A Planar Leaky Wave Antenna Operating in Two Frequency Bands

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***Abstract*— The investigation and design of a leaky wave antenna is presented in this paper. The antenna has a planar structure composed of a substrate integrated waveguide. This waveguide is designed as a composite right/left-handed transmission line operating in two balanced frequency bands with closed gaps between the left- and right-handed regions. The novelty of the structure lies in its dual band operation. An effective way of determining the complex dispersion characteristics of the antenna is presented, and an equivalent circuit of a line unit cell is derived. The antenna was fabricated and the measured characteristics are in good agreement with those predicted by the simulation. The advantage of the antenna lies in its planar structure, which is suitable for cheap mass production.**

Keywords*— *Leaky wave antenna, substrate integrated waveguide, dispersion characteristic, equivalent circuit.

I. Introduction

Leaky wave antennas (LWA) are antennas working with a traveling wave. The energy of this wave is continually radiated as the wave travels along the antenna, assuming that it is a fast wave, i.e., its phase constant is lower than the free space phase constant. These antennas have been investigated for more than 50 years [1,2]. A great number of LWAs have been proposed on the basis of particular transmission lines able to transmit leaky waves at different frequency bands [3,4]. For the purposes of modern technology, planar transmission lines are used as they can easily be integrated with T/R circuits and into antenna arrays.

A substrate integrated waveguide (SIW), the planar equivalent of a rectangular waveguide, is a low profile planar transmission line that can be designed and fabricated simply [5]. The SIW LWA concept was proposed in [6]. 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 [7]. The SIW was used as an LWA able to steer the radiation pattern main beam by changing the frequency from nearly backward direction to forward direction [8]. This antenna is based on a balanced composite right/left-handed (CRLH) transmission line working in balanced mode, i.e., without a frequency gap between the LH and RH bands. Exactly the same concept was used in [9].

Balanced CRLH lines offer the behavior in 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 [10], 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.

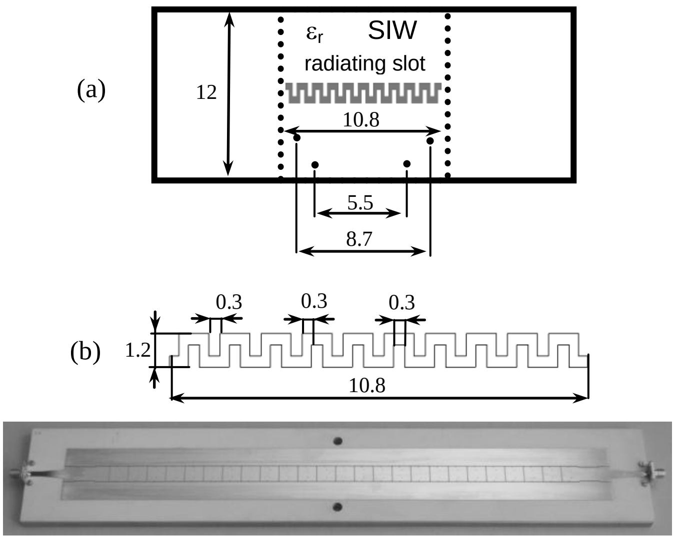
A new dual band SIW LWA based on the CRLH line working in two frequency bands proposed in this paper was designed and fabricated. The idea and the design are inspired by the antenna structure originally presented in [11]. The antenna is fed via a microstrip line using a standard transition to SIW [5]. The antenna radiates through meander slots etched in the top metallization wall. Its behavior was verified by measurements of its characteristics. The results correspond well to the characteristics predicted by simulations.

The complex dispersion characteristics of the antenna were studied in detail, and a new method for determining them was proposed. The results are compared with other techniques. The antenna unit cell equivalent circuit (EQC) corresponds well to the circuit proposed in [10].

II. Antenna Design

The idea of the antenna design is based on the conclusions of [10] concerning dual band/quad band operation of the CRLH transmission line. The equivalent circuit of such a line unit cell is composed of series and parallel resonant L-C circuits in both the through and shunt branches. This is respected by the proposed antenna unit cell structure, as shown in Fig. 1. The series elements are represented mainly by the meander slots, which enable the antenna to radiate, see Fig. 1b. The parallel elements are represented by four conducting vias. All these elements are however mutually coupled, and the EQC of the cell derived from its dispersion characteristic fully corresponds to the EQC presented in [10].

An analysis of the SIW antenna structure was performed by the CST Microwave Studio (CST MWS) using solid PEC walls terminating the SIW from the sides in order to simplify the computation process. A Rogers RO4003C substrate 1.524 mm in thickness with relative permittivity 3.38 ± 0.05 and loss factor 0.0027 was used. The presented structure was designed with the aim to reduce the reflection losses and at the same time to improve the shape of the radiation pattern, i.e., to reduce the spurious radiation that occurred in the original structure [11]. The spurious radiation is due to the Bragg reflections that occur at the Bragg condition $\beta d = \pi$, β is phase constant, d is the cell length. This happens at the edges of the dispersion characteristics branches. The design of the antenna was performed by a coarse optimization performed at CST MWS, with the aim to close the bands between the LH and RH bands. However, some gaps are finally left. For the presented structure with the cell 12 mm in length, the gaps are 25 and 85 MHz wide. This antenna dispersion characteristic is discussed in the next paragraph.



(c)

Fig. 1 SIW unit cell (a), layout of the meander slot (b), fabricated antenna composed of 25 cells (c).

The antenna radiation pattern was predicted by substituting the antenna by an array of radiating elements representing the meander slots. The cell length, i.e., the element distance of this array that ensures a structure without the spurious radiation reported in [11] was found to be 11 mm. Finally, the antenna structure was designed with the cell 12 mm in length. This is a compromise between a length of 11 mm, suggested by the approximate analysis, and the design aimed at closing the gaps between the LH and RH bands. The final dimensions of the unit cell are shown in Fig. 1a,b.

Matching circuits were designed for the antenna. A quarter-wavelength transformer was used to transform the real part of Z_{in} to nearly the same value as the impedance of the empty SIW. The transformer was located at the point where $\mathrm{Im}(Z_{in})$ is almost equal to zero. The main advantage of this type of matching is that it matches the first band of the antenna, making coefficient S_{11} in the center of the first band better, but it simultaneously does not affect the second band of the antenna. The SIW periodic antenna structure is connected to the input and output 50 Ω SMA connectors via tapered microstrip line transitions [5].

The designed antenna was fabricated by a planar printed circuit board technology in two specimens differing by the number of cells. The shorter antenna has 15 cells, while the longer antenna has 25 cells. A photograph of the longer antenna is shown in Fig. 1c.

III. Complex Dispersion Characteristic and Unit Cell Equivalent Circuit

The complex propagation constant of an infinitely long periodic 1D structure $\gamma = \alpha + j\beta$, where α is attenuation constant and β is phase constant calculated as [12],

$$\cosh(\gamma d) = \frac{A + D}{2} = 1 + ZY \qquad (1)$$

where A, D are elements of the ABCD transmission matrix $\mathbf{A}$ of one unit cell, Z and Y are series impedance and parallel admittance of the unit cell EQC. The periodic transmission line is composed of a chain of elementary cells that are tightly coupled, and additionally the behavior of the first cell and the last cell is modified by the presence of a source used to calculate or to measure the transmission matrix. The behavior of an “inner” cell that includes the coupling with all neighbor cells can be obtained using the matrix of the whole chain $\mathbf{A}_c$

$$\mathbf{A} = \sqrt[N]{\mathbf{A}_C} \;. \qquad (2)$$

This procedure was applied to the SIW LWA described in the previous paragraph. The ambiguity is removed by calculating the dispersion characteristic based on a rough knowledge of the frequency centers of the two antenna frequency bands. This distinguishes our method from those proposed in [13]. An equivalent procedure is presented in [14]. It is however applied to determine not the dispersion characteristic but the parameters of the cell equivalent circuit. The dispersion characteristics in dependence on the number of cells up to $N = 11$ are plotted in Fig. 2. The convergence is relatively fast, apart from the values in the stop bands below 8.4 GHz and between 10.2 and 13.8 GHz. So finally $N = 9$ is a sufficient number of cells. The analysis was done at CST MWS (computation of matrix $\mathbf{A}_c$). The data that was provided describes the analyzed periodic structure very rigorously.

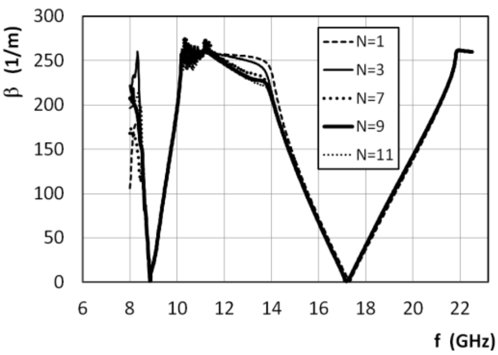
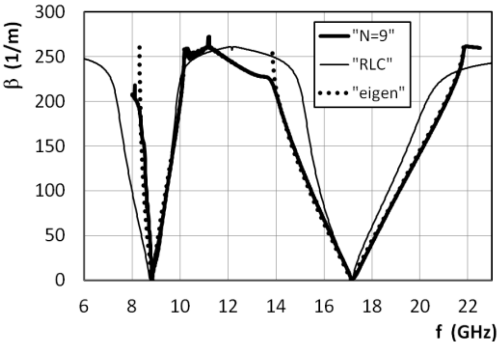
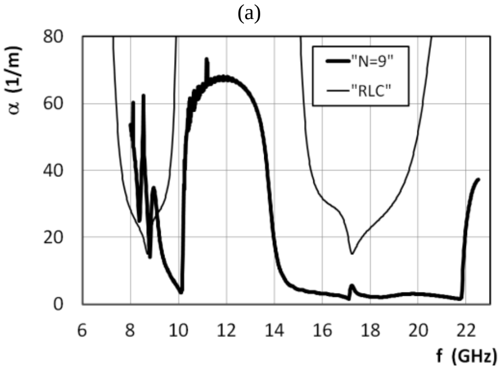


Fig. 2 Evolution of the phase constant calculated according to (1-2) with increasing number of cells N.

The dispersion characteristics were alternatively determined by the CST MWS eigenmode solver. This solver takes into account only lossless resonators, so only the real resonant frequency can be determined and, using this way, only the phase constant can be calculated. The radiation cannot be accounted for. The analyzed unit cell must be fully enclosed. It was terminated by periodic boundaries in longitudinal direction, PEC and PMC walls from bottom and top and PMC walls from the sides. The values are plotted in Fig. 3a, marked as "eigen". Here, this phase constant is compared with the data from Fig. 2. The agreement is excellent.



(a)



(b)

Fig. 3 Phase (a) and attenuation (b) constants of the LWA with $d = 12$ mm. Particular lines are described in the text.

The cell lumped equivalent model was derived by modifying the model of the CRLH line presented in [14]. The complex dispersion characteristic plotted in Fig. 3 for $N = 9$ was used for this. The parallel admittance was calculated from the impedance matrix element Z_{12} of one antenna cell calculated by CST MWS. The EQC is shown in Fig. 4. The complex dispersion characteristic is then calculated by (1). This characteristic is denoted as "RLC" in Fig. 3a,b. The agreement of the phase constant is good around the frequency points where $\beta = 0$, i.e. in areas where the linearization mentioned in [14] is valid. The attenuation constants, plotted in Fig. 3b, do not fit mutually as well as the phase constants. The data obtained by the procedure described by (1)-(2) takes into account all losses in the dielectric, in the metal, and the radiation. The line denoted as $N = 9$ in Fig. 3b therefore shows the correct values of the attenuation constant.

IV. EXPERIMENT

The scattering parameters of the fabricated antennas were measured, and are compared in Fig. 5 with the parameters calculated by CST MWS. The simulated data and the measured data match relatively well.

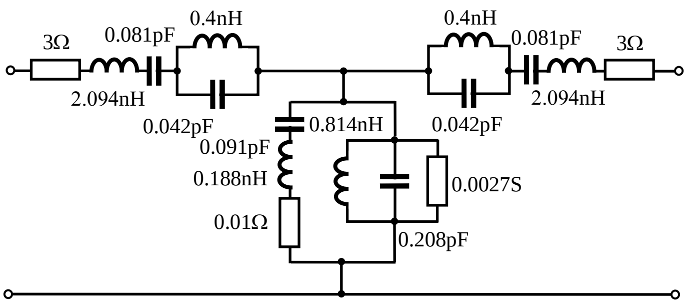


Fig. 4 The unit cell lumped equivalent circuit.

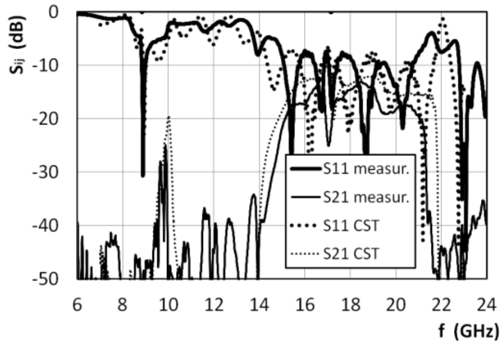


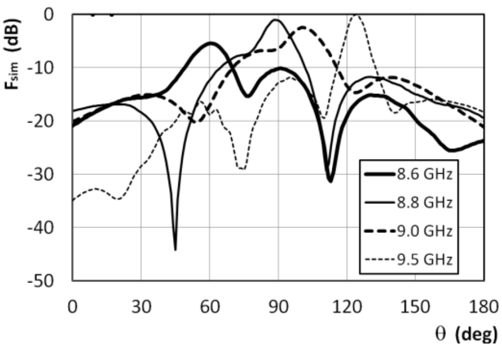
Fig. 5 Calculated and measured scattering parameters of the antenna with 25 cells.

The radiation patterns of the antennas taken in the longitudinal plane normal to the antenna surface were calculated by CST MWS and were also measured; see Fig. 6. Angle θ was measured from the backward direction and equals 90 deg at broadside. The patterns show the main advantage of an LWA based on the CRLH line, steering the direction of the main lobe from backward direction to forward direction by changing the frequency in the two frequency bands. The behavior of the shorter antenna is similar, except that the beams are wider.

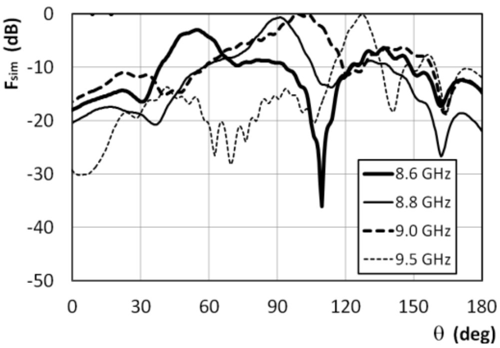
The narrow main beam is present from about 8.6 up to 9.5 GHz in the lower CRLH band. The main lobe of the radiation pattern can be steered from 65 to 125 deg in this frequency band. The radiation patterns exhibit spurious side lobes around 150 deg that are only about 6 to 10 dB lower than the main lobes. These lobes, and similarly the lobe at 8.8 GHz directed to 90 deg, are caused by spurious radiation of the SMA-microstrip transition, as characteristics calculated for the antenna model without these transitions are free of this spurious radiation.

The second CRLH band is wider than the first band, and spans from about 15 up to 19 GHz. The beam is narrower than in the lower band. The beam steering is less sensitive here, and can be done in the span of 65 to 105 deg. The radiation patterns suffer from the existence of a side lobe, directed in elevation angles between 130 and 170 deg., which is about 6 to 12 dB smaller in the measured plots than the main beam. The decrease in antenna efficiency with increasing frequency may be due to residual radiation of the feeding cables used in the measurement setup but not included in the EM model.

The antenna gain evaluated by the comparison method using DRH20 measurement by double ridge horns, see [15], is 6.5 and 16.0 dBi at 8.8 and 17.15 GHz, respectively.



(a)



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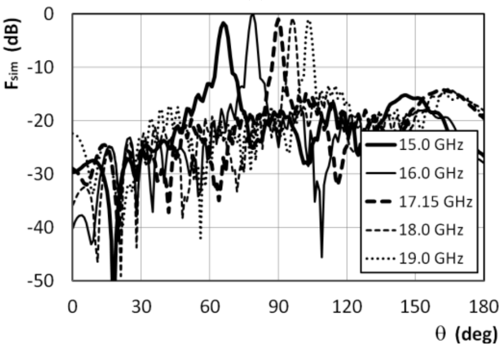

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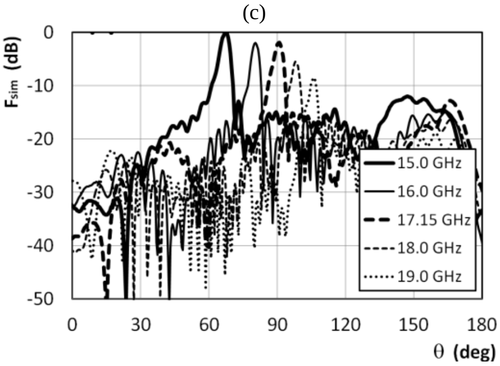

(d)

Fig. 6 Calculated and measured radiation patterns of the antenna with 25 cells for varying frequency in the first band (a), (b), and in the second band, (c), (d), respectively.

V. CONCLUSIONS

A dual band substrate integrated waveguide leaky wave antenna was designed, fabricated and measured. The balanced CRLH substrate integrated waveguide was used to give the possibility to scan the radiated beam from the forward direction to the backward direction by changing the frequency. The antenna radiates the narrow beam in two frequency bands spanned from approx. 8.6 up to 9.5 GHz and from 15.0 up to 19.0 GHz. The exact scanning ability is 60 deg across the broadside direction in the lower band, and about 40 deg across the broadside direction in the upper band. The complex dispersion characteristics were determined by a new efficient method proposed in this paper, which can be considered as a unique source of data applicable to a wide class of radiating periodic structures. The analysis performed by CST Microwave Studio verifies well the measured antenna characteristics. The designed antenna is aimed for integration into antenna arrays and into T/R systems.

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