MetaBeam: A High-Gain Pencil-Beam Array Antenna based on corporately fed CRLH Meta-Lines for the 24 GHz ISM Band

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Abstract— **One of the objectives in the "MetaBeam" research project was the development of a high-gain pencil-beam array antenna based on composite right/left-handed (CRLH) metamaterial transmission-lines, shortly referred to as CRLH meta-lines. This paper presents an initial prototype for this work-package. We aimed for applications within the 24 GHz ISM band, like automotive radar systems, where low-cost is a major concern. Therefore, the antennas have been realized with a standard multi-layer printed circuit board technology based on Rogers RO4350/4450 laminates, which are approved for automotive applications. The antenna with a two-dimensional aperture is essentially based on corporately fed one-dimensional CRLH meta-lines, which have an electrically long extent and operate therefore as leaky-wave antennas (LWAs) in the fast-wave regime. A conventional corporate feeding network based on Wilkinson power dividers is used to uniformly distribute the power to the different columns. Here, the results of an eight-column array antenna, where each meta-line is composed of 20 unit cells are presented. The overall dimensions are 44 mm (8 times a pitch of 5.5 mm) by 45 mm (20 times the period of 2.25 mm), which roughly corresponds to an electrical size of (4 λ_0)^2, and a gain of 17.4 dB at 24.5 GHz has been measured.**

Index Terms—**pencil-beam, array antenna, CRLH transmission-line, leaky-wave antenna, multi-layer PCB, 24 GHz ISM band, automotive and industrial sensor.**

I. INTRODUCTION

In the field of antennas metamaterial inspired concepts have led to many interesting radiative structures [1-3]. Especially 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 with improved performance or extended functionality [4].

Around the transition frequency of a frequency-balanced CRLH meta-line (ω_0) an infinite-wavelength propagation with no phase-lag ($\beta = 0$) along the line has been utilized for resonant high-gain fan-beam antennas that are terminated by an open- or short-circuit [4, 5]. By increasing the length of such a CRLH meta-line, it more and more functions as a leaky-wave antenna. The power is almost completely leaked out along the line before a reflection at the hard termination occurs and a standing wave can be established, which is an indication for a resonant operation [6]. One-dimensional meta-lines have already been utilized for 2-D pencil-beam antennas, even steerable ones [4, 7]. These related publications on CRLH antennas have in common, that the presented proof of principle prototypes usually operate at frequencies mostly in the lower GHz range (< 10 GHz) [4].

Within the Transfer.NRW research project "MetaBeam", which is funded by the science-to-business pre-seed program of the State of NRW [8], we have successfully bridged the gap between initial research results with proof of concept studies towards real applications, where concerns about cost and reliability play an important role. First results of the MetaBeam activity on 24 GHz fan-beam CRLH antennas have been already published [9]. We investigated the influence of the unavoidable tolerances occurring in low-cost PCB technologies on the performance of the antennas. A significant influence has been observed. Therefore more robust CRLH unit cell designs are necessary at these higher operation frequencies.

In addition to the challenge of robustness against tolerances, CRLH antennas with 2-D apertures have been developed within a work-package of the MetaBeam project. The use of a conventional corporate feeding network based on Wilkinson power dividers to excite several 1-D CRLH meta-lines in an in-phase and equal-amplitude manner is the simplest and probably most reliable technique to form a 2-D aperture antenna based on the CRLH concept. Several 2-D array antennas with different number and length of columns have been designed and fabricated in the project. Here, the measurement results of an eight-column array antenna, where each metamaterial line separated by a pitch of 5.5 mm encompasses 20 unit cells with a period of 2.25 mm are presented.

II. AN EIGHT-COLUMN ARRAY-ANTENNA BASED ON CORPORATELY FED CRLH META-LINES

The CRLH unit cell has been designed by applying the "dispersion engineering approach" [1] using the HFSS eigen-mode solver including periodic boundary conditions along the cascade direction. The multi-layer stack-up is the same as in [9] and is depicted in Fig. 1 (a). The stack encompasses core and pre-preg layers of the Rogers' substrate materials RO4350 (core) and RO4450 (pre-preg), which are suitable for multi-layer PCBs. The layout of the unit cell is given in Fig. 1 (b). It has been slightly changed towards an asymmetric design in order to overcome the gain degradation usually occurring at broadside for periodic leaky-wave antennas (LWAs).

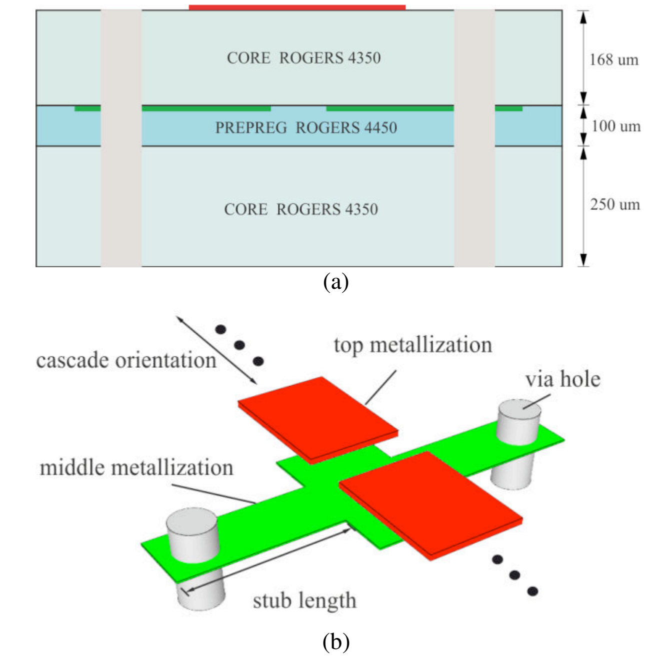


Fig. 1. Layout of the CRLH unit cell: multi-layer stack based on standard Rogers laminates (a) and perspective view of one CRLH unit cell including MIM capacitor and stub inductor (b).

The asymmetry has been fine-tuned such that the Bloch impedance (either in the positive or negative cascade direction) of the periodic structure remains constant around the transition frequency. Additionally to the well-known resonance-frequency-balancing [1] a Q-factor-balancing of the resonators in the series and shunt paths is involved. The details of this novel approach for the case of a series fed patch array antenna will be reported in [10].

As already mentioned in the introduction a conventional corporate feeding network based on Wilkinson power dividers has been applied to excite several 1-D CRLH meta-lines in an in-phase and equal-amplitude manner. A back-to-back prototype of the network is depicted in Fig. 2 – the network itself is located on the backside (cf. Fig. 2(a)), while 8 microstrip-lines on the front-side do connect the two one-to-eight Wilkinson power divider based networks (cf. Fig. 2(b)) in order to determine the insertion loss induced by the network. Later on these microstrip-transmission lines will be replaced by CRLH LWAs including 20 unit cells. The design of this 24 GHz power distributor network has been carried out with the memory-efficient FDTD solver EMPIRE XCcel. The same is true for the array antenna itself.

The eight-column array antenna is depicted in Fig. 3 – it is composed of the CRLH meta-lines on the front-side and the power-distributing and -collecting networks on the back-side. We have chosen this two-port setup in order to evaluate how much power is reaching the second port, and therefore is not radiated by the nearly 4 λ_0 long CRLH LWAs. For the coaxial-to-microstrip-line transitions two on-board mini SMP connectors have been used (cf. Fig. 3(a)).

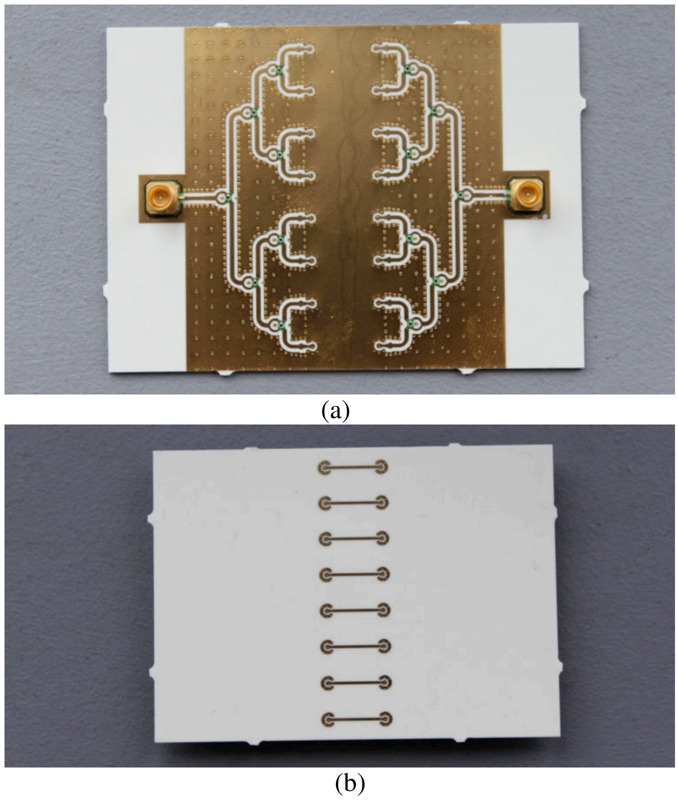


Fig. 2. Back-to-back prototype of a one-to-eight Wilkinson-power-divider based network: back-side with the two networks (a) and front-side with 8 microstrip-lines that do connect the two networks (b).

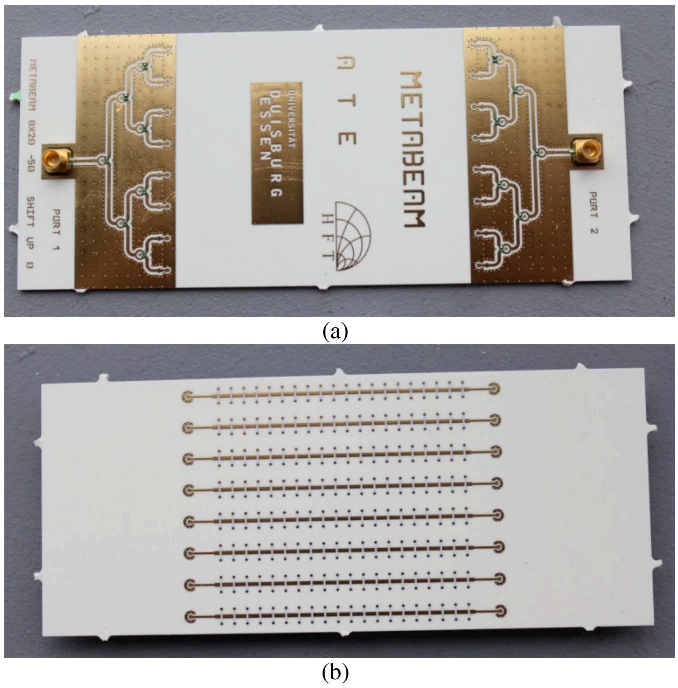


Fig. 3. Eight-column pencil-beam array-antenna: back-side with the in-phase and equal-magnitude feeding network (a) and front-side with the CRLH LWAs encompassing 20 unit cells each (b).

The measured two-port scattering parameters are given in Fig. 4. Due to the asymmetric unit cell design the refection coefficients of two-port antenna differ from each other. Here port 1 should be used to feed the array antenna. In this case a return loss of better than 15 dB is measured over the whole 24 GHz ISM band. The overall insertion loss amounts to more than 25 dB. Considering the losses in the two one-to-eight power dividers of around 1.5 dB each, we can expect a intrinsic loss along the LWAs of more than 22 dB. Thus, the power is nearly completely leaked out at the end of the CRLH antennas.

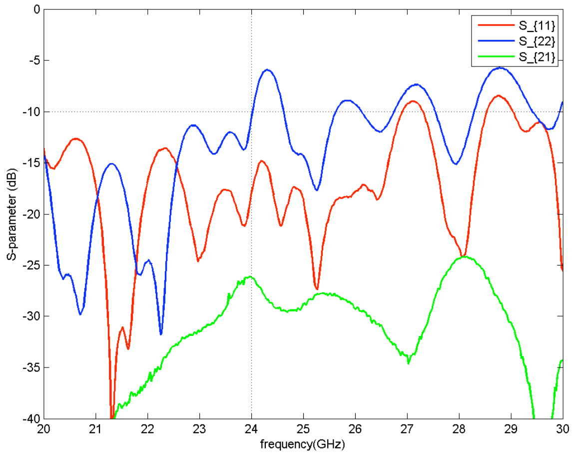
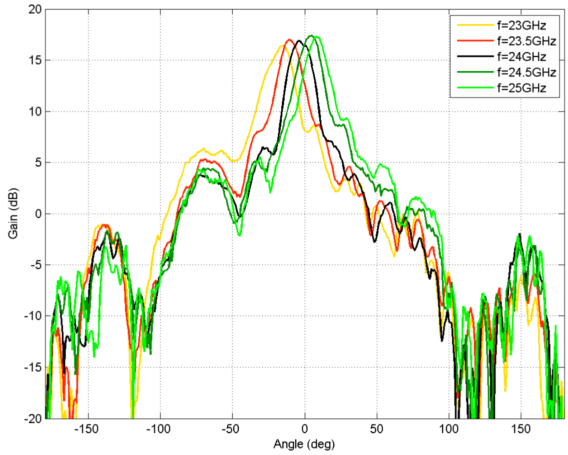


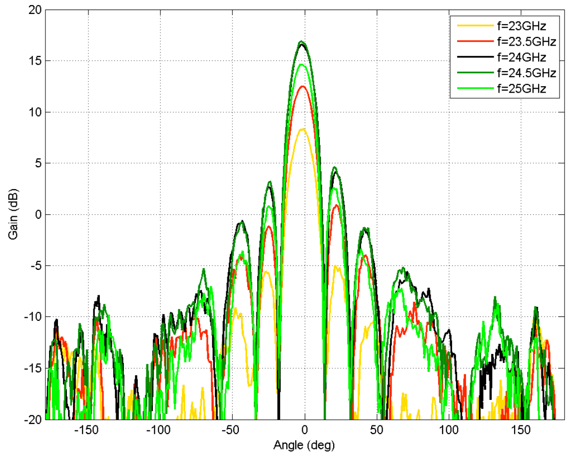
Fig. 4. Measured S-parameter of the two-port array-antenna: The two reflection coefficients differ from each other due to a novel asymmetric CRLH unit cell design. The insertion loss indicates that the power is completely leaked out at the end of the CRLH LWAs.

Finally, the measured radiation pattern for the co-polarisation, which is parallel to the one-dimensional meta-lines, are presented for the E- (ϕ = 0°) and H-plane (ϕ = 90°) cuts. The two plots are given in Fig. 5. The pattern have been measured for altogether five frequencies, ranging from 23 GHz up to 25 GHz with a frequency step of 0.5 GHz, in order to investigate the frequency dependant scan through broadside, and most importantly, the stable gain behaviour around this direction.

For the E-plane cut (fixed angle ϕ = 0°) the constant-gain-scanning of the pencil-beam through broadside is depicted in Fig. 5(a), while in the H-plane cut the direction of the beam remains constant as expected. In the later cut the gain decreases for the non-broadside frequencies, simply because the pencil beam is not pointing in a ϕ = 90° direction anymore. The maximal measured gain amounts to 17.4 dB for a frequency of 24.5 GHz, slightly off-broadside.



(a)



(b)

Fig. 5. Measured radiation pattern for the co-polarization in the E-plane (ϕ = 0° plane along the meta-line, (a)) and in the H-plane (ϕ = 90° plane orthogonal to the meta-line, (b)). The co-pol. direction corresponds to the orientation of the meta-lines.

III. Conclusion

A high-gain pencil beam array antenna based on CRLH metamaterial lines for the 24 GHz ISM band has been presented. The eight columns are fed by a corporate feeding network. A broadband matching has been obtained due to the leaky-wave operation of the electrically long 1-D antennas – rather than a resonant operation. The antenna has been realized on Rogers RO4350/4450 multi-layer low-cost technology. Several prototypes have been fabricated and measured to confirm the maturity of this low cost approach.

Future work includes the incorporation of the presented metamaterial antennas in a complete radar system working at 24 GHz. This will enable a more radar-system-wise evaluation.

IV. ACKNOWLEDGEMENT

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