

A Dual Band CRLH Substrate Integrated Waveguide Leaky Wave Antenna

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Abstract — This paper presents the application of a substrate integrated waveguide (SIW) for the design of a leaky wave antenna radiating simultaneously in two independent frequency bands. The antenna is based on a compensated right-left handed SIW transmission line. Due to this, the direction of the main lobe of the antenna radiation pattern can be steered by changing the frequency from backward to forward direction. The structure novelty is in a dual band operation. The characteristics and radiation aspects of the antenna are discussed. The measured antenna characteristics are in good agreement with those predicted by the simulation. Due to the SIW technology, the antenna is suitable for integration into T/R circuits and antenna arrays.

Index Terms — Compensated right/left-handed transmission line, leaky wave antenna, metamaterial radiation, substrate integrated waveguide.

I. INTRODUCTION

Low profile planar antennas have been of great interest to researchers and designers for more than thirty years. The main advantage of these antennas is that they save space and can be located on the external surface of various bodies. They are cheap, can be fabricated easily and are therefore suitable for mass production. A substrate integrated waveguide (SIW) represents a possible version of a low profile planar transmission line that can be simply designed and fabricated [1]. An SIW leaky wave antenna (LWA) concept was proposed in [2]. This antenna radiates energy through the SIW side wall with sparsely located shortening vias. The concept of an LWA based on radiation through the wide slot in the SIW top wall due to a leaky wave of the first order was proposed in [3]. The SIW was used as an LWA able to steer the radiation pattern main beam by changing the frequency from nearly backward to forward directions [4,5]. This antenna is based on a compensated right/left-handed (CRLH) transmission line working in the compensated mode, i.e., without the frequency gap between the LH and RH bands. Exactly the same concept was used in [6].

CRLH lines offer one pass-band composed of left-handed and directly adjoined right-handed bands without a band gap. A line offering this behavior in two frequency bands was proposed in [7], where the condition for this feature was derived. This line is composed of elementary cells consisting of combinations of a series and parallel resonant circuits in

both through and shunt branches. This concept was applied to a number of dual and quad band circuits in [8].

An SIW LWA based on the CRLH line working in two independent frequency ranges proposed in this paper was designed and fabricated. The antenna is fed through a microstrip line using a standard transition [9]. The antenna radiates one main beam that can be steered from the backward to the forward direction by changing frequency. The measured antenna characteristics are in good agreement with those predicted by the simulation.

II. DESIGN OF THE ANTENNA UNIT CELL

The SIW used to design the leaky wave antenna [4-6] is a standard CRLH transmission line. In order to get a line with the ability to close the LH and RH bands at two independently selected frequency bands, the unit cell of such a line has to contain more than one element so as to have more than one degree of freedom to design it [7]. This structure can be built using properly selected SIW inclusions. An interdigital capacitor [5] is applied. Its equivalent circuit can be composed of a series L-C circuit modeling the interdigital structure itself [10] in combination with a parallel L-C circuit representing the radiating slot in the waveguide wall [11]. LWA radiates through the meander slots of these capacitors. The shunt components of the cell equivalent circuit are represented by four inductive metal pins short circuiting SIW [11]. The SIW used here works below its cutoff in the lower frequency LH band, and its cut off frequency is at the point $\beta = 0$. The cell layout is shown in Fig. 1.

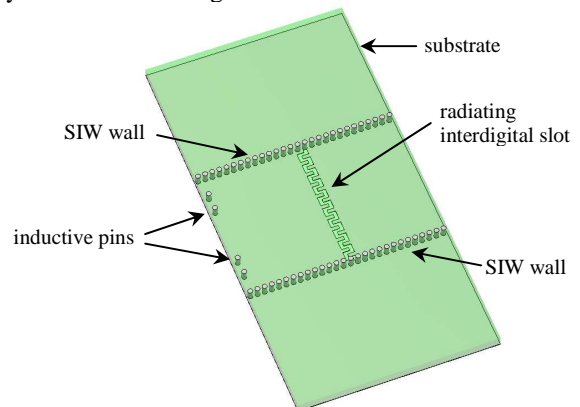


Fig. 1 Layout of the SIW unit cell. View from the rear side, rear metallization is invisible and substrate is transparent.

Finally, we have an equivalent circuit similar to that described in [6], which is able to obey the resonant condition [6, Eq. 4] to close the stopbands and to ensure CRLH operation in two frequency bands. Due to the frequency dependence of all elements of the equivalent circuit, the cell design is not straightforward. We therefore used a complex optimization process performed in this very first design procedure in the CST Microwave Studio (CST MWS).

The Rogers RO4003C substrate 0.813 mm in thickness with relative permittivity 3.38 ± 0.05 and loss factor 0.002 was used. To simplify the analysis performed at CST MWS, SIW sidewalls composed of rows of conducting pins were substituted by PEC walls. The unit cell shown in Fig. 1 was used to determine the antenna dispersion characteristics. Choosing the lower and upper frequencies of the zero value propagation constant equal to 8 GHz and 14 GHz, respectively, the dispersion plot shown in Fig. 2 was obtained. The final values of the frequencies defined above are 8.29 and 14.27 GHz. In fact, residual gaps about 15 and 100 MHz in width are left between the LH and RH bands. The cell dimensions are: length 16.8 mm, distance of the side walls 11.2 mm, pin diameter 0.4 mm. The interdigital slot has 10 and 9 fingers from the two sides. Its dimensions are shown in Fig. 3.

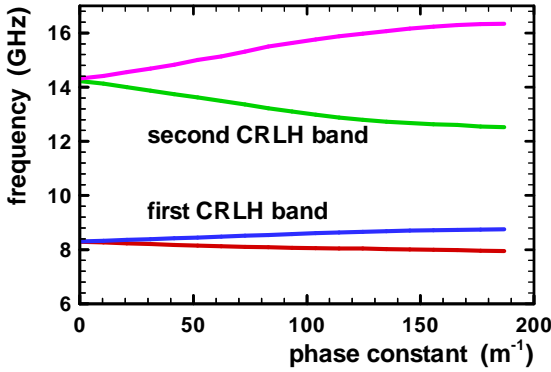


Fig. 2 Dispersion characteristics of CRLH SIW with operation in two frequency bands around 8 and 14 GHz.

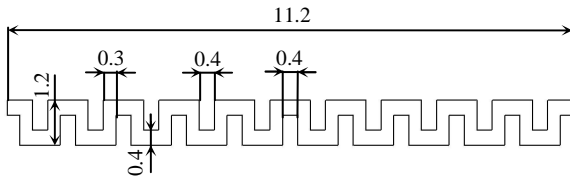


Fig. 3 Detail of the interdigital slot with dimensions in mm.

III. ANTENNA DESIGN AND MEASUREMENT

The antenna was designed and fabricated as a cascade of 10 cells, see Fig. 1, so that its final active length is 168 mm. The layout and a photograph of the fabricated antenna are shown in Fig. 4. The ground plane of the prototype is extended about 15 mm in width on each side due to a mounting fixture. The input microstrip line 1.8 mm in width feeds the antenna periodic structure through a microstrip taper and a widened SIW part that is above the cutoff in the lower LH band to improve reflection. The output microstrip line is terminated by

a 50 Ω resistor to minimize reflections, or can be used to measure transmission. Fig. 4 shows the complete SIW antenna with side walls composed of rows of shorting pins. The diameter and the distance of these pins were chosen according to [1] to be 0.4 and 0.6 mm. The SIW width defined by the distance of the centers of the two rows of pins was chosen to be 11.5 mm instead of the originally designed waveguide width 11.2 mm [1]. The shapes of the microstrip tapers were optimized by CST MWS, again using PEC side walls instead of pins to get minimum reflection. The output taper geometry has a negligible influence on the behavior of the antenna. The taper lengths and widths are 14 and 16 mm at the input, and 9 and 7 mm at the output.

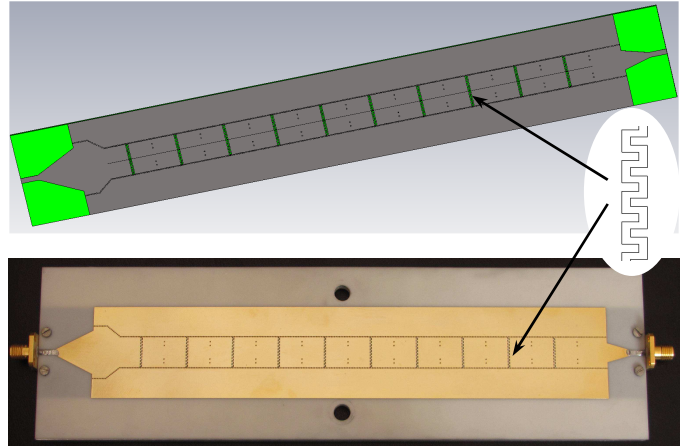


Fig. 4 The antenna layout, and a photograph of the prototype.

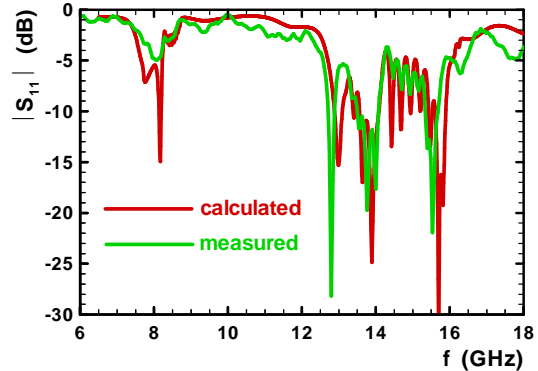


Fig. 5 Antenna input reflection measured and calculated by CST MWS.

The antenna input reflection calculated by CST MWS and measured is plotted in Fig. 5. The plot clearly shows the two antenna working bands that correspond to the two CRLH bands shown in the dispersion characteristics in Fig. 2. Unfortunately, the reflection coefficient $|S_{11}|$ of the current antenna version is only around -6 dB, and in the lower RH band it is only about -5 dB. The plot in Fig. 5 represents the behavior of the whole antenna structure from Fig. 4 terminated by a 50 Ω resistor. The agreement between the simulated and measured data can be considered very good. Three main simulation minima in the upper band 12.986 GHz/-15.3 dB, 13.895 GHz/-24.9 dB, and 15.700 GHz/-33.2 dB are shifted relatively from the measured values 12.791 GHz/-28.2 dB,

13.767 GHz/-19.7 dB, and 15.535 GHz/-21.9 dB about 1.50 %, 0.92 %, and 1.05 %, respectively.

The antenna radiation patterns were originally calculated by CST MWS. These patterns are plotted in Fig. 6 for the first CRLH band and in Fig. 7 for the second CRLH band. The patterns are taken in the longitudinal central plane perpendicular to the antenna top surface (E-plane). Angle θ is measured from the forward direction. The patterns show the main advantage of an LWA based on the CRLH line, i.e. the ability to steer the direction of the radiation pattern main lobe from backward to forward direction by changing the frequency, and in the case of the antenna presented here, in two frequency bands. The first CRLH band is narrow from about 7.8 up to 8.65 GHz, but the steering of the radiation pattern is more sensitive to frequency variation. The main lobe of the radiation pattern can be steered from 50 to 130 deg here, i.e. about ± 40 deg from broadside direction. The measured and calculated scanning sensitivity is plotted in Fig. 8.

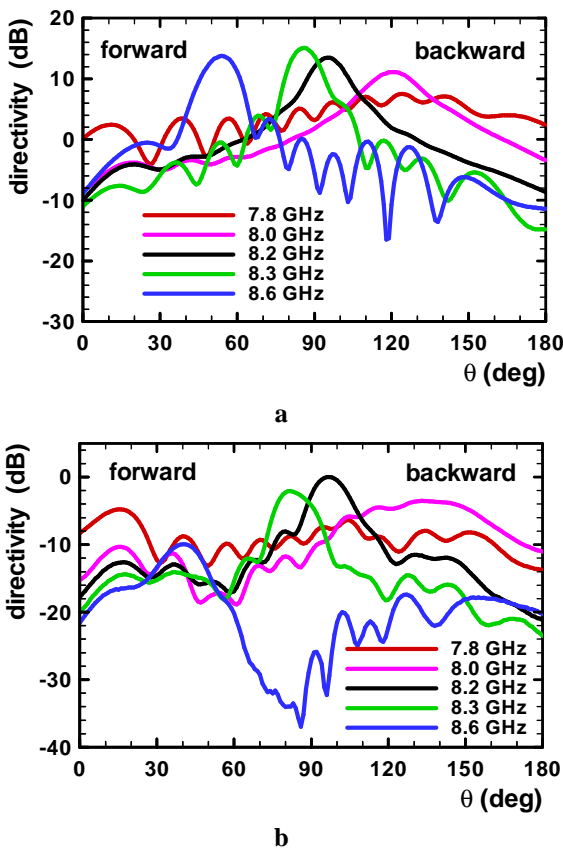


Fig. 6 Antenna E-plane radiation patterns calculated (a), and measured (b) in the first CRLH band. Angle θ is measured from the forward direction, so $\theta = 90$ deg corresponds to the broadside direction.

The second CRLH band is wider than the first band. It spans from about 12.52 up to 16.34 GHz. The beam steering is here less sensitive and can be done in the span of ± 25 deg from the broadside direction. This steering beam ability versus frequency is plotted in Fig. 8. The radiation patterns in the second CRLH band at frequencies close to the edges of this band suffer from the existence of an intensive side lobe

mirrored into the direction opposite to the main lobe direction. These are, e.g., the mirror lobe at 13 GHz radiating into the direction defined by angle 20 deg, and the mirror lobe at 15.5 GHz radiating into the direction at 150 deg. The main lobe directions at 13 and 15.5 GHz are 72 and 115 deg, respectively.

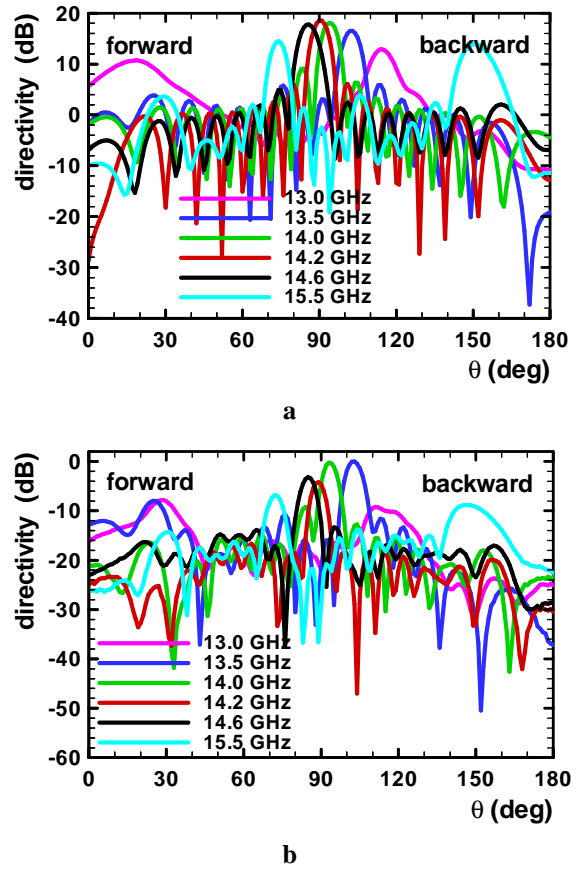


Fig. 7 Antenna E-plane radiation patterns calculated (a), and measured (b) in the second CRLH band. Angle θ is measured from the forward direction, so $\theta = 90$ deg corresponds to the broadside direction.

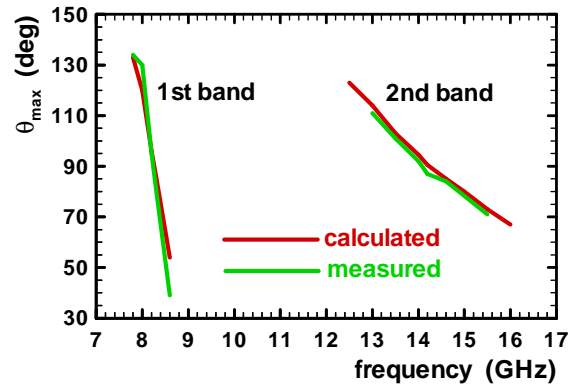


Fig. 8 Calculated and measured scanning sensitivity of the E-plane radiation pattern main beam. Angle θ_{max} is the direction of the main radiation. Angle θ is measured from the forward direction, so $\theta = 90$ deg corresponds to the broadside direction.

The calculated and measured radiation patterns are shown in different plots, in order not to create pictures that are too dense. Most of directions of the main radiation lobes read from the calculated and measured radiation patterns correspond with each other in both frequency bands. There are, however, some differences in the main lobes intensities. The reason of these discrepancies is probably in the fabricated prototype that includes the bodies of connectors with cable and terminating load, has wider substrate used to fix a mounting fixture, and in imperfections of the PCB fabrication process.

IV. CONCLUSIONS

A dual band substrate integrated waveguide leaky wave antenna based on the CTRL transmission line has been designed, fabricated and measured. The antenna radiates in two frequency bands, and in each of them the SIW transmission line fulfills the condition of the CRLH line with a nearly closed gap between the LH and RH bands. The antenna has been designed so that these two bands span from 7.8 up to 8.65 GHz and from 12.52 up to 16.34 GHz. Residual gaps about 15 and 100 MHz in width are left between the LH and RH bands. As it is one of the firstly designed antenna versions it still needs further optimization to improve its reflection losses in both frequency bands of operation, and possibly to suppress the mirror side lobes of the radiation patterns in the second operational band. Reflection losses can be reduced by more precise antenna design that assures better closing of the gaps in the two pass bands. The antenna shows the scanning possibility of the radiation patterns typical for leaky wave antennas based on CRLH transmission lines in both working bands.

The measured S-parameters fit very well with the calculated results. Similarly, the measured radiation patterns correspond with the calculated patterns.

The designed antenna is aimed for integration into antenna arrays and into all transmitting or receiving systems where beam scanning and double band operation are required at the same time. The standard PCB process is applied to fabricate this antenna.

ACKNOWLEDGEMENT

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