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Gap Waveguide Leaky Wave Antenna

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***Abstract*—A novel leaky wave antenna, realized using gap waveguide concept, is here proposed. Both, the feeding structure and the antenna are realized in groove gap waveguide technology, thus simplifying the whole structure. A complete design procedure, starting from a given groove waveguide to the final radiation mechanism, is described in this paper. The results are supported with measurements of a prototype that operates in the X-band. The realized antenna has a gain around 18 dB between 9 GHz and 11.5 GHz, demonstrating the potential of the proposed radiation technology.**

***Index Terms*—Groove gap waveguide, leaky wave antenna, metasurface, metamaterial.**

I. Introduction

RECENTLY, a new technology, called gap waveguide, was introduced to build new type of waveguide components with special interest for the millimeter frequency range. Basically, gap waveguide is a two-dimensional metamaterial structure inside a parallel-plate waveguide which inhibits propagation along the structure, i.e. it generates a stop band for parallel-plate waveguide modes. The operation of gap waveguides is inspired by the concept of soft and EBG surfaces which stop the propagation of the electromagnetic waves along the surface in one or two directions, respectively [1], [2].

A gap waveguide is a modified parallel-plate waveguide where the bottom metallic plate is replaced by a textured surface with periodic elements, usually metallic pins, which act as an artificial magnetic conductor (AMC). By placing a metallic plate at a distance smaller than $\lambda/4$ from the top of the pins, no electromagnetic waves can propagate between the AMC and the plate. In order to guide the waves in a desired direction, ridges, strips or grooves are introduced and surrounded by those metallic pins [3]-[6]. In this way there is a possibility to guide most of the electromagnetic energy along those modifications with a minimum of lateral leakage of energy.

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There are many potential applications of the gap waveguide technology, in particular for frequencies above 30 GHz. Gap waveguide components can be used for packaging microstrip and coplanar waveguide (CPW) circuits [7] or to replace some standard RF components, like waveguides, filters [8]-[10], couplers [11], feeding network for slot antennas [12]-[15], etc. In comparison with classical waveguides, gap waveguides do not have a problem with leakage of the energy through the joints between multiple plates. In fact, the gap waveguide components are manufactured in two pieces that do not need to be in contact in the final structure (gap waveguide can be even manufactured without side walls), which is a real advantage for high frequency technology. In addition, gap waveguides introduce low losses, smaller than microstrip and CPW transmission lines [16].

Despite the enormous potential of this technology, until now, there have not been many proposed antennas in gap waveguide technology. There have been some initial works on arrays of slot-type antennas where the slots are placed on the top metallic plate, usually as one or two-dimensional configuration. The feeding network for those antennas is mostly realized using gap waveguide technology, like ridge or groove transmission lines [12, 13, 17]. If slots are fed by separate transmission lines, the array will have high side lobes since it is difficult to ensure element distances close to 0.5λ (for example, in [12] the element distance was 0.875λ). Besides that, extensive optimization needs to be carried out in order to achieve good performance of the feeding network that is translated into a low coupling between the feeding network and the slots.

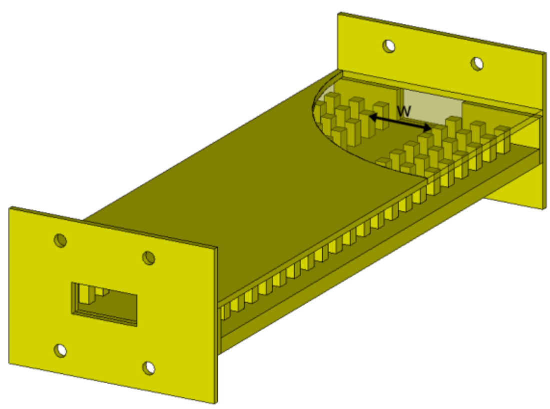
There are many possibilities for combining gap waveguide technology with other technologies, especially in the area of the antennas. An effective way was proposed in [18] for the design of a leaky wave antenna, where a low profile gap waveguide (ridge gap waveguide) was used to form a wide transmission line with uniform field distribution as a feeding network. This innovative design overcame the usual drawbacks of high frequency technology (unwanted radiation and high dielectric losses of the feeding waveguide). Although this proposed design was proven to be very efficient, it requires an independent feeding with respect to the radiating structure. Consequently, that feeding increases the total physical length of the antenna.

The purpose of this paper is to present a novel design procedure for practical realization of leaky wave antennas based on gap waveguide technology. The concept is proved through an antenna design supported with measurements. In the proposed design, the feeding structure is not physically separated from the radiating part. The feeding network is designed using groove gap waveguide technology, and it is also employed to leak the electromagnetic fields at one side of the groove. This radiation mechanism can be considered as a classical leaky wave antenna [19, 20]. Therefore, the main advantage of our proposed antenna design is its simplicity. The proposed design represents the first implementation of a leaky wave antenna fully integrated in gap waveguide technology.

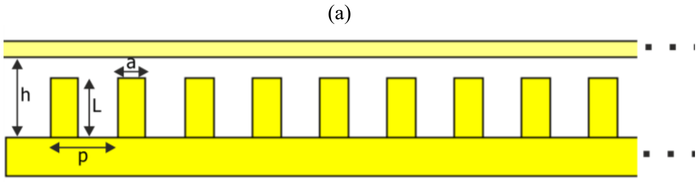
II. Gap Waveguide Design

The first step in the realization of our leaky wave antenna is the design of an appropriate transmission line based on the groove gap waveguide technology. This transmission line will be composed of a groove surrounded by three rows of pins on each side, as illustrated in Fig. 1. Three rows of pins are enough to ensure a low leakage of energy in the lateral waveguide direction. In order to design such a transmission line, the first step is to calculate the dispersion diagram of the infinite 2D periodical structure made of pins, as it is shown in Fig. 2. This is done by applying periodic boundary conditions on a single unit cell (one element of the periodic structure). The structure dimensions are selected to ensure no propagation of the electromagnetic waves (stop band) around 10 GHz: a = 3.5 mm, p = 8.5 mm and h = 10 mm. Pins with two heights are considered, L = 7.5 mm and L = 6.5 mm. It can be seen that the height of the pins strongly influences the lower cut-off frequency of the stop band, 8.02 GHz and 9.13 GHz, respectively. However the higher cut-off frequency remains constant at 13.7 GHz in both cases. All the calculations were made using *CST Microwave Studio* [21].

The next step in the design process is to further characterize the groove gap waveguide propagation characteristics. Three widths of the groove waveguide were considered, 22 mm, 20.4 mm and 18.8 mm. They are slightly smaller than the width of the standard WR90 rectangular waveguide, which ensures a smooth transition from the standard feeding waveguide. The distribution of the E-field magnitude inside the transmission line at 9.5 GHz is presented in Fig. 3. As seen, after three rows of pins, the field strength is almost negligible. The obtained attenuation is around 50 dB for higher pins (L = 7.5 mm), i.e. for smaller distance between the pins and the upper plate. For the shorter pins (L = 6.5 mm) the obtained attenuation after three rows is around 30 dB.



(a)



(b)

Fig. 1. Sketch of the groove gap-waveguide: (a) Perspective view of a groove gap waveguide which is connected to a rectangular waveguide WR90; (b) Side view.

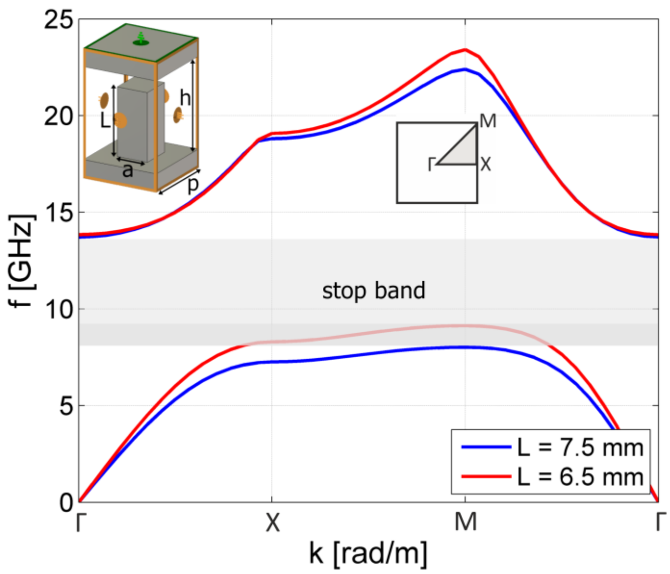


Fig. 2. Dispersion diagram of a periodic pin (unit cell); dimensions: a = 3.5 mm, p = 8.5 mm, h = 10 mm. Labels X, M and Γ define the irreducible Brillouin zone of the two-dimensional periodic pin structure [22].

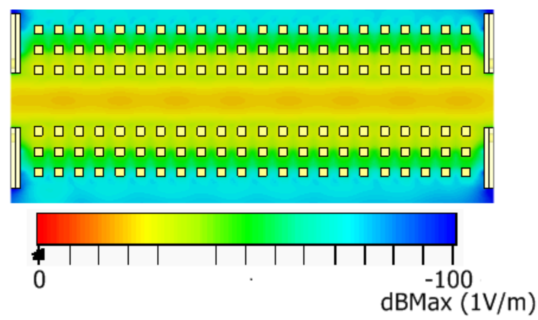


Fig. 3. Electric field distribution at 9.5GHz for the groove gap waveguide (top view, the cutting plane is located at h/2). The height of pins is L = 7.5 mm.

III. Leaky Wave Antenna Design

In order to leak enough electromagnetic energy along the waveguide, two rows of the pins were removed from one of the lateral sides of the groove waveguide. Therefore, one of the sides remains with three rows of pins of height 7.5 mm, while only one row remains in the opposite side, as it is shown in Fig. 4. Additionally, in order to enhance the leakage of the electromagnetic energy, the height of the pins is reduced to 6.5 mm at the one-row side. As demonstrated in the Section II, a decrease of the height of the pins produces a higher radiation due to the proximity of the first mode of propagation (the lowest (TM) propagation mode in the lateral gap waveguide). This TM mode can even propagate at the lowest frequencies of operation of the leaky wave antenna.

The first step in designing the leaky wave antenna is to determine the complex propagation constant $\gamma = \alpha + j\beta$ of the groove gap-waveguide (with only one row of pins at one lateral wall). The real part α describes the losses, i.e. the radiated energy and the imaginary part is the phase propagation constant and will determine the angle of the main beam. Since the phase constant is frequency dependent it provides a beam scanning capability which can be predicted as [20]:

$$\phi = sin^{-1}(\beta/k_0) \quad (1)$$

where k_0 represents the free space propagation constant. Fig. 5 shows a sketched top view of the antenna with marked propagation constants.

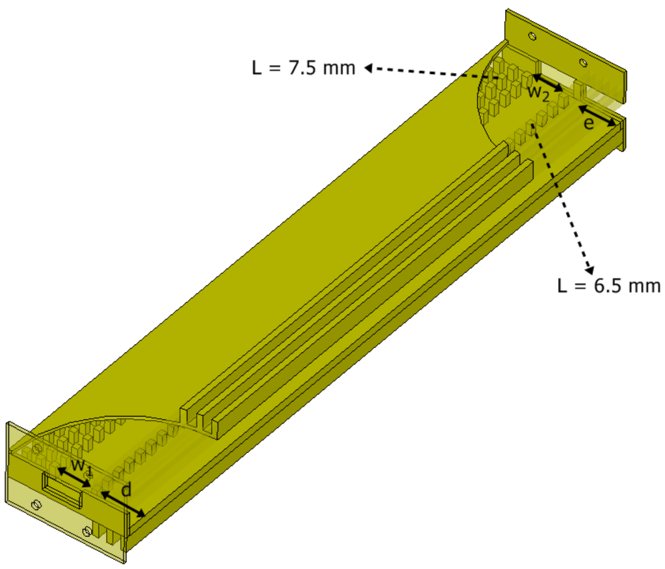


Fig. 4. Perspective view of the leaky groove waveguide antenna

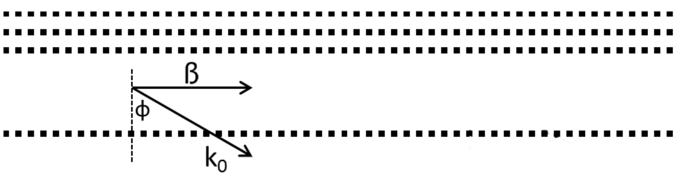


Fig. 5. Direction of the propagation constant inside and outside of the waveguide (qualitative top view).

The waveguide phase constant (β) can be extracted from the dispersion diagram shown in Fig. 6, which was calculated for a one-dimensional infinite periodic structure made of one cross-section of the considered groove waveguide (here the periodic boundary conditions are used only in longitudinal direction, while PMC boundary conditions are used at the lateral walls). It can be seen that the wave propagation along the groove (red, green and black lines) occurs in the stop band of the periodic structure containing only pins (shown in Fig. 2). The value of the propagation constant can be determined using classical formula for metallic rectangular waveguide $\beta = k_0\sqrt{1-(\lambda/2w_{eff})^2}$, where w_{eff} is the effective width of the groove gap-waveguide. To our best knowledge, there is no simple formula which can determine the effective width w_{eff}. It can be larger or smaller than the width of the groove as it has been discussed in [23]. In the considered case in Fig. 6 the effective width is 20 mm, 19.2 mm, 18 mm for the groove waveguides of width 22 mm, 20.4 mm and 18.8 mm, respectively.

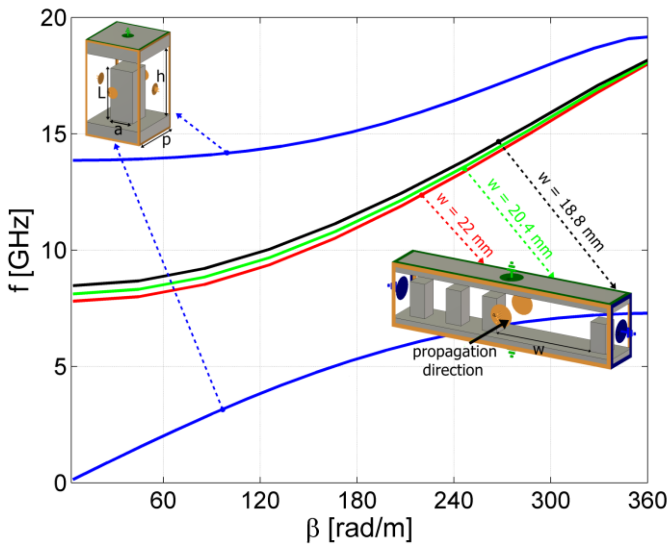


Fig. 6. Dispersion diagram of the groove gap waveguide (unit cell); versus the dispersion diagram of the pins (Γ-X of Fig. 2) for the dimensions: L = 7.5 mm, a = 3.5 mm, p = 8.5 mm, h = 10 mm, (w = 22 mm, 20.4 mm and 18.8 mm).

The selection of the value α is crucial in the designing process of the leaky wave antenna. As a first approximation the electromagnetic energy leaks through the holes between the pins (similar effect is present in SIW, surface integrated waveguides) and through the gap between the upper conductor and the pins. For SIW and for slits in metallic waveguides there are approximate formulas that estimate the radiation losses [20], [24]. In both cases the constant α depends on geometrical parameters and on the guided wavelength inside the waveguide $\lambda_g = \lambda/\sqrt{1-(\lambda/2w_{eff})^2}$. A good approximation of α is obtained with $\alpha \sim \left[\lambda/\sqrt{1-(\lambda/2w_{eff})^2}\right]^4$, which is evidenced in Fig. 7 where the attenuation constant α is presented as a function of frequency and the width of the groove gap waveguide. The coefficient α is calculated from the normalized S_{21} parameter (i.e. from $|S_{21}|^2/(1-|S_{11}|^2)$). A physical picture of this phenomenon is based on the size of the holes between pins that is seen by the electromagnetic waves (i.e. on the size of the projection of the holes to the direction of the electromagnetic wave propagation within the groove waveguide). As seen from Fig. 5 this projection decreases with increasing the propagation angle ϕ (that means with increasing the frequency).

In order to achieve good radiation characteristics, the value of α must be carefully chosen. It can be seen that for wavelengths a bit smaller than $2w_{eff}$ (i.e. for frequencies just above the cut-off frequency of the groove waveguide) large percent of the electromagnetic energy is rapidly radiated through the lateral wall. However, in order to get a high-gain antenna, we should tailor this attenuation along the waveguide to obtain approximately a 90% of the incoming power radiated. If the value of α is too big, most of the energy is radiated in the first part of the antenna and the effective aperture (and consequently the gain) is small compared to the physical size of the antenna. On the other side, if the value of α is too small, the antenna will radiate less than the desired 90% of power. According to the Fig. 7, for an antenna length of the 39 cm (our antenna model) the ideal attenuation constant α is around 26 dB/m.

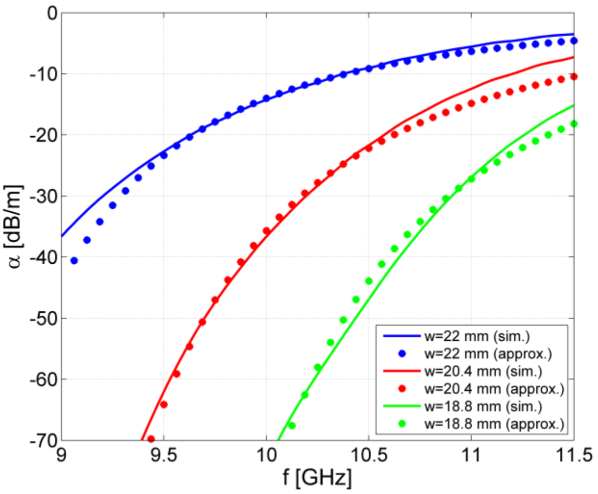


Fig. 7. Attenuation constant α as a function of frequency for three different waveguide widths: w = 22 mm, w = 20.4 mm, w = 18.8 mm.

Having in mind the frequency behavior of the attenuation constant α, we have decided to gradually (linearly) change the width of the groove waveguide, see Fig. 4. The starting and ending widths of the groove waveguide are w_1 = 22 mm and w_2 = 18.8 mm, respectively. The antenna was designed to operate between 9 GHz and 11.5 GHz; and the dimensions employed in Section II are here maintained. The width of the radiating parallel-plate waveguide is set to d = 24 mm. One should note that one of the flanges (the one at the end of the waveguide) was cut in order to fit to the dimensions of the side antenna wall. The size of this cut has a length e = 22.63 mm and it was used to reduce the reflections of the leaky waves at the end of the flange. The total length of the antenna is 39 cm. The antenna is excited by the WR90 rectangular waveguide at the wider groove side, and the second port is terminated using the WR90 waveguide with a matched load.

Illustration of the electromagnetic energy leakage at the radiating antenna side is shown in Fig. 8 where the E-field distribution is presented. The phase distribution shows that the electromagnetic field is leaking out of the structure with a certain angle and forming the main beam of the radiation pattern at that direction.

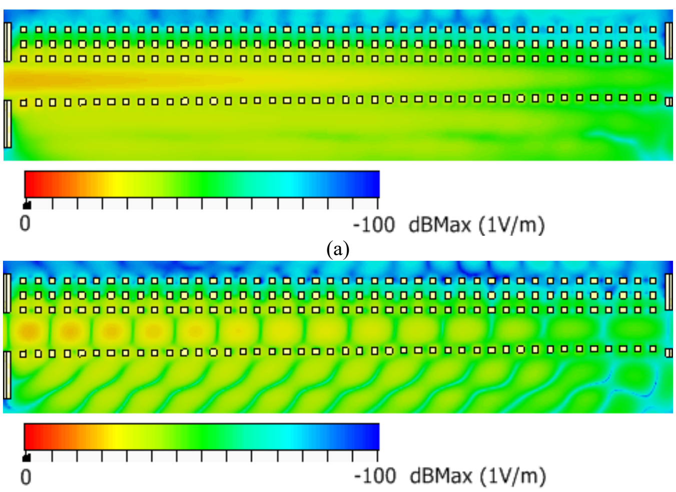


Fig. 8. E-field distribution of the leaky antenna at 9.5 GHz (top view without flanges, cutting plane at $h/2$): (a) magnitude of the field distribution (b) snapshot of the field distribution.

We have added several corrugations on the top and bottom plate of the antenna. Their purpose is to prevent the diffraction of the field over the edges of the plates and to stop the radiation of the antenna on the back side (i.e. on the non-radiating side) within the operating frequency bandwidth. Dimensions of the corrugations are chosen to ensure a stop band between 9.5 GHz and 11.5 GHz; the depth of the corrugations is equal to 9.0 mm, thickness is 3.5 mm and finally the period is 8.5 mm (same as for the metallic pins inside the antenna).

IV. Antenna Prototype

The antenna prototype was built following the dimensions given in the previous section. The picture of the antenna prototype is given in Fig. 9.

Fig. 9. Gap waveguide leaky wave antenna prototype.

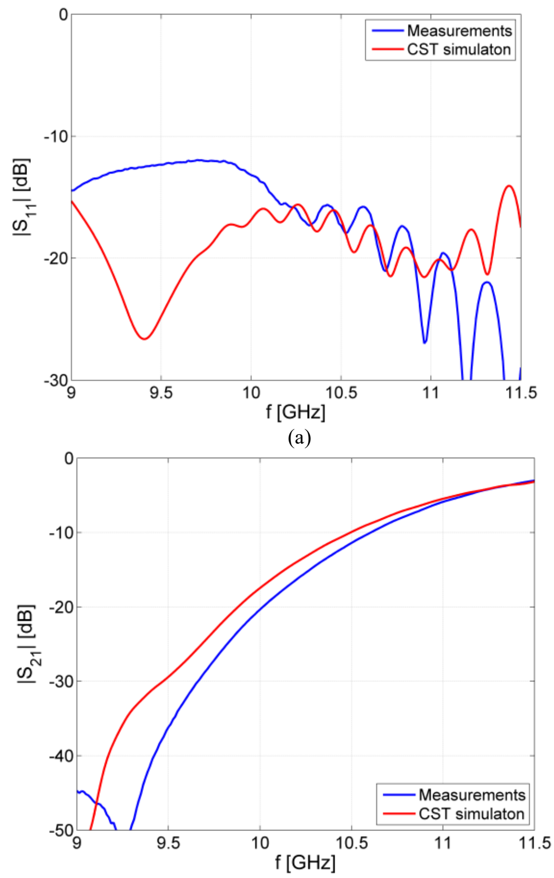


Fig. 10. Simulated and measured S-parameters (a) $|S_{11}|$ parameter, (b) $|S_{21}|$

parameter.

The comparison of simulated and measured S-parameters of the realized antenna is given in Fig. 10. There is a good agreement between them, in particular between the S_{21} parameters, while S_{11} parameter shows that the antenna is well matched at the frequency band of interest, although there are some discrepancies between the results in particular at the beginning of the working frequency band. The value of the S_{21} parameter indicates that more than 90% of energy is radiated around the central frequency.

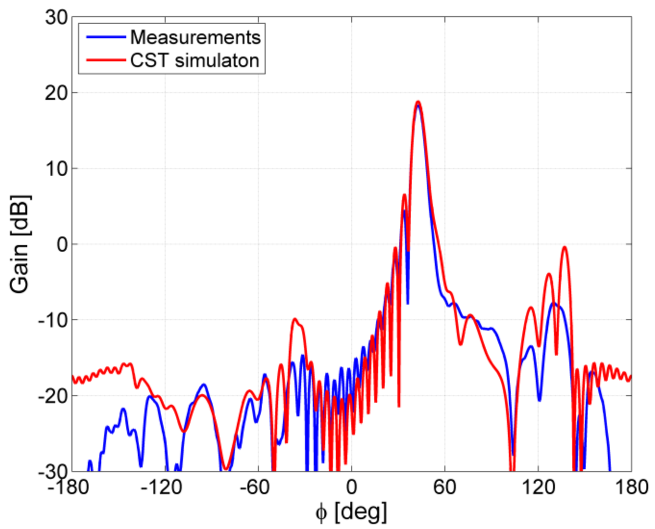


Fig. 11. Comparison between measured and simulated radiation patterns at 10.5 GHz.

The radiation pattern at 10.5 GHz is presented in Fig. 11. There is a very good agreement between calculated and measured radiation patterns. The direction of the main beam is 45 deg. from the broadside direction, and the obtained gain is approximately 19 dB for both simulation and measurement. The frequency dependence of the main beam direction is presented in Fig. 12, where the simulated results are compared with the measurements. There is a difference up to 5º between the measurements and the value obtained from Eq. (1) when applied to the calculated β calculated by the dispersion diagram (Fig. 6, w=20.4 mm). Therefore, the basic properties of the proposed leaky wave antenna can be predicted with characterizing the groove waveguide [25]. Fig. 12 also illustrates that the scanning range of the antenna is around 19 deg. in the frequency band of interest.

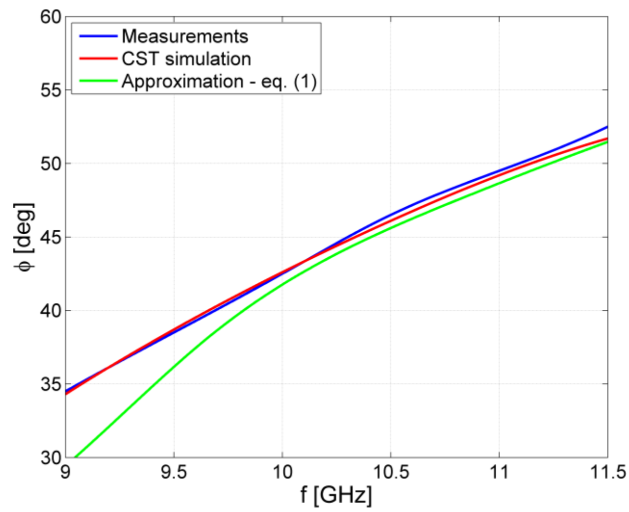


Fig. 12. Direction of the main beam as a function of frequency.

Measured radiation patterns at all frequencies of interest are presented in Fig. 13. Because of the gradual change of the width of the groove waveguide (from w_1 to w_2 as shown in Fig. 4), the antenna gain is stable when enlarging the frequency (i.e. the gain is not decreasing with frequency as in the case of leaky wave antenna with groove waveguide of constant width).

The side lobe level slightly changes with frequency and is lower than -10 dB in the whole frequency band (see Fig. 14). The highest side lobe is located next to the main while the next side lobe is smaller than -20 dB. The level of the cross polarization is lower than -30 dB.

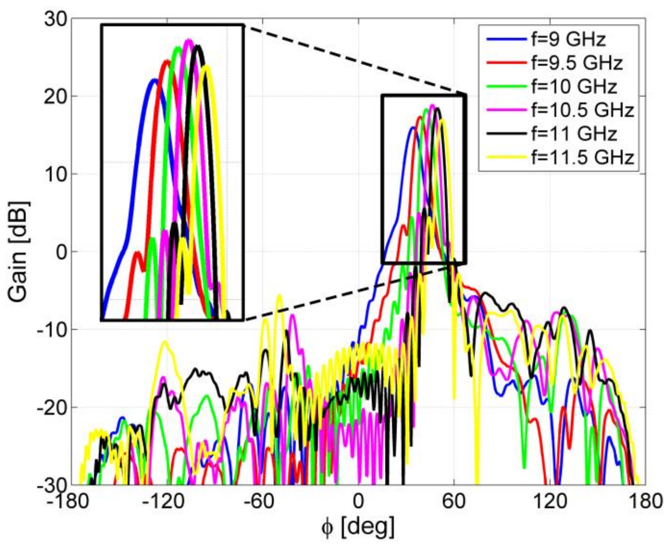


Fig. 13. Measured radiation patterns in frequency range of interest (9 GHz-11.5 GHz).

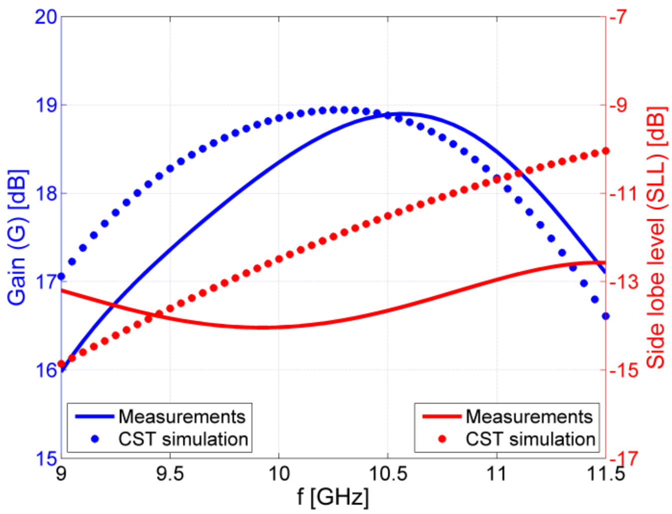


Fig. 14. Variation of the antenna gain and side lobe level as a function of the operational frequency.

V. Conclusion

A novel leaky wave antenna based on the gap waveguide technology was proposed and manufactured. The main advantage of the developed antenna is its simplicity and easiness of integration with both the new gap waveguide and the traditional waveguide technology, while high gain and low side lobe level are retained. The results have been validated with the manufacturing and measuring of a prototype operating in the X-band.

References

[1] P. S. Kildal, "Definition of artificially soft and hard surfaces forb electromagnetic waves," *Electronics Letters*, vol. 24, pp. 168-70, 1988.

[2] D. Sievenpiper, Z. Lijun, R. F. J. Broas, N. G. Alexopolous, and E. Yablonovitch, "High-impedance electromagnetic surfaces with a forbidden frequency band," *IEEE Transactions on Microwave Theory and Techniques*, vol. 47, pp. 2059-2074, 1999.

[3] P.-S. Kildal, "Three metamaterial-based gap waveguides between parallel metal plates for mm/submm waves," Proceedings of 3rd European Conference on Antennas and Propagation (EuCAP), 2009, pp.28-32.

[4] P. S. Kildal, A. U. Zaman, E. Rajo-Iglesias, E. Alfonso, and A. Valero-Nogueira, "Design and experimental verification of ridge gap waveguide in bed of nails for parallel-plate mode suppression," *IET Microwaves, Antennas & Propagation*, vol. 5, pp. 262-270, 2011.

[5] A. Valero-Nogueira, M. Baquero, J. I. Herranz, J. Domenech, E. Alfonso, and A. Vila, "Gap Waveguides Using a Suspended Strip on a Bed of Nails," *IEEE Antennas and Wireless Propagation Letters*, vol. 10, pp. 1006-1009, 2011.

[6] E. Rajo-Iglesias and P. S. Kildal, "Groove gap waveguide: A rectangular waveguide between contactless metal plates enabled by parallel-plate cut-off," Proceedings of 4th European Conference on in Antennas and Propagation (EuCAP), 2010, pp. 1-4.

[7] E. Rajo-Iglesias, A. U. Zaman, and P. S. Kildal, "Parallel plate cavity mode suppression in microstrip circuit packages using a lid of nails," *IEEE Microwave and Wireless Components Letters*, vol. 20, pp. 31-3, 2010.

[8] E. Pucci, A. U. Zaman, E. Rajo-Iglesias, P. S. Kildal, and A. Kishk, "Study of Q-factors of ridge and groove gap waveguide resonators," *IET Microwaves, Antennas & Propagation*, vol. 7, pp. 900-908, 2013.

[9] A. U. Zaman, P. S. Kildal, and A. A. Kishk, "Narrow-Band Microwave Filter Using High-Q Groove Gap Waveguide Resonators With Manufacturing Flexibility and No Sidewalls," *IEEE Transactions on Components, Packaging and Manufacturing Technology*, vol. 2, pp. 1882-1889, 2012.

[10] A. Berenguer, M. Baquero-Escudero, D. Sanchez-Escuderos, B. Bernardo-Clemente, and V. E. Boria-Esbert, "Low insertion loss 61 GHz narrow-band filter implemented with Groove Gap Waveguides," Proceedings of International Microwave Symposium, IEEE-MTT 2014.

[11] E. Alfonso, A. U. Zuman, E. Pucci, P. S. Kildal, "Gap Waveguide Components for Millimetre-Wave Systems: Couplers, Filters, Antennas, MMIC Packaging," Prooceedings of ISAP2012, Nayoga, Japan.

[12] A. U. Zaman and P. S. Kildal, "Wide-Band Slot Antenna Arrays With Single-Layer Corporate-Feed Network in Ridge Gap Waveguide Technology," *IEEE Transactions on Antennas and Propagation*, vol. 62, pp. 2992-3001, 2014.

[13] A. Valero-Nogueira, J. I. Herranz-Herruzo, M. Baquero, R. Hernandez-Murcia, and V. Rodrigo, "Practical Derivation of Slot Equivalent Admittance in Periodic Waveguides," *IEEE Transactions on Antennas and Propagation*, vol. 61, pp. 2321-2324, 2013.

[14] S. Martinez Giner, A. Valero-Nogueira, J. I. Herranz Herruzo, and M. Baquero Escudero, "Excitation of untilted narrow-wall slot in groove gap waveguide by using a parasitic dipole," Proceedings of 7th European Conference on Antennas and Propagation (EuCAP), 2013, pp. 3082-3085.

[15] E. Pucci, E. Rajo-Iglesias, J.-L Vazquez-Roy, P.-S. Kildal, "Planar Dual-Mode Horn Array With Corporate-Feed Network in Inverted Microstrip Gap Waveguide," *IEEE Transactions on Antennas and Propagation*, vol.62, no.7, pp.3534-3542, July 2014.

[16] E. Pucci, A. U. Zaman, E- Rajo-Iglesias, P. S. Kildal, "Losses in Ridge Gap Waveguide Compared with Rectangular Waveguides and Microstrip Transmition Lines", Proceedings of 4th European Conference on Antennas and Propagation (EuCAP), 2010, 12-16.

[17] A. U. Zaman and P. S. Kildal, "Slot antenna in ridge gap waveguide technology," Proceedings of 6th European Conference on Antennas and Propagation (EUCAP), 2012, pp. 3243-3244.

[18] M. A. Sharkawy, A. Foroozesh, A. A. Kishk, "A Robust Horn Ridge Gap Waveguide Launcher for Metal Strip Grating Leaky Wave Antenna", *IEEE Transaction on Antennas and Propagation*, vol. 62, pp. 6019-6026, 2014.

[19] Hines, J. N., V. H. Rumsey, and C. H. Walter. "Traveling-wave slot antennas," *Proceedings of the IRE,* vol. 41, no. 11 (1953): 1624-1631.

[20] L. O. Goldstone, A. A. Oliner, "Leaky Wave Antennas I: Rectangular Waveguides," *IRE Transaction on Antennas and Propagation*, vol. 7, pp. 307 – 319, 1959.

[21] CST Microwave Studio™ 2014*, Computer Simulation Technology AG*, www.cst.com, Darmstadt, Germany.

[22] J.D. Joannopoulos, S.G. Johnson, J.N. Winn, R. D. Meade, *Photonic Crystals: Molding the Flow of Light,* Princeton University Press, 2008, Appendix B.

[23] A. Berenguer, V. Fusco, D.E. Zelenchuk, D. Sanchez-Escuderos, M. Baquero-Escudero, V.E. Boria-Esbert, "Propagation Characteristics of Groove Gap Waveguide Below and Above Cutoff", *IEEE Transactions on Microwave Theory and Techniques*, Early Access, DOI: 10.1109/TMTT.2015.2504501.

[24] M. Bozzi, M. Pasian, L. Perregrini, "Modeling of Losses in Substrate Integrate Waveguide Components", 2014 International Conference on Numerical Electromagnetic Modeling and Optimization for RF Microwave and Terahertz Applications (NEMO), 2014, pp. 1-4.

[25] O. Quevedo-Teruel, "Controlled radiation from dielectric slabs over spoof surface plasmon waveguides", *Progress in Electromagnetics Research*, vol. 140, pp: 169-179, 2013.