Leaky Wave Antennas Designed on a Substrate Integrated Waveguide

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***Abstract*— This paper presents the results of an investigation of leaky wave antennas designed on a substrate integrated waveguide. The antennas are of the following types: antenna radiating from a slot in the top waveguide wall, CRLH and dual band CRLH leaky wave antennas. The substrate integrated waveguide can easily be integrated with planar microwave circuits. Antennas designed on this transmission line have a planar structure, and can be fabricated by a standard PCB technology, so they are suitable for mass production.**

Keywords—surface integrated waveguide; leaky wave antenna; planar transmission line

I. Introduction

Low-profile planar antennas can be integrated with other circuits and can be easily fabricated. They are therefore suitable for cheap mass production. They have been of great interest to researchers and designers for more than thirty years. There are two kinds of low-profile planar antennas, which differ in the way that they radiate. Resonant structures are in principle narrow band, and their radiation patterns are more or less fixed, defined by the antenna structure. Traveling wave antennas – leaky wave antennas (LWA) – are broad band, and their radiation pattern can be steered by changing the frequency.

In recent years, a new concept for the design of microwave and millimeter-wave waveguide structures and components has been proposed [1, 2]. Substrate integrated waveguide (SIW) structures, also known as laminated waveguide or post-wall waveguide structures, use this concept. SIWs are based on the equivalence between well-known metallic waveguide structures [3] (usually a waveguide of rectangular cross-section) and waveguiding structures on a dielectric substrate using rows of metal posts (vias), see Fig. 1. Cost-effective microwave SIW circuits are simple to design using this approach [1, 2].

The SIW leaky wave antenna concept was proposed in [4]. 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 [5]. The SIW designed as a balanced right/left-handed (CRLH) transmission line was used as an LWA able to steer the radiation pattern main beam by changing the frequency from nearly backward direction to forward direction [6, 7].

A line offering CRLH behavior in two frequency bands was proposed in [8], where the condition for this feature was derived. Based on these results, a new dual band SIW LWA working in two frequency bands was designed and fabricated [9, 10]. The antenna radiates one main beam that can be steered from the backward direction to the forward direction by changing the frequency in both frequency bands. Radiation occurs through meander slots etched in the top metallization wall.

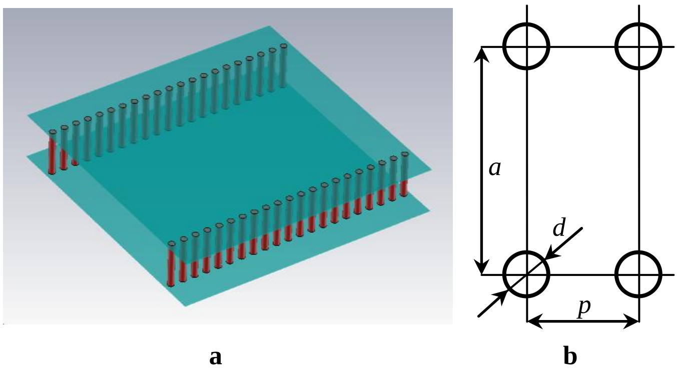


Fig. 1. Substrate integrated waveguide structure (a), post dimensions and geometry (b).

Another novel form of a dual band SIW LWA was presented in [11]. The structure was designed on the basis of a circuit model that predicts its behavior.

This paper summarizes the results of SIW LWA research done by the author and published namely in [5, 9, 10]. The aim is to design antennas with a planar structure that can be integrated simply with transmitter/receiver circuits and can easily be mounted on surfaces of large bodies without deteriorating their shapes.

II. Substrate Integrated Waveguide

A substrate integrated waveguide is a synthetic rectangular electromagnetic waveguide formed in a dielectric substrate by two rows of metallized posts or via-holes which connect the upper and lower metal plates of the substrate. This is a direct analogy to the rectangular shape waveguide with metallic walls [3], where the side walls are created by the two rows of posts, see Fig. 1 [1]. The waveguide can be fabricated easily with low-cost and mass-production, using through-hole techniques. The SIW has similar guided wave and mode characteristics to the conventional rectangular waveguide with the equivalent guided wavelength. The discontinuous side walls prevent the SIW from guiding TM modes.

The main guidelines for the SIW design were presented in [12, 13]. This involves designing SIW width *a*, post diameter *d*, and post spacing *p*, Fig. 1b. The SIW width defines the cutoff frequency λ_c [3], which is determined by the effective width – the width of the equivalent rectangular waveguide a_e , that is [13]

$$a_e = a - 1.08\frac{d^2}{p} + 0.1\frac{d^2}{a} \quad . \tag{1}$$

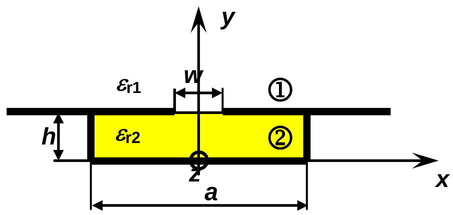
For given d/λ_c, keeping naturally $p > d$, the post spacing has to be chosen within the interval

$$0.05 < \frac{p}{\lambda_c} < 0.25 \ , \tag{2}$$

where the lower limit is defined by the mechanical firmness of the substrate, and the upper limit is defined by omitting the stop-band working regime [12] defined by a Bragg condition. Post diameter *d* is then defined by the leakage losses [12].

III. Antenna Radiating from a Slot in the Broad Wall

An SIW LWA radiating from a longitudinal slot etched in the upper wide wall was designed and fabricated [5]. The antenna is fed through a microstrip line, Fig. 2, and the first space leaky mode with odd symmetry is excited along the line. The antenna radiates a beam that can be steered as in the case of standard LWAs in the forward direction by changing the frequency. The Rogers 4350B substrate with $h = 0.508$ mm in thickness with relative permittivity $\varepsilon_r = 3.48$ and loss factor $\tan\delta = 0.0037$ was used. To get the maximum radiation in the frequency band around 19 GHz we chose according to the dispersion characteristics shown in [5, 14] SIW width $a = 9$ mm and slot width $w = 5$ mm, see the antenna cross-section in Fig. 2a.



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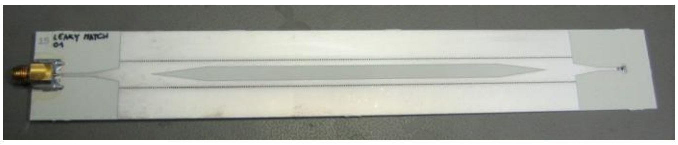

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Fig. 2. Antenna cross-section (a), fabricated antenna radiating from a slot in the broad wall (b) [5].

The chosen antenna length was l = 100 mm, measured along the slot with the full width, see Fig. 2, due to the requirement that the amplitude of the space leaky mode at the end of the antenna should be 10% of its magnitude on the feeding tip at mean operating frequency 19 GHz. The antenna gain might be increased by prolonging the antenna, since with the fabricated structure about 10% of the power coupled to the antenna is lost in the terminating impedance. The radiating slot was terminated by wedges to minimize reflections. The final antenna width *g* was chosen three times wider than the SIW width *a*.

The measured S-parameters, and the S-parameters calculated by the CST Microwave Studio, of the SIW LWA are plotted in Fig. 3. For the simulation, no dielectric losses and no electric losses were considered, which can be seen in the difference between the measured results and the simulated results. The operating frequency band defined by a reflection coefficient lower than -10 dB starts at 18 GHz, and from above it is limited by the existence of the space leaky mode documented in the dispersion characteristics [5], which is about 20.5 GHz. A comparison of the measured and calculated radiation patterns at 20 GHz is shown in Fig. 4, with very good agreement. The measured radiation patterns normalized to 0 dB are plotted in Fig. 5. The antenna radiates a beam steered in the vertical plane from 48° at 18 GHz to 15° at 21 GHz, measured from the forward direction. The full width at half power of the main antenna beam in the vertical plane varies from around 13° at 18 GHz to 21° at 21 GHz. The side lobes are about 10 dB below the level of the maximum radiation.

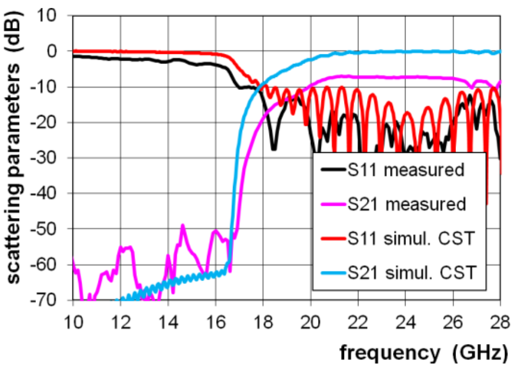

Fig. 3. Measured and simulated (CST Microwave Studio) scattering parameters of the antenna from Fig. 2 [5].

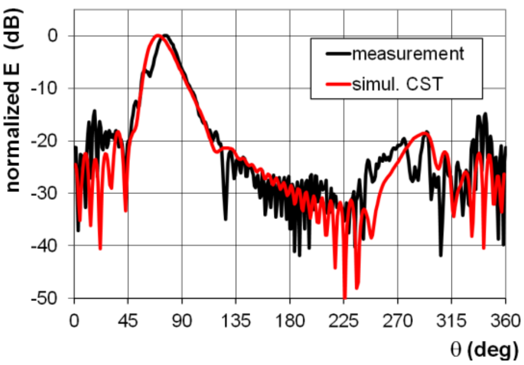

Fig. 4. Measured and simulated radiation patterns of the antenna from Fig. 2 at 20 GHz [5].

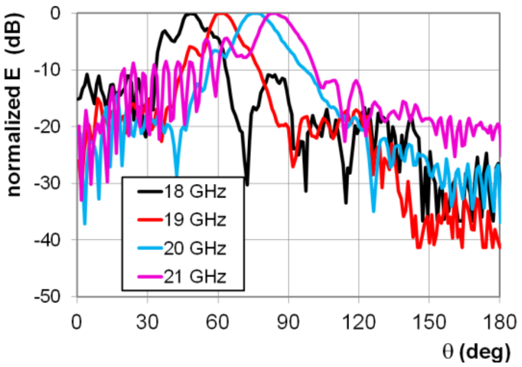

Fig. 5. Measured radiation patterns of the antenna from Fig. 2 [5].

IV. An Antenna Based on CRLH SIW

An SIW-based antenna similar in form to the antenna already published in [6] was designed for application in an antimissile radar system. The advantage was the ability to steer the angle of the main radiation beam simply by changing the frequency. The SIW is designed on the Rogers RO4003C substrate 1.524 mm in thickness and with permittivity 3.38. The antenna structure composed of 26 CRLH cells is shown in Fig. 5. The SIW cell is 9.5 mm in length and $a = 9$ mm. The antenna radiates through meander slots that represent series capacitors of the CRLH equivalent circuit. Shunt inductors are represented by two shunt inductive posts located in each SIW cell. The frequency band of this antenna operation is documented by the dispersion characteristic calculated by the CST Microwave Studio eigen mode solver in Fig. 7. The SIW CRLH line is balanced, with no band gap. The free space propagation constant k_o limits the frequency band of the radiation from about 8.6 GHz to 11.7 GHz. This band is verified by the frequency characteristic of the scattering parameters plotted in Fig. 8.

The calculated radiation patterns and the radiation patterns simulated by the CST Microwave Studio are compared in Fig. 9. They are normalized to 15 dB. The antenna radiation pattern main lobe varies continuously with changing frequency from -50° to 70°, measured from the broadband direction. The steering of the radiation pattern by changing the frequency is documented in Fig. 10, where the calculated radiation patterns are plotted.

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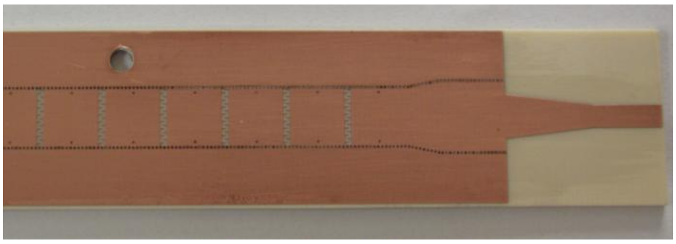

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Fig. 6. Fabricated CRLH SIW LWA (a), a detail of the structure with the transition to the microstrip and widened SIW that works above its cut off (b).

The parameters of the fabricated antenna specimen were deteriorated by improperly mounted SMA connectors to relatively wide 50 Ω microstrip transmission lines, see Fig. 6b. However, a pair of these antennas works well in the designed radar system.

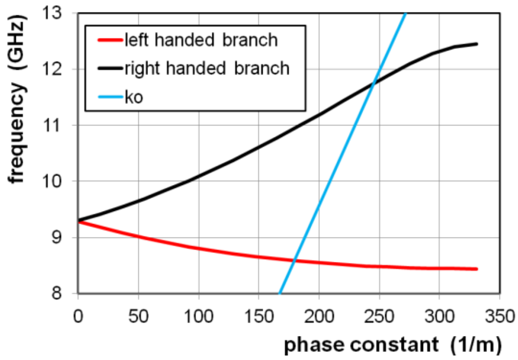


Fig. 7. Dispersion characteristic of the antenna from Fig. 6, calculated by the CST Microwave Studio.

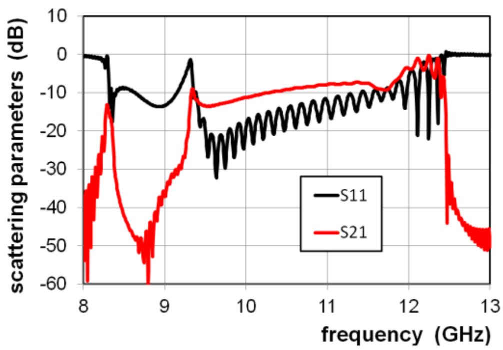


Fig. 8. Calculated (CST Microwave Studio) S_{11} and S_{21} of the antenna shown in Fig. 6.

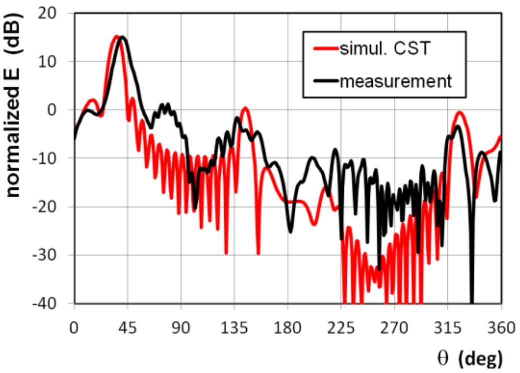


Fig. 9. Measured and simulated radiation patterns of the antenna from Fig. 6 at 11 GHz. 90° corresponds to the broad side, 180° corresponds to the forward direction.

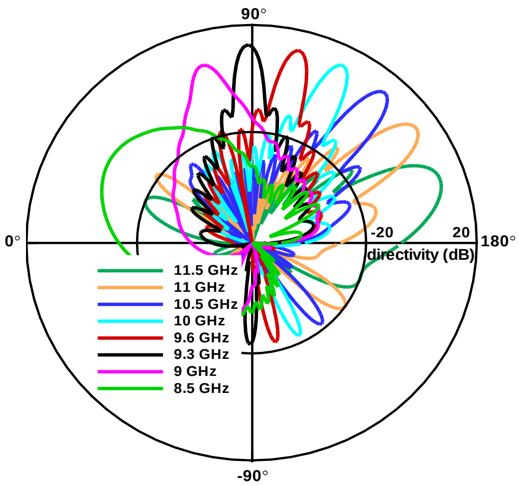
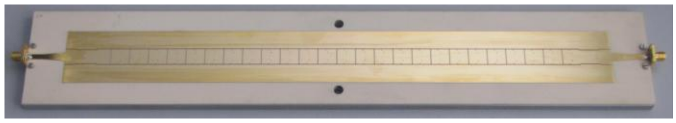


Fig. 10. Steering of the radiation pattern (normalized) of the antenna shown in Fig. 6. 90° corresponds to the broad side, 180° corresponds to the forward direction.

V. Dual Band CRLH SIW Antenna

The design of the antenna is based on the conclusions of [8] concerning the dual band/quad band operation of the CRLH transmission line. The equivalent circuit (EQC) of such a line is composed of combinations of series and parallel resonant L-C circuits both in the through branch and in the shunt branch. This is taken into account by the proposed antenna unit cell structure shown in Fig. 11. The series elements are represented mainly by the meander slots through which the antenna radiates, see Fig. 11b. 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 [9] fully corresponds to the EQC presented in [8].

The designed antenna was fabricated by a planar printed circuit board technology in two specimens having 15 and 25 cells. Fig. 11a shows a photograph of the longer antenna.



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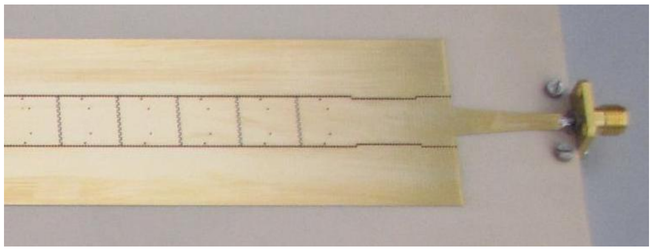

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Fig. 11. Fabricated CRLH SIW LWA (a), detail of the structure showing particular cells and the matching circuit with the transition to the microstrip line (b), [9].

An analysis of the SIW antenna structure was made by the CST Microwave Studio using solid PEC walls terminating the SIW from the sides in order to simplify the computation process [9, 10]. A Rogers RO4003C substrate 1.524 mm in thickness with relative permittivity 3.38 ± 0.05 and loss factor 0.0027 was used. The design of the antenna was performed by a coarse optimization performed in the CST Microwave Studio, aimed at closing the band gaps between the LH and RH bands. However, there are finally some gaps left. For the structure presented here, with the cell 12 mm in length and 10.8 mm in width, the gaps are at 25 and 85 MHz in width. The complex dispersion characteristics of this antenna were calculated by the method introduced in [10] and show clearly the two antenna working bands, Fig. 12.

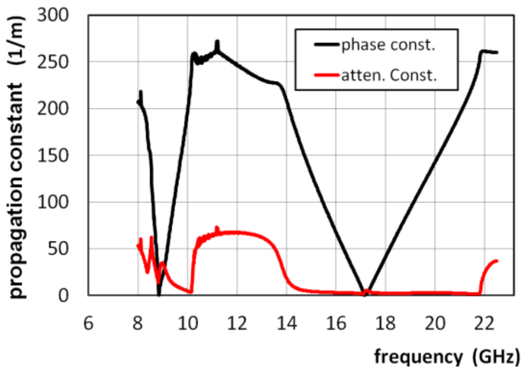


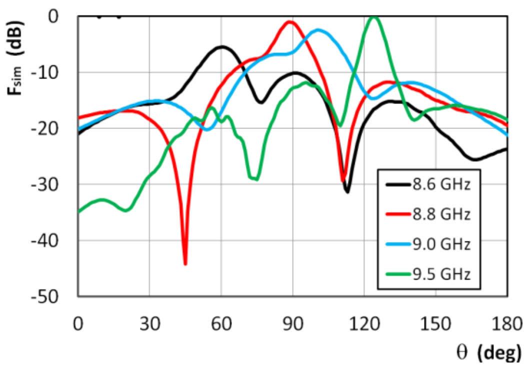
Fig. 12. Complex dispersion characteristics phase and attenuation constants of the antenna from Fig. 11 [10].

The radiation patterns of the longer antenna with 25 cells taken in the longitudinal plane normal to the antenna surface were calculated by CST MWS, and were also measured; see Fig. 13. Angle θ was measured from the backward direction, and equals 90° at the broad side. The patterns show the main advantage of this 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 radiated 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° in this frequency band. The radiation patterns exhibit side lobes around 150° that are only about 6 to 10 dB lower than the main lobes. These lobes 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°. The radiation patterns suffer from the existence of a side lobe, directed in elevation angles between 130° and 170°, 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 was evaluated by the comparison method, which uses measurements performed by DRH20 double ridge horns, see [15]. This gain is 6.5 dBi at 8.8 GHz, and 16 dBi at 17.15 GHz.



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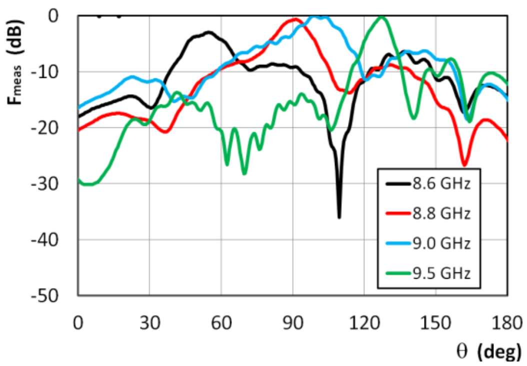

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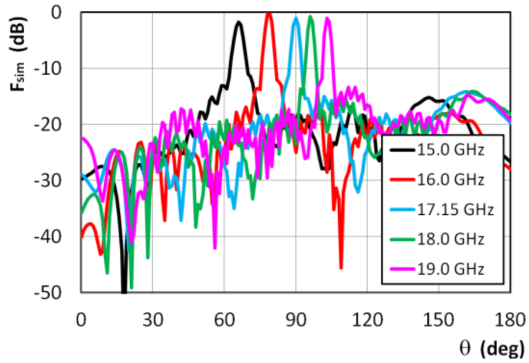

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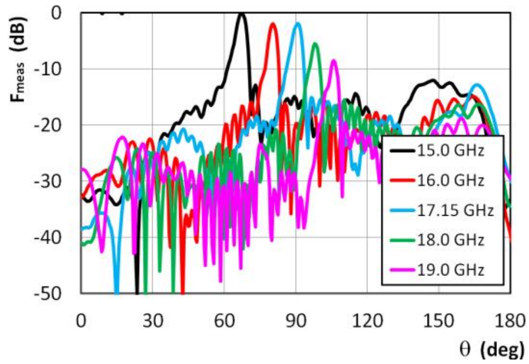

d

Fig. 13. Calculated and measured radiation patterns for varying frequency in the first band (a), (b), and in the second band, (c), (d), respectively, of the antenna from Fig. 11 [10].

VI. CONCLUSIONS

This paper has summarized the results of the author's investigation of leaky wave antennas designed on a substrate integrated waveguide. The antennas are: an antenna radiating from a slot in the broad wall – flat waveguide LWA, a CRLH substrate integrated waveguide antenna, and a CRLH substrate integrated waveguide antenna radiating two frequency bands.

A substrate integrated waveguide leaky wave antenna radiating from a slot in the broad wall parallel to its axis was designed and fabricated. The initial dimensions of the SIW and of the slot were obtained from analytical expressions for equivalent rectangular waveguides and from the dispersion characteristics. The SIW, the antenna layout and the feeding circuit were then optimized, using the CST Microwave Studio. The measured S-parameters and antenna characteristics fit well with the calculated results. The operating frequency band is from 18 GHz to 21 GHz, and the gain is about 7 dB at 19 GHz. The antenna radiates a beam steered in the vertical plane from 48° at 18 GHz to 15° at 21 GHz measured from the forward direction.

A CRLH substrate integrated waveguide leaky wave antenna was designed and fabricated. This antenna operated in the frequency band from 8.6 GHz to 11.7 GHz, and the main beam of the radiation pattern can be steered by changing the frequency from -50° to 70°, measured from the broad side direction. This antenna works in an antimissile radar system.

A dual band substrate integrated waveguide leaky wave antenna was designed, fabricated and measured. The balanced CRLH substrate integrated waveguide was used to provide the possibility to scan the radiated beam from backward direction to forward 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° across the broad side direction in the lower band, and about 40° across the broad side direction in the upper band. The analysis performed by CST Microwave Studio verifies the measured antenna characteristics well.

The designed flat - planar antennas are intended to be integrated into antenna arrays, and directly into T/R systems where beam scanning is required. The flat antenna can easily be mounted on surfaces of large bodies (e.g., aircraft) without deteriorating their shape. The antennas are fabricated by a simple PCB process, and are therefore cheap and suitable for mass production.

Acknowledgment

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