm).

The radiation patterns have been evaluated at the two edge frequencies of the 24 GHz ISM band. The minor gain discrepancy between measured and simulated results might be explained by an additional microstrip feeding line and the end launch connector used for the measurement, which is not included in the simulation setup. The quite bulky end launch connector disturbs the pattern around the back-fire direction at $\Theta = +90°$ as depicted in Fig. 6.

The pure standing-wave operation of the 5-cell ZORA yields a frequency stable pattern over the whole 24 GHz ISM band (cf. Fig. 6a) which exhibits no side lobes due to the electrically small length of 0.9 λ_0. The 10-cell ZORA extents to 1.8 λ_0, thus side lobes appear. The side lobe level (SLL) is around 13 dB, which is equal to the theoretical value of a uniform aperture distribution. Therefore we can conclude that the periodic CRLH structure with its local near-field inhomogenities acts far-field-wise like a quasi-uniform aperture.

IV. CONCLUSION

The feasibility of CRLH ZOR antennas for the 24 GHz ISM band on Rogers RO4350/4450 multi-layer low-cost technology has been evaluated. Several prototypes of ZOR antennas have been fabricated and measured to confirm the maturity of this low cost approach.

Future work includes the design of more robust MIM CRLH unit cells with less sensitivity to tolerances.

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