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Low-dispersive Leaky-wave Antenna Integrated in Groove Gap Waveguide Technology

Lei Wang, *Member, IEEE*, José Luis Gómez-Tornero, *Senior Member, IEEE*, Eva Rajo-Iglesias, *Senior Member, IEEE*, Oscar Quevedo-Teruel, *Senior Member, IEEE*

Abstract—**In this paper, the use of a dispersive prism with a triangular shape is proposed to reduce the dispersive radiation nature of a leaky-wave antenna in groove gap waveguide technology. The operation of gap waveguide technology is based on the use of metallic pins that act as an artificial magnetic conductor, so the electromagnetic fields are confined and guided in the desired directions. To control a leaky-wave radiation of these confined fields is possible by tailoring the height of the pins, its periodicity and the waveguide width. This radiation, as in any conventional leaky-wave antenna, is dispersive, leading to beam squint as frequency is varied. Here, we mitigate this beam squint by using a prism made of dispersive pins and choosing appropriately their periodicity and height. With this prism, the leaky-wave radiation is focused into one single direction in a wide frequency-band.This concept is demonstrated with a prototype designed to radiate at φ=41° with a central frequency of 12 GHz and high-gain of 16.5 dBi. A 22% frequency bandwidth for the 3-dB realized gain at φ=41° is achieved, and the main radiating direction, with half-power beamwidth of 5°, steers only ±0.5° from 11.4 to 13.4 GHz.**

Index Terms—**Dispersive prism, gap waveguide, leaky-wave antenna.**

I. INTRODUCTION

GAP waveguide is a recent and promising technology for high frequency devices [1]–[3]. Among the advantages of this technology we can point out three. On one hand, the manufacturing is made in two pieces (top and bottom), which simplifies the construction of large and complex devices. Additionally, its losses are low since the propagation is mainly in air, which is only surrounded by a fully-metallic structure in the groove and ridge versions. Finally, no physical contact is needed between the two layers when assembling together, since the electromagnetic band gap (EBG) required in any gap waveguide, inhibits any leakage out of the structure.

Typically, the EBG is constructed with pin-type structures, although other alternatives were proposed in the literatures to reduce their size or cost [4]–[6]. In this paper, we will focus our attention in the classical pin-type configuration. One of the recent challenges in this gap waveguide is to realize efficient and directive antennas [7], [7]–[9], [9]–[21]. In [7], [7]–[9], [9]–[21], leaky-wave antennas (LWAs) were proposed as an interesting solution due to its structural simplicity and single feeding mechanism. Unfortunately, their principal drawback is that the radiation pattern is dispersive, i.e., the main beam is frequency-scanned [22], thus creating unwanted beam squint which reduces the practical bandwidth with high gain at the desired scanning direction.

The squint effect of leaky-wave antennas is well-known [23]- [28], and many authors have tried to overcome this limitation to keep high gain at the desired scanning direction over a wide band. For example, in [29]- [33], a width-tapering technology is used to improve this characteristic. However, the side effect is a decrease in the directivity or a broaden beam, as discussed in [34]- [36]. Other solutions include the use of coupled-cavity antennas [37], [38], metamaterials [39], metasurfaces [40], anisotropic materials [41], non-reciprocal materials [42], or active non-Foster circuits [43], [44]. All these implementations require of complex structures, multi-layer configurations, expensive materials, or DC biasing that decrease the total efficiency of the system. Also, in [45] a non-dispersive leaky-lens was proposed by immersing a leaky slot line inside a dense dielectric substrate. It is important to note that most of the previous solutions for LWA with reduced beam squint are limited to specific technologies, and they do not present any common solution to reduce the beam squint in general LWAs. For instance, [29], [30], are limited to tapered microstrip LWAs, [31]–[33] can only be implemented in half-width substrate integrated waveguide (SIW) technology, and coupled-SIW technology is required to implement [37], [38]. Similarly [39] is based on metamaterial-based LWAs, the techniques proposed in [41], [42] can only be applied in LWAs with anisotropic or nonreciprocal materials, [43], [44] require active LWAs, and [45] is limited to slot lines leaking power inside a 3D dielectric lens.

In this sense, a novel general technique to reduce the beam squint in any type of LWA was recently proposed in [46]. It is based on the use of a lens which is coupled to the LWA radiation aperture, so that the complementary dispersion of the lens can correct the frequency beam-squint of any dispersive LWA. This technique was demonstrated for the first time in [46] for a LWA in SIW technology, increasing the squint-free bandwidth from 11% to 20%. However, the low-dispersive SIW LWA with a prism proposed in [46] shows a low radiation efficiency of 24% due to the inherent dielectric ohmic losses, resulting in low realized gain of 8.5 dBi in the operating squint-free band.

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L. Wang is with the Institute of Electromagnetic Theory, Hamburg University of Technology, 21079 Hamburg, Germany (e-mail: wanglei@ieee.org).

J. L. Gómez-Tornero is with the Department of Communication and Information Technologies, Technical University of Cartagena, Cartagena 30202, Spain (e-mail: josel.gomez@upct.es).

E. Rajo-Iglesias is with the Department of Communications and Signal Theory, Carlos III University, 28911 Madrid, Spain (e-mail: eva@tsc.uc3m.es).

O. Quevedo-Teruel is with Electromagnetic Engineering Lab of School of Electrical Engineering and Computer Science, KTH Royal Institute of Technology, SE-100 44 Stockholm, Sweden (e-mail: oscarqt@kth.se).

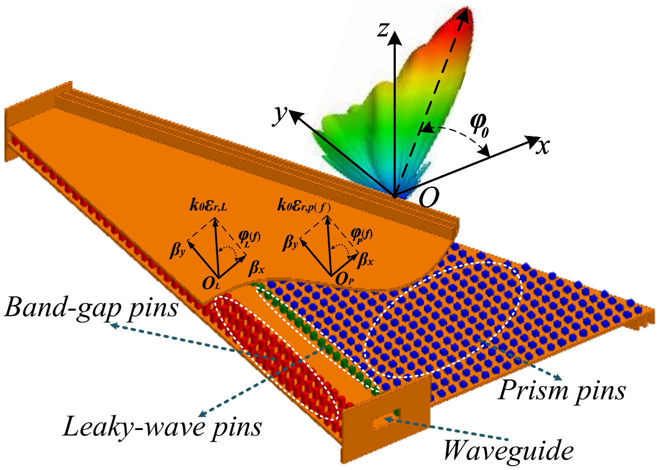


Fig. 1. Non-dispersive leaky-wave antenna in groove gap waveguide technology.

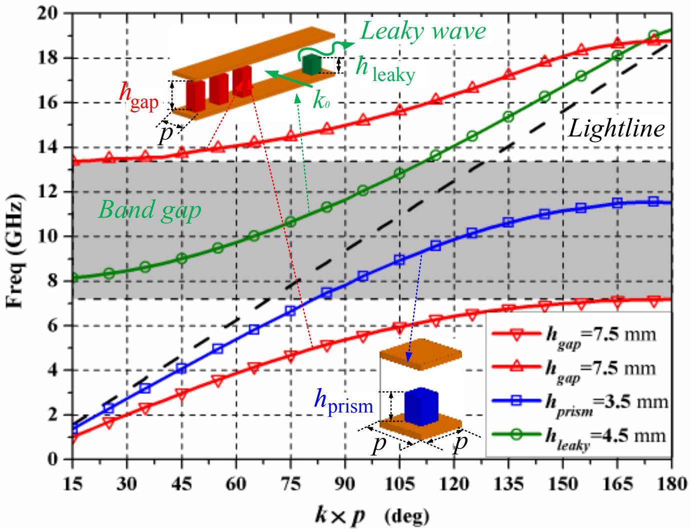


Fig. 2. Dispersion diagram of pins for groove gap waveguide with leaky-wave radiation.

In this paper, we apply this complementary-dispersion prism-coupling technique to reduce the beam squint of a LWA in low-loss groove-gap waveguide technology (GGW), initially proposed in [8]. We demonstrate that the prism-coupling technique can be applied to diverse leaky transmission-line technologies. By choosing GGW technology, lower ohmic losses and higher radiation efficiency than the SIW LWA in [46] are obtained, thus demonstrating for the first time that high-gain and beam-squint reduction are compatible. Moreover, the prism and the GGW LWA are made in the same technology using metallic pins tailored in a common integrated parallel-plate structure, reducing the complexity of the overall device if compared to bulky solutions as the 3D leaky lens in [45]. Our design has a gain of 16.5 dBi with 22% squint-free bandwidth, which is the best performance in terms of gain and squint-free bandwidth for a planar LWA reported so far.

The contents of the paper are as following. Section II presents the dispersion diagram analysis both of the GGW LWA and the dispersive prism, and the design of a proposed antenna is presented in details. Full-wave simulations of the designed antenna are included in Section III whilst the experimental verification constitutes Section IV. A discussion of the designed LWA and a comparative analysis with other reduced-squint LWAs is performed in Section V. Finally the main conclusions of the work are discussed in Section VI.

II. ANTENNA ANALYSIS AND DESIGN

The configuration of our proposed low-dispersive leaky-wave gap-waveguide antenna is shown in Fig. 1. It consists of two parts, a LWA in GGW technology (created by the red and green pins) and a dispersive metasurface prism (blue pins). The three rows of red pins act as an EBG at the operation frequency, whereas the green row, with pins that are shorter than the red ones, controls the leaky-wave radiation as presented in [8]. Finally, the blue pins, which are the shortest in the structure are aimed to design a dispersive prism which compensates for the dispersion of the leaky wave radiated by the LWA. The general equations which describe the conditions for dispersion compensation via prism-coupling can be found in [46], and they are not repeated here for the sake of brevity. In the following subsections, this technique is applied for the case of a LWA and a prism integrated in GGW technology as shown in Fig. 1.

A. Operational Frequency and Dispersion Properties

The first step is to design a groove gap waveguide in X-band by designing the EBG pins (red in Fig. 1). The dispersion characteristic of the metallic pins with a stopband in the X-band is represented in Fig. 2 in red. The red curves show that the red square pins, with a width of 3.5 mm, a height h_{gap} of 7.5 mm and a periodicity p of 8.5 mm, have a stopband from 7.2 GHz to 13.4 GHz (grey region). This will be the bandwidth of operation of the groove gap waveguide. In all cases discussed in this paper, the height of the parallel plate structure is considered the height of 10 mm.

As previously demonstrated in [8], a gap waveguide leaky-wave antenna can be designed if one lateral side of a groove structure is replaced by one row made of shorter pins (i.e., h_{leaky}=4.5 mm) which enables the radiation, as shown in Fig. 2 in green. Its dispersion characteristics are the ones of a conventional TE_{10}-mode in rectangular waveguides, i.e. a fast wave.

Finally, in the same figure, we represent in blue the dispersion characteristics of periodic metallic pins with a shorter height, (h_{prism}=3.5 mm, blue curve) which is under the light line. This mode has the conventional response of a dispersive dense material, i.e. a slow wave.

It is found that the curve trend of the dispersive prism (blue) is opposite to the one of the leaky-wave gap waveguide (green). Although one is convex and the other is concave, since both have the same trend, it is possible to combine both structures to compensate the overall dispersive behaviour.

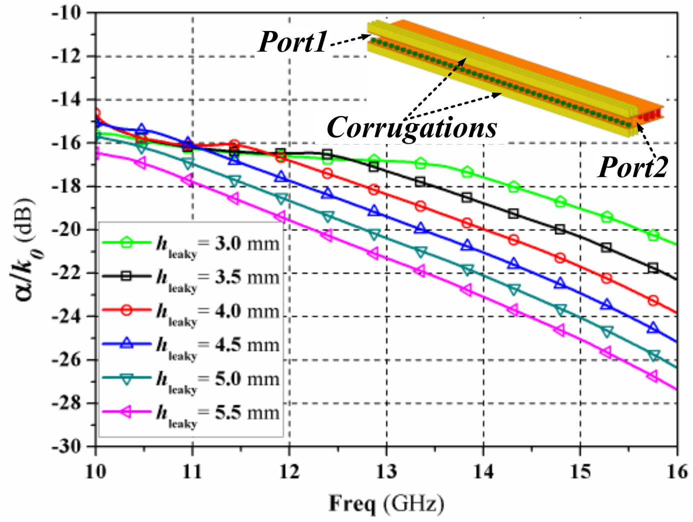


Fig. 3. Amount of radiation of the leaky-wave gap waveguide.

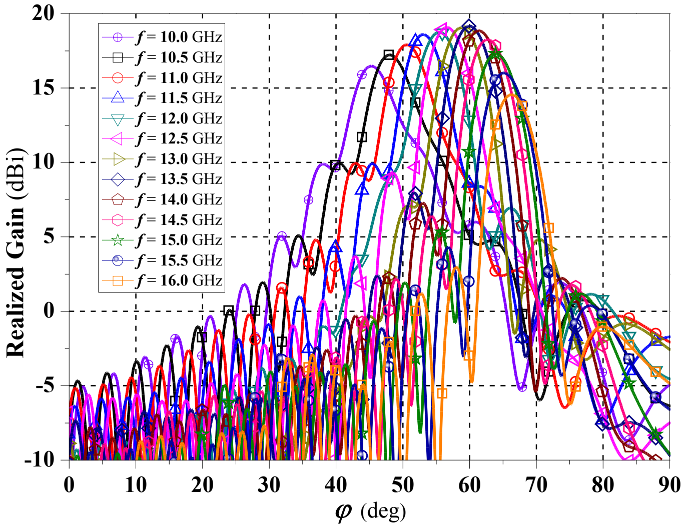


Fig. 4. Beam-steering characteristic of the leaky-wave gap waveguide.

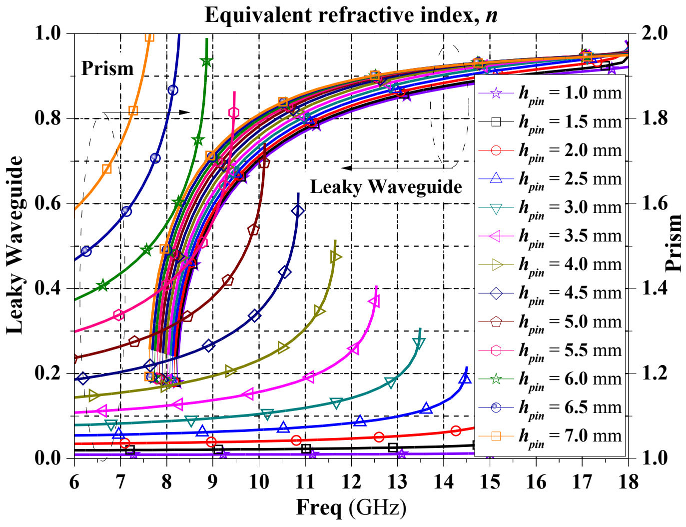


Fig. 5. Equivalent refractive index of periodic pins and the leaky waveguide.

B. Design of the Leaky-wave Gap Waveguide

After the previous analysis, the design of an antenna with center-frequency at 12 GHz is proposed using the developed methodology in [8]. The designed groove gap-waveguide has a height of 10 mm, a waveguide width of 22 mm and a total length of L=374 mm ($15\lambda_0$).

The selection of the leaky-pin height cannot only be based on the radiation direction (depending on β_y, shown in Fig. 1) of the leaky-wave gap-waveguide, but also a proper leakage constant (α) needs to be defined in order to provide optimal radiation and aperture efficiency [22]. The amount of leakage for a number of heights of the pins is represented in Fig. 3 for an aperture length of L_R=$L\cos(41°)$=282.3 mm. In this study, three corrugated grooves are also added at the aperture of the leaky-wave waveguide as shown in the inset of Fig. 3. These corrugations are employed to reduce the back radiation and hence to increase the gain. This technique was already introduced in [8]. The leakage is calculated as:

$$1 \quad |S_{11}|^2 \quad |S_{21}|^2 = 1 \quad e^{\;4\pi\frac{\alpha}{k_0}\frac{L_A}{\lambda_0}} \tag{1}$$

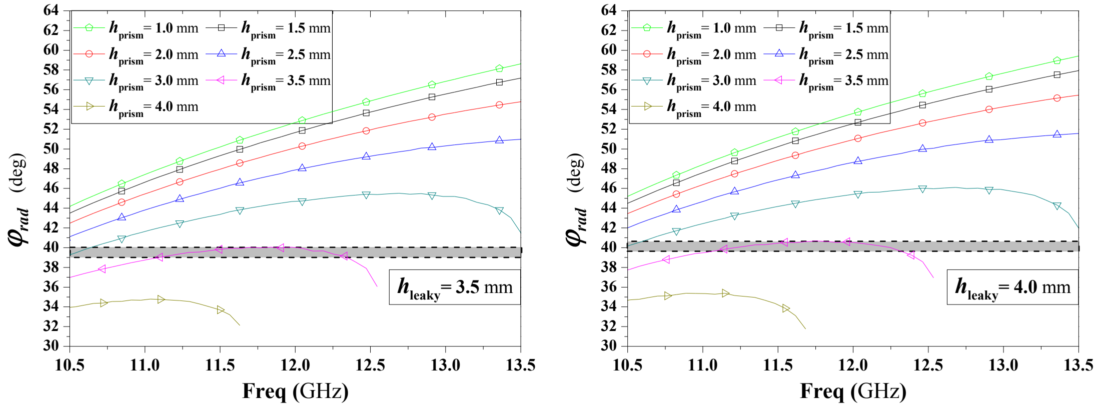
Fig. 3 shows that the leakage with a pin's height of h_{leaky}=5.5 mm is insufficient and this will create low radiation efficiency and therefore poor associated gain. On the other hand, leaky pins with a h_{leaky}=3.0 mm will leak the electromagnetic energy extremely fast, reducing in this case the effective aperture efficiency and leading to poor directivity and gain. Heights of 3.5, 4.0, 4.5 and 5.0 mm are a good compromise for this example.

However, although their α is appropriate, the radiation direction of this common gap-waveguide leaky-wave antenna presented in [8] will strongly change with the frequency. For example, for h_{leaky}=4.5 mm, the radiation patterns are shown in Fig. 4 from 10.0 to 16.0 GHz. The main-beam angle steers from φ=45° to φ=65°, and the realized peak gain varies from 14 to 19 dBi. As mentioned, this frequency-beam steering strongly reduces the gain bandwidth for a fixed angular direction. This effect is more evident for narrow-beam antennas as the ones needed for high-gain point-to-point wireless links. In our case, the half-power beamwidth is 6° as it corresponds to an aperture length of L_R=282.3 mm at 12 GHz.

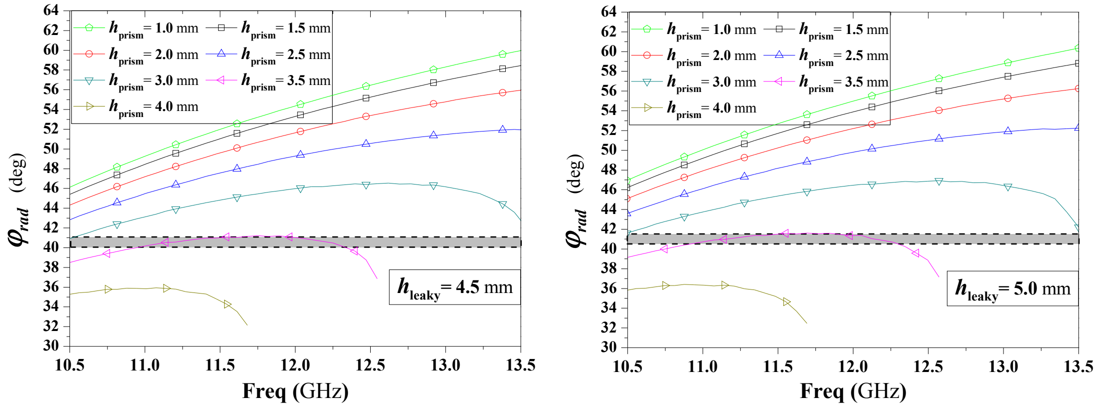
C. Design of Metasurface Prism

Fig. 2 shows two opposite dispersive performance of the GGW LWA and lower-height blue pins, which can be now used to mitigate the squint effect of the designed GGW LWA with the use of a metasurface prism [46]. If we assume that leaky-wave gap waveguide must be designed with h_{leaky} from 3.5 to 5.0 mm, we must find the appropriate height of the pins of the prism h_{prism}, to compensate their dispersion.

1) Equivalent Refractive Index: From the dispersion diagram in Fig. 2, the equivalent refractive index $n_P(f)$ of the



(a) Height of leaky pin h_{leaky} = 3.5 mm (b) Height of leaky pin h_{leaky} = 4.0 mm



(c) Height of leaky pin h_{leaky} = 4.5 mm (d) Height of leaky pin h_{leaky} = 5.0 mm

Fig. 6. Calculated radiation direction in the dispersive prism excited with a leaky-wave gap waveguide.

dispersive prism and $n_L(f)$ of the leaky-wave gap-waveguide can be calculated [46], [47]. Fig. 5 shows both the equivalent refractive indexes of the dispersive prism and the leaky-wave gap-waveguide, for different pin heights, h_{pin}, varying from 1.0 mm to 7.0 mm. It can be found that the equivalent refractive index of the prism $n_P(f)$ is concave with frequencies, whereas that of the leaky-wave gap-waveguide $n_L(f)$ is convex.

2) *Radiation Direction:* Fig. 6 shows the calculated radiation directions (φ_{rad}) when the height h_{prism} varies from 1.0 to 4.0 mm for h_{leaky} varying from 3.5 to 5.0 mm. It can be concluded that with a proper prism design, it is possible to obtain wideband radiation directions. The grey regions in the different figures of Fig. 6 highlight the region where the radiation direction varies only ±0.5° around the center frequency of 12.0 GHz.

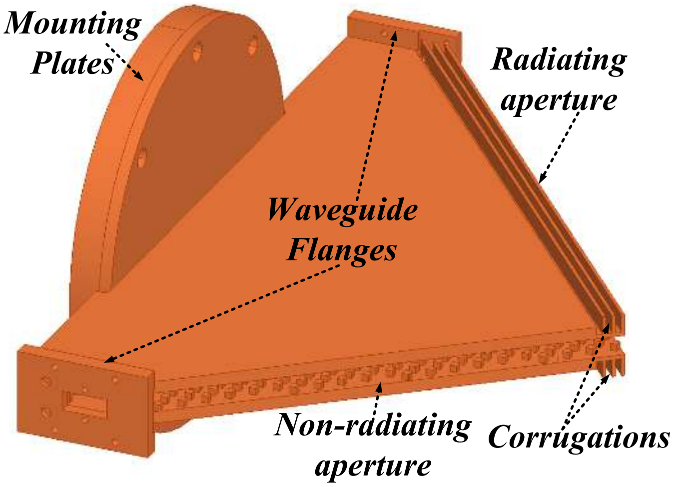
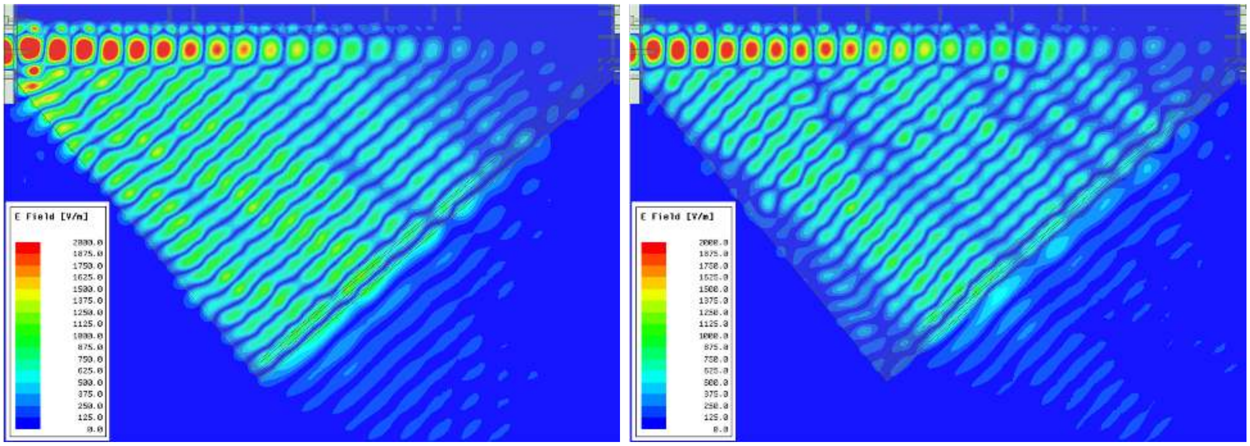


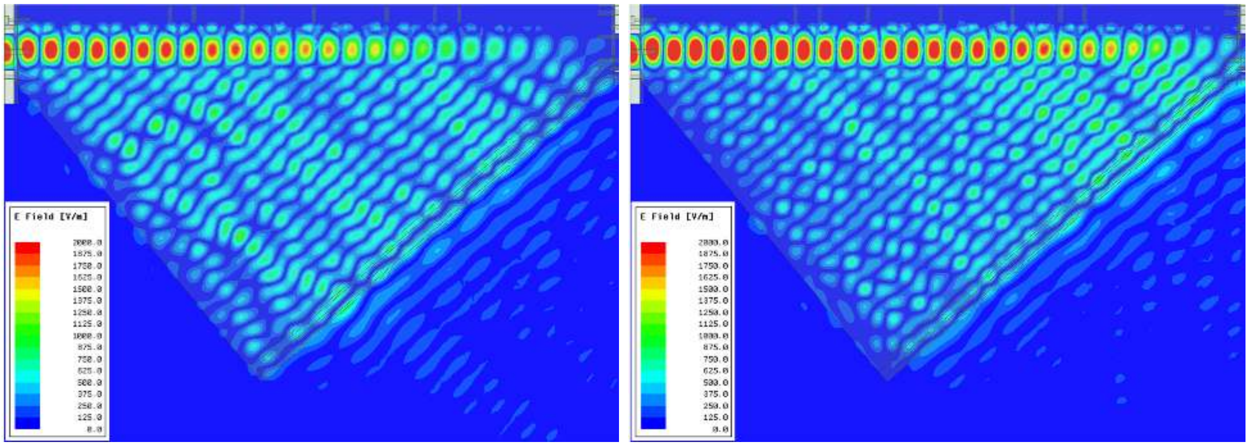
Fig. 7. Complete antenna structure, including flanges, corrugations, and circular plate for the mounting into the anechoic chamber for testing.

D. Design of the Complete Antenna

Based on the previous leaky-wave gap waveguide and prism study, a pair of h_{leaky}=4.5 mm and h_{prism}=3.5 mm has been selected for the proposed antenna design. The leaky gap-waveguide aperture lengths is L=374 mm. According to Fig. 6(c), the radiation will be directed at φ=41°. Therefore, the metasurface prism must be cut into a triangle shape with 41° angle and projected length L_R, to make sure the electromagnetic waves arrive perpendicularly to the radiating aperture. Fig. 7 shows the complete antenna structure, including the two waveguide flanges and three corrugated grooves to improve the radiation efficiency and to reduce the edge diffraction. Moreover, a circular plate is designed to mount the proposed antenna into the rotating platform at the KTH



(a) 11.5 GHz (b) 12.0 GHz



(c) 12.5 GHz (d) 13.0 GHz

Fig. 8. Amplitude distribution of the electric-field of the proposed antenna.

anechoic chamber. This circular plate has no significant effect in the radiation of the antenna, it is only used for measurement purposes. Finally, in order to reduce the size and weight of the antenna, a cut on the non-radiating side of the prism was made, which is also an improvement from the previous prism in [46].

III. Full-wave Simulation

A. Electric-field Distribution

The completed antenna has been modeled and simulated in Ansys HFSS software for validation. The amplitude of the electric-field at four frequencies (11.5, 12, 12.5 and 13 GHz) is represented in Fig. 8. At the four frequencies the electromagnetic waves travel perpendicularly to the radiating aperture. We can also conclude that the leakage α at low frequencies is stronger than at high frequencies, as is common in leaky-wave antennas [8]. As a result, the aperture efficiency is higher at higher frequencies. On the other hand, at higher frequencies, the amount of radiated fields is lower, so more energy is absorbed by the second port, and the antenna efficiency is decreased. These effects were taken into account and in our design, the total antenna efficiency is higher than 98% from 11.5 to 13.0 GHz.

TABLE I
Radiation direction comparison

Radiation Directions φ (deg)					
Leaky-wave Antennas	11.5 GHz	12.0 GHz	12.5 GHz	13.0 GHz	Beam Squinting
Without Prism	53.6	55.7	57.5	59.2	5.6
With Prism	40.6	40.9	41.1	40.5	0.6

B. Radiation Patterns

Table. I summarizes the radiation directions including a comparison to the original leaky-wave gap waveguide antenna without the prism. Our proposed leaky-wave antenna has a radiation with a change of only 0.6° in the main radiation direction from 11.5 to 13.0 GHz, whereas the original one has a variation of 5.6°.

Fig. 9 shows the calculated radiation patterns at 11.5, 12.0, 12.5 and 13.0 GHz with realized gain varying from 16.3 to 16.6 dBi. The main-beam half-power width is 5 °, as it corresponds to the projected radiating aperture length of the prism (282.3 mm). The main-beam radiation direction remains almost constant at φ=41°. The 3-dB patterns are zoomed to highlight the accuracy of our predictions, as well as to emphasize the obtained 3-dB narrow beamwidth of 5°.

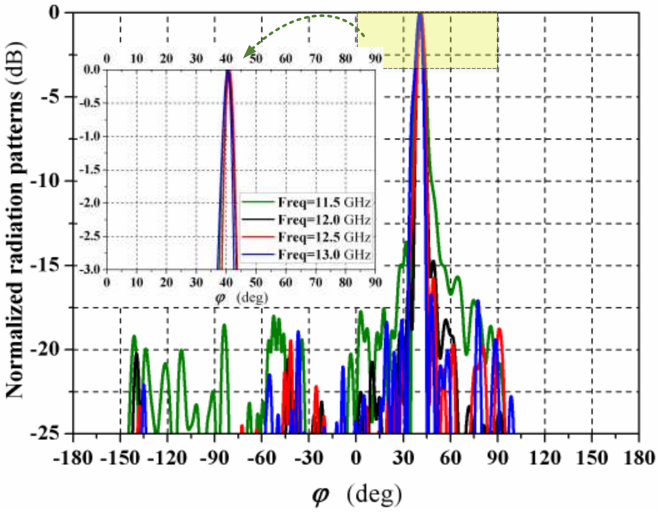


Fig. 9. Radiation patterns at different frequencies.

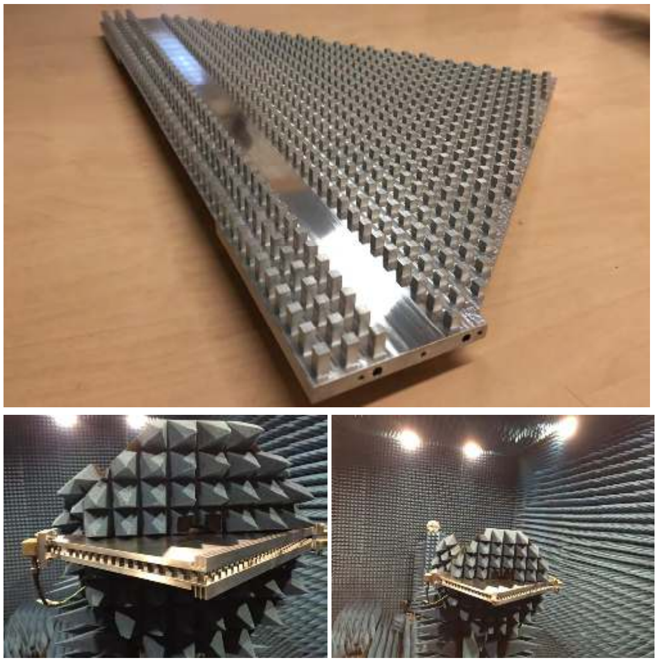


Fig. 10. Prototype of the proposed leaky-wave antenna and measurement setup in the anechoic chamber at KTH.

IV. PROTOTYPE AND EXPERIMENTAL RESULTS

A prototype antenna has been manufactured in aluminium as shown in Fig. 10. The prototype was milled in four parts: top cover plate, bottom pins, two feeding waveguide flanges and the circular piece to fix the antenna in the anechoic chamber. These four parts were afterwards assembled together.

A. Scattering Parameters

The scattering parameters are shown in Fig. 11. Both simulations and measurements exhibit a good agreement, especially in the S_{21} parameter. The S_{11} is below -10 dB from 10.0 to 14.0 GHz, and the S_{21} is below -15 dB from 10.0 to 13.3 GHz.

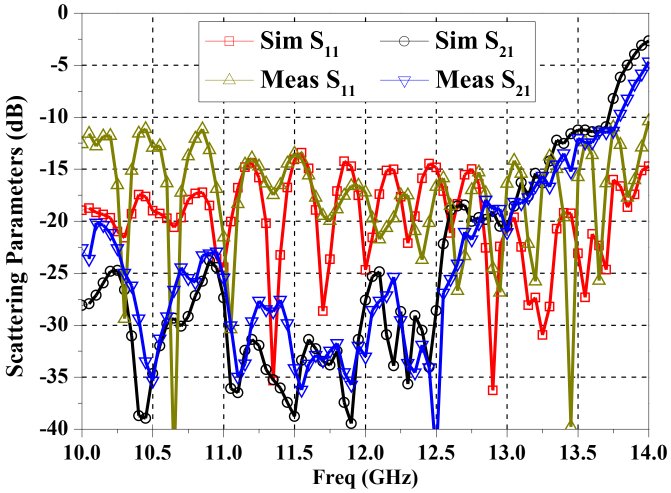


Fig. 11. Scattering parameters of the proposed leaky-wave antenna.

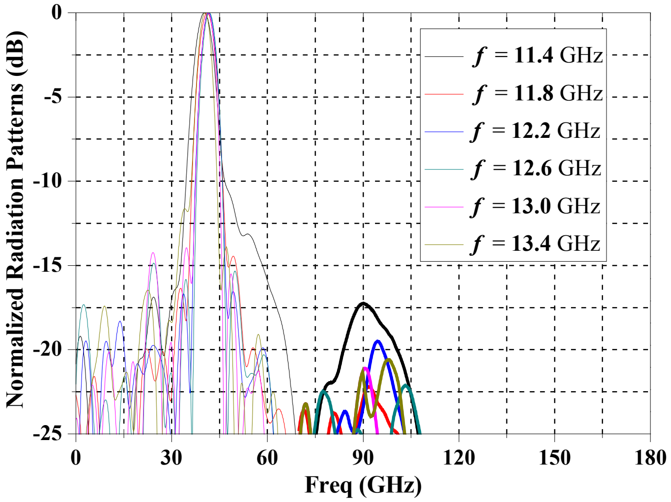


Fig. 12. Measured radiation patterns at different frequencies from 11.4 to 13.4 GHz.

B. Radiation Patterns

Fig. 12 shows the measured radiation patterns from 11.4 to 13.4 GHz with a 0.4-GHz step. In all the band, the radiation patterns are directed to φ=41° with ±0.5° difference, which agrees with both the theoretically calculated directions and the full-wave simulations. Moreover, the side-lobe levels (SLL) are all below -13 dB and the half-power beamwidths are around 5°. The peak realized gain at those frequencies also stays very stable, varying from 16.1 to 16.5 dBi, whereas the directivity varies from 16.4 to 16.8 dBi.

Fig. 13 describes the antenna performance in terms of the realized gain at a specific radiation direction as a function of the frequency. It can be found that the proposed low-dispersive leaky-wave antenna has a 22% (2.6 GHz) frequency bandwidth for a measured half-power realized gain at φ=41°, whereas a conventional leaky-wave antenna without prism has a 12.5% (1.5 GHz) frequency bandwidth and its main radiation

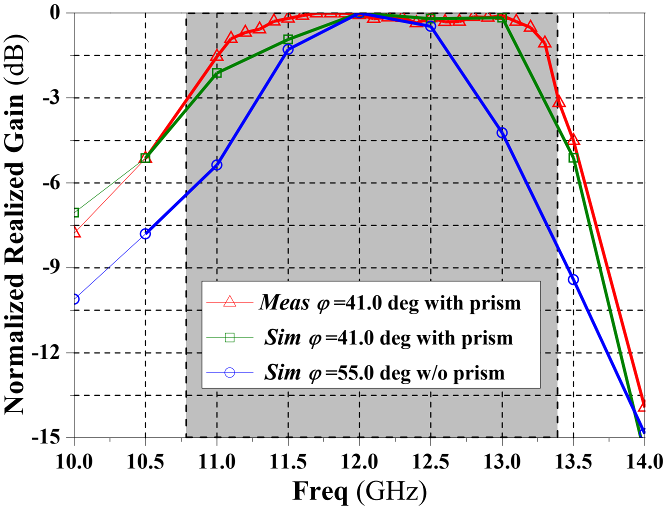


Fig. 13. Normalized realized gain at a specific radiation direction over different frequencies.

direction is φ=55°.

V. DISCUSSION

The proposed antenna is compared with other published techniques to increase the bandwidth of LWAs [29]-[45]. First, it must be commented that the width-tapering technique applied for microstrip [29]-[30] and SIW [31]-[33] LWAs, produces a strong reduction of the antenna gain. This is due to the associated loss of directivity generated by the broaden of the main beam as explained in [34], [35]. Therefore, this technique is not suitable for high-gain point-to-point directive radio links. Second, most of the solutions proposed in the literature are technology dependent, so that they cannot be applied to any type of LWA whose dispersion wants to be reduced. For instance, the use of coupled cavities proposed in [37]-[38] can only be applied to LWAs based on resonant cavities. In the same manner, the use of metamaterials [39], anisotropic [41], or non-reciprocal [42] materials, can only be applied to LWAs based on such type of artificial materials. Similarly, non-Foster circuits [43], [44] can only be used on LWAs loaded with active circuits, and all these techniques cannot be made extensive to general passive LWAs. Likewise, the LWA lens solution proposed by Neto in [45] can only be applied to a slot-line LWA embedded in a denser medium, and this cannot be extended to other types of LWAs.

On the contrary, the prism-coupling technique used in this paper is independent on the technology of the original LWA (microstrip, SIW, waveguide) whose dispersion has to be reduced. For instance, the authors applied this prism coupling technique to reduce the dispersion of a SIW LWA in [46]. By applying the same technique to a LWA in groove-gap waveguide, we demonstrate its versatility. This versatility is only comparable with the solution proposed in [40] for a coplanar waveguide (CPW) LWA. Therefore, the metasurface solution of [40] and the prism-coupling solution originally proposed in [46], are the only two squint-reduction techniques that can be applied to general LWAs. For this reason, [40] and [46] are compared with this work in Table II.

First, our solution is much more compact than [40], since the prism can be integrated in a single component together with the original LWA. On the contrary, the metasurface in [40] is coupled to the original LWA via radiation and refraction (as done in transmitarrays), leading to a less compact antenna formed by two distinct parts. This topology can also suffer from reduced efficiency due to diffraction and spillover losses (see Fig.19 in [40]). As summarized in Table II, while the original CPW LWA presented high radiation efficiency of 90%, the addition of the Huygens metasurface strongly reduces the overall antenna efficiency below 50%. On the contrary, the application of the prism-coupling technique to the original dispersive GGW LWA in [8] does not deteriorate its original high-radiation efficiency of 96% as shown in Table II.

Also, our prism loading technique shows better beam squint reduction performance than the use of the Huygens metasurface in [40]. As summarized in Table II, the addition of the prism has demonstrated to reduce the beam squinting to one tenth (from 5.6° to 0.6 °) in a 10% fractional bandwidth (from 11.5 GHz to 13 GHz). This is a stronger mitigation of the beam squinting than the one-half reduction reported in [40] (from 23.5° to 12° in a similar 10% fractional bandwidth). Also, we show in Table II that the Huygens solutions [40] presents lower peak gain of 5 dBi than our design with a high gain of 16.5 dBi, as a result of the reduced efficiency of the overall LWA + metasurface system. Definitely, the prism-coupling technique used in our work shows a much more compact and efficient solution that integrates the LWA and the prism in a single component.

Compared to the SIW LWA with via prism coupling in [46], the proposed gap-waveguide LWA with prism has much higher total antenna efficiency (95% vs. 24%) due to the absence of dielectric ohmic losses. Hence, the proposed LWA has much higher realized antenna gain than [46] (16.5 dBi vs. 8.5 dBi). Even more, the proposed LWA has narrower 3-dB beamwidth (5° vs. 9°), and it achieves better beam squinting performance (0.6° vs. 1.0°), as summarized in Table II. Moreover, the proposed LWA also has better side-lobe levels (SLLs) (-13 dB vs. -10 dB) and better impedance matching ($|S_{11}| <$ -13 dB vs. -10 dB), and the prism size also gets reduced by cutting the unused prism. Besides, this proposed design is fully metallic thanks to the use of gap waveguide technology instead of SIW. This allows its use for space and for high-power applications.

Furthermore, the LWA design in this paper has an excellent agreement between theoretical, simulated and measured radiation angle (φ=41°). This is due to the easy implementation of the prism in GGW technology. In the case of the SIW prism, the tight tolerances of design and fabrication of the SIW pins and surrounding slots, create stronger differences between theoretical calculations (φ=28.5°), full-wave simulations (φ=24°), and measured radiation angle (φ=31°) as reported [46]. In conclusion, this work is a better candidate to demonstrate the scenario of loading dispersive prism to LWA in order to reduce the beam squinting or dispersion, not only from the antenna performance, but also from the agreement between theory, full-wave simulation and prototype

TABLE II
COMPARISON BETWEEN DIFFERENT TECHNIQUES AND TECHNOLOGIES TO REDUCE THE DISPERSION OF GENERAL LWAS

Antenna Type	**Frequency Band (GHz)**	**Beam Angle at Center Frequency (°)**	**3-dB Beamwidth (°)**	**Beam Squinting (°)**	**Peak Gain (dBi)**	**Antenna Efficiency**	**SLL (dB)**	**Integration**
CPW LWA [40]	8.4-9.25	15	≈ 16	23.5	4	90%	-4	Two Components (LWA + Metasurface)
CPW LWA + Metasurface [40]	9.5-10.45	14	≈ 14	12	5	$< 50\%$	-6	
GGW LWA [8]	11.5-13.0	55	6	5.6	18	96%	-8	LWA and Prism Integrated in a Single Component
SIW LWA + Via Prism [46]	35.0-40.0	31	9	1.0	8.5	24%	-10	
Gap Waveguide LWA + Pin Prism (this work)	11.5-13.0	41	5	0.6	16.5	95%	-13	

experiment which makes the design more reliable.

VI. CONCLUSION

We proposed and designed a low-dispersive leaky-wave gap-waveguide antenna, including a theoretical derivation, full-wave simulations and an experimental demonstration. Our proposed methodology is based on the compensation of the dispersion of a leaky-wave radiation with a dispersive metasurface prism, as originally proposed in [46]. Both the antenna and the prism are realized in the same groove-gap waveguide (based on the use of metallic pins on a parallel plate as periodic structure) and its integration as one single component is straightforward.

Our proposed leaky-wave antenna has demonstrated to reduce the beam-squint from 6° to 1° in the frequency band of 11.4-13.4 GHz, while maintaining a high directivity of 16.5 dBi with only 5° half-power beamwidth. With the inclusion of a metasurface prism, the frequency bandwidth of the half-power realized gain has been increased from 12.5% to 22%. Although the prism-coupling technique can be applied to other antenna technologies, as demonstrated with a SIW LWA in [46], gap-waveguide technology was selected as a case study due to the reduced ohmic losses. A 95% antenna efficiency in measurement was achieved in our design at the X-band, reporting a much superior performance compared to previous SIW LWA with prism solution [46] in terms of gain due to reduced ohmic losses. Similar superior performance in terms of antenna efficiency is reported when compared to the use of a Huygens metasurface for dispersion-reduction in [40], which suffers from high diffraction losses. To the authors knowledge, the proposed design offers the highest gain and free-squint bandwidth compared to previous squint-free LWAs, and in a compact planar structure, avoiding the use of 3D dielectric lenses as the one proposed in the leaky-lens in [45]. We have also demonstrated that the complementary dispersion prism-coupling technique is not limited to a particular LWA technology, so that it can be applied to low-loss fully-metallic leaky waveguides as the groove-gap guide. These results are very promising for future millimeter-wave point-to-point broadband wireless link applications, where high gain at a given angle must be kept over a wide frequency band. Finally, in terms of contribution to antenna designs with gap waveguide technology, this contribution is also very relevant as it is the second proposed design in groove gap waveguide technology of a leaky-wave antenna (after [8]). All the advantages of this technology (only metal, contact-less, low loss, easily scalable) are evidenced in this design. It is shown how this technology is probably the most suitable to implement the prism-coupling technique to reduce beam-squinting in leaky-wave antennas.

REFERENCES

[1] P. S. Kildal, E. Alfonso, A. Valero-Nogueira, and E. Rajo-Iglesias, "Local metamaterial-based waveguides in gaps between parallel metal plates," *IEEE Antennas Wireless Propag. Lett.*, vol. 8, pp. 84–87, 2009.

[2] P.-S. Kildal, A. 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 Microw. Antennas Propag.*, vol. 5, pp. 262–270(8), February 2011.

[3] E. Rajo-Iglesias and P.-S. Kildal, "Numerical studies of bandwidth of parallel-plate cut-off realised by a bed of nails, corrugations and mushroom-type electromagnetic bandgap for use in gap waveguides," *IET Microw. Antennas Propag.*, vol. 5, pp. 282–289(7), February 2011.

[4] E. Rajo-Iglesias, P. S. Kildal, A. U. Zaman, and A. Kishk, "Bed of springs for packaging of microstrip circuits in the microwave frequency range," *IEEE Trans. Compon. Packag. Manuf. Technol.*, vol. 2, no. 10, pp. 1623–1628, Oct 2012.

[5] M. Ebrahimpouri, E. Rajo-Iglesias, Z. Sipus, and O. Quevedo-Teruel, "Cost-effective gap waveguide technology based on glide-symmetric holey EBG structures," *IEEE Trans. Microw. Theory Techn.*, vol. PP, no. 99, pp. 1–8, 2017.

[6] M. Ebrahimpouri, O. Quevedo-Teruel, and E. Rajo-Iglesias, "Design guidelines for gap waveguide technology based on glide-symmetric holey structures," *IEEE Microw. Wireless Compon. Lett.*, vol. 27, no. 6, pp. 542–544, June 2017.

[7] M. A. Sharkawy, A. Foroozesh, A. A. Kishk, and R. Paknys, "A robust horn ridge gap waveguide launcher for metal strip grating leaky wave antenna," *IEEE Trans. Antennas Propag.*, vol. 62, no. 12, pp. 6019–6026, Dec 2014.

[8] M. Vukomanovic, J. L. Vazquez-Roy, O. Quevedo-Teruel, E. Rajo-Iglesias, and Z. Sipus, "Gap waveguide leaky-wave antenna," *IEEE Trans. Antennas Propag.*, vol. 64, no. 5, pp. 2055–2060, May 2016.

[9] A. Farahbakhsh, D. Zarifi, and A. U. Zaman, "60-GHz groove gap waveguide based wideband H -plane power dividers and transitions: For use in high-gain slot array antenna," *IEEE Trans. Microw. Theory Techn.*, vol. 65, no. 11, pp. 4111–4121, Nov 2017.

[10] J. Cao, H. Wang, S. Mou, S. Quan, and Z. Ye, "W-band high-gain circularly polarized aperture-coupled magneto-electric dipole antenna array with gap waveguide feed network," *IEEE Antennas Wireless Propag. Lett.*, vol. 16, pp. 2155–2158, 2017.

[11] A. Khaleghi, Z. TalePour, and M. Ramazan, "Resonant slot antenna array on a ridge gap waveguide," *IET Microw. Antennas Propag.*, vol. 11, no. 8, pp. 1092–1097, 2017.

[12] M. S. Sorkherizi, A. Dadgarpour, and A. A. Kishk, "Planar high-efficiency antenna array using new printed ridge gap waveguide technology," *IEEE Trans. Antennas Propag.*, vol. 65, no. 7, pp. 3772–3776, July 2017.

[13] A. Vosoogh, P. S. Kildal, and V. Vassilev, "Wideband and high-gain corporate-fed gap waveguide slot array antenna with ETSI class II radiation pattern in V-band," *IEEE Trans. Antennas Propag.*, vol. 65, no. 4, pp. 1823–1831, April 2017.

[14] J. Liu, A. Vosoogh, A. U. Zaman, and J. Yang, "Design and fabrication of a high-gain 60-GHz cavity-backed slot antenna array fed by inverted microstrip gap waveguide," *IEEE Trans. Antennas Propag.*, vol. 65, no. 4, pp. 2117–2122, April 2017.

[15] A. Dadgarpour, M. S. Sorkherizi, T. A. Denidni, and A. A. Kishk, "Passive beam switching and dual-beam radiation slot antenna loaded with ENZ medium and excited through ridge gap waveguide at millimeter-waves," *IEEE Trans. Antennas Propag.*, vol. 65, no. 1, pp. 92–102, Jan 2017.

[16] B. Cao, H. Wang, and Y. Huang, "W-band high-gain TE_{220}-mode slot antenna array with gap waveguide feeding network," *IEEE Antennas Wireless Propag. Lett.*, vol. 15, pp. 988–991, 2016.

[17] A. Vosoogh and P. S. Kildal, "Corporate-fed planar 60-GHz slot array made of three unconnected metal layers using AMC pin surface for the gap waveguide," *IEEE Antennas Wireless Propag. Lett.*, vol. 15, pp. 1935–1938, 2016.

[18] B. Cao, H. Wang, Y. Huang, and J. Zheng, "High-gain L-probe excited substrate integrated cavity antenna array with LTCC-based gap waveguide feeding network for W-band application," *IEEE Trans. Antennas Propag.*, vol. 63, no. 12, pp. 5465–5474, Dec 2015.

[19] A. J. Sáez, A. Valero-Nogueira, J. I. Herranz, and B. Bernardo, "Single-layer cavity-backed slot array fed by groove gap waveguide," *IEEE Antennas Wireless Propag. Lett.*, vol. 15, pp. 1402–1405, 2016.

[20] J. I. H. Herruzo, A. Valero-Nogueira, S. M. Giner, and A. V. Jiménez, "Untilted narrow-wall slots excited by parasitic dipoles in groove gap waveguide technology," *IEEE Trans. Antennas Propag.*, vol. 63, no. 11, pp. 4759–4765, Nov 2015.

[21] X. Dong, H. Wang, F. Xue, and Y. Liu, "Design and measurement of a novel seamless scanning leaky wave antenna in ridge gap waveguide technology," *Progress In Electromag. Research M*, vol. 58, pp. 147–157, 2017.

[22] A. A. Oliner and D. R. Jackson, "Leaky-wave antennas," *Antenna Engineering Handbook*, vol. 4, p. 12, 1993.

[23] F. Xu and K. Wu, "Guided-wave and leakage characteristics of substrate integrated waveguide," *IEEE Trans. Microw. Theory Techn.*, vol. 53, no. 1, pp. 66–73, 2005.

[24] J. Xu, W. Hong, H. Tang, Z. Kuai, and K. Wu, "Half-mode substrate integrated waveguide (HMSIW) leaky-wave antenna for millimeter-wave applications," *IEEE Antennas Wireless Propag. Lett.*, vol. 7, pp. 85–88, 2008.

[25] Y. J. Cheng, W. Hong, and K. Wu, "Millimeter-wave half mode substrate integrated waveguide frequency scanning antenna with quadri-polarization," *IEEE Trans. Antennas Propag.*, vol. 58, no. 6, pp. 1848–1855, 2010.

[26] F. Xu, K. Wu, and X. Zhang, "Periodic leaky-wave antenna for millimeter wave applications based on substrate integrated waveguide," *IEEE Trans. Antennas Propag.*, vol. 58, no. 2, pp. 340–347, 2010.

[27] Y. J. Cheng, W. Hong, K. Wu, and Y. Fan, "Millimeter-wave substrate integrated waveguide long slot leaky-wave antennas and two-dimensional multibeam applications," *IEEE Trans. Antennas Propag.*, vol. 59, no. 1, pp. 40–47, 2011.

[28] D. Zelenchuk, A. J. Martinez-Ros, T. Zvolensky, J. L. Gomez-Tornero, G. Goussetis, N. Buchanan, D. Linton, and V. Fusco, "W-band planar wide-angle scanning antenna architecture," *Journal of Infrared Millimeter and Terahertz Waves*, vol. 34, no. 2, pp. 127–139, 2013.

[29] V. Nalbandian and C. Lee, "Tapered leaky-wave ultrawide-band microstrip antenna," in *Antennas and Propagation Society International Symposium, 1999. IEEE*, vol. 2. IEEE, 1999, pp. 1236–1239.

[30] W. Hong, T.-L. Chen, C.-Y. Chang, J.-W. Sheen, and Y.-D. Lin, "Broadband tapered microstrip leaky-wave antenna," *IEEE Trans. Antennas Propag.*, vol. 51, no. 8, pp. 1922–1928, 2003.

[31] N. Nguyen-Trong, T. Kaufmann, and C. Fumeaux, "A wideband omnidirectional horizontally polarized traveling-wave antenna based on half-mode substrate integrated waveguide," *IEEE Antennas Wireless Propag. Lett.*, vol. 12, pp. 682–685, 2013.

[32] ——, "A semi-analytical solution of a tapered half-mode substrate-integrated waveguide with application to rapid antenna optimization," *IEEE Trans. Antennas Propag.*, vol. 62, no. 6, pp. 3189–3200, 2014.

[33] N. Nguyen-Trong, L. Hall, T. Kaufmann, and C. Fumeaux, "Wideband millimeter-wave antennas with magnetic-dipole patterns integrated in metallic structures," *IEEE Trans. Antennas Propag.*, vol. 64, no. 11, pp. 4877–4882, 2016.

[34] A. J. Martinez-Ros, J. L. Gómez-Tornero, and G. Goussetis, "Holographic pattern synthesis with modulated substrate integrated waveguide line-source leaky-wave antennas," *IEEE Trans. Antennas Propag.*, vol. 61, no. 7, pp. 3466–3474, 2013.

[35] P. Burghignoli, F. Frezza, A. Galli, and G. Schettini, "Synthesis of broad-beam patterns through leaky-wave antennas with rectilinear geometry," *IEEE Antennas Wireless Propag. Lett.*, vol. 2, no. 1, pp. 136–139, 2003.

[36] J. L. Gómez-Tornero, A. R. Weily, and Y. J. Guo, "Rectilinear leaky-wave antennas with broad beam patterns using hybrid printed-circuit waveguides," *IEEE Trans. Antennas Propag.*, vol. 59, no. 11, pp. 3999–4007, 2011.

[37] J. L. Gómez-Tornero, A. Martínez-Ros, A. Álvarez-Melcón, F. Mesa, and F. Medina, "Substrate integrated waveguide leaky-wave antenna with reduced beam squint," in *Microwave Conference (EuMC), 2013 European*. IEEE, 2013, pp. 491–494.

[38] J. L. Gómez-Tornero, M. Poveda-García, R. Guzmán-Quirós, and D. Cañete-Rebenaque, "Reducing the beam squint in scanned leaky-wave antennas using coupled SIW cavities," in *Antennas and Propagation (APSURSI), 2016 IEEE International Symposium on*. IEEE, 2016, pp. 77–78.

[39] N. Nasimuddin, Z. N. Chen, and X. Qing, "Substrate integrated metamaterial-based leaky-wave antenna with improved boresight radiation bandwidth," *IEEE Trans. Antennas Propag.*, vol. 61, no. 7, pp. 3451–3457, 2013.

[40] A. Mehdipour, J. W. Wong, and G. V. Eleftheriades, "Beam-squinting reduction of leaky-wave antennas using huygens metasurfaces," *IEEE Trans. Antennas Propag.*, vol. 63, no. 3, pp. 978–992, 2015.

[41] A. Shahvarpour, A. A. Melcon, and C. Caloz, "Bandwidth enhancement and beam squint reduction of leaky modes in a uniaxially anisotropic meta-substrate," in *Antennas and Propagation Society International Symposium (APSURSI), 2010 IEEE*. IEEE, 2010, pp. 1–4.

[42] A. Porokhnyuk, T. Ueda, Y. Kado, and T. Itoh, "Nonreciprocal metamaterial for non-squinting leaky-wave antenna with enhanced beam steering," in *Antennas and Propagation Society International Symposium (APSURSI), 2013 IEEE*. IEEE, 2013, pp. 2289–2290.

[43] H. Mirzaei and G. V. Eleftheriades, "An active artificial transmission line for squint-free series-fed antenna array applications," in *Microwave Conference (EuMC), 2011 41st European*. IEEE, 2011, pp. 503–506.

[44] ——, "Arbitrary-angle squint-free beamforming in series-fed antenna arrays using non-foster elements synthesized by negative-group-delay networks," *IEEE Trans. Antennas Propag.*, vol. 63, no. 5, pp. 1997–2010, 2015.

[45] A. Neto, S. Bruni, G. Gerini, and M. Sabbadini, "The leaky lens: a broad-band fixed-beam leaky-wave antenna," *IEEE Transactions on Antennas and Propagation*, vol. 53, no. 10, pp. 3240–3246, Oct 2005.

[46] L. Wang, J. L. Gmez-Tornero, and O. Quevedo-Teruel, "Substrate integrated waveguide leaky-wave antenna with wide bandwidth via prism coupling," *IEEE Transactions on Microwave Theory and Techniques*, pp. 1–9, 2018.

[47] O. Quevedo-Teruel, "Controlled radiation from dielectric slabs over spoof surface plasmon waveguides," *Progress In Electromag. Research*, vol. 140, pp. 169–179, 2013.

Lei Wang (S'09-M'16) was born in Nanjing, China, in October 1986. He received the B.S. degree in applied physics from the Nanjing University of Posts and Telecommunications, Nanjing, China, in June 2009, and the Ph.D. degree in electromagnetic field and microwave technology from the Southeast University, Nanjing, China, in March 2015.

From September 2014 to September 2016, he was a Research Fellow and Postdoc in the Laboratory of Electromagnetics and Antennas (LEMA), Swiss Federal Institute of Technology (EPFL) in Lausanne, Switzerland. From October 2016 to November 2017, he was a Postdoc Research Fellow in Electromagnetic Engineering Laboratory of KTH Royal Institute of Technology in Stockholm, Sweden. From November 2017 to present, he is an Alexander von Humboldt Fellow in the Institute of Electromagnetic Theory of Hamburg University of Technology (TUHH) in Hamburg, Germany.

He was awarded the Chinese National Scholarship for PhD Candidates by Chinese government in 2014. He was also granted the Swiss Government Excellence Scholarship by Swiss government to conduct research on SIW horn antennas and applications in 2014. And he was granted the Alexander von Humboldt Research Scholarship by German government to take research on antenna modeling and optimization in 2016. He was awarded the Best Poster Award in 2018 IEEE International Workshop on Antenna Technology (iWAT).

His research includes the antenna theory and applications, active electronically scanning arrays (AESAs), integrated antennas and arrays, substrate-integrated waveguide antennas, leaky-wave antennas, horn antennas, numerical modeling and optimization of small antennas, microwave front-ends and systems.

José Luis Gómez-Tornerol (S'01-M'06-SM'14) was born in Murcia, Spain, in 1977. He received the Telecommunications Engineer degree from the Polytechnic University of Valencia (UPV), Valencia, Spain, in 2001, and the Laurea (Ph.D.) degree (cum laude) in telecommunication engineering from the Technical University of Cartagena (UPCT), Cartagena, Spain, in 2005. In 2000, he joined the Radio Frequency Division, Industry Alcatel Espacio, Madrid, Spain, where he was involved with the development of microwave active circuits for telemetry, tracking, and control (TTC) transponders for space applications. In 2001, he joined the Technical University of Cartagena (UPCT), where he has been an Associate Professor since 2008. He was Vice Dean for Students and Lectures affairs as a member of the Telecommunication Engineering Faculty, UPCT. He has been a Visiting Researcher/Professor with the University of Loughborough, Loughborough, U.K., Heriot-Watt University, Edinburgh, U.K., Queens University of Belfast, Belfast, U.K., and CSIRO-ICT Centre, Sydney, N.S.W., Australia. In February 2010, he was appointed a CSIRO Distinguished Visiting Scientist by the CSIRO ICT Centre.

He has co-authored more than 50 peer-reviewed journal papers, and more than 100 conference papers. His current research interests include the development of numerical methods for the analysis and design of leaky-wave devices in planar and waveguide technologies; their application for telecoms, RF identification/localization, microwave heating/sensing, wireless power transmission/harvesting, hyperthermia, and analog signal processing; the innovation in the area of higher education teaching/learning.

Dr. Gmez-Tornero was the recipient of the National Award from the foundation EPSON-Ibrica for the best Ph.D. project in the field of technology of information and communications (TIC) in 2004. He was the recipient of the Vodafone Foundation Award for the best Spanish Ph.D. thesis in the area of advanced mobile communications technologies in 2006. His thesis was also awarded the Best Thesis in the area of electrical engineering by the Technical University of Cartagena in 2006. His Ph.D. students thesis have received the 2014 Hispasat prize and the 2015 Hisdesat prize to the best Ph.D. thesis in Satellite Communication technologies. He was the corecipient of the 2010 IEEE Engineering Education Conference Award, the 2011 EuCAP Best Student Paper Prize, the 2012 EuCAP Best Antenna Theory Paper Prize, the 2012 and 2013 Spanish URSI Prize for the best student paper, and the 2018 iWAT Best Poster Award.

Eva Rajo-Iglesias (SM'08) was born in Monforte de Lemos, Spain, in 1972. She received the M.Sc. degree in telecommunication engineering from the University of Vigo, Spain, in 1996, and the Ph.D. degree in telecommunication engineering from the University Carlos III of Madrid, Spain, in 2002. She was a Teacher Assistant with the University Carlos III of Madrid from 1997 to 2001. She joined the Polytechnic University of Cartagena, Cartagena, Spain, as a Teacher Assistant, in 2001. She joined University Carlos III of Madrid as a Visiting Lecturer in 2002, where she has been an Associate Professor with the Department of Signal Theory and Communications since 2004. She visited the Chalmers University of Technology, Gteborg, Sweden, as a Guest Researcher, in 2004, 2005, 2006, 2007, and 2008, and has been an Affiliate Professor with the Antenna Group, Signals and Systems Department, since 2009 to 2016. She has co-authored more than 70 papers in JCR international journals and more than 100 papers in international conferences. Her current research interests include microstrip patch antennas and arrays, metamaterials, artificial surfaces and periodic structures, gap waveguide technology, MIMO systems and optimization methods applied to electromagnetism.

Dr. Rajo-Iglesias was the recipient of the Loughborough Antennas and Propagation Conference Best Paper Award in 2007, the Best Poster Award in the field of Metamaterial Applications in Antennas, at the conference Metamaterials 2009, the 2014 Excellence Award to Young Research Staff at the University Carlos III of Madrid and the Third Place Winner of the Bell Labs Prize 2014. She is currently an Associate Editor of the IEEE ANTENNAS AND PROPAGATION MAGAZINE and has served as Associate Editor of the IEEE ANTENNAS AND WIRELESS PROPAGATION LETTERS (2011-2017).

Oscar Quevedo-Teruel (M'10-SM'17) received his M.Sc. degree in Telecommunication Engineering from Carlos III University of Madrid, Spain, in 2005 and went on to complete his Master of Engineering degree at Chalmers University of Technology in Gothenburg, Sweden.

He received his Ph.D. degree from Carlos III University of Madrid in 2010. He was then invited into a post-doctoral research position at Delft University of Technology in the Netherlands. From 2010 to 2011, he was with the Department of Theoretical Physics of Condensed Matter, Universidad Autonoma de Madrid, as a Research Fellow, and went on to continue his post-doctoral research with Queen Mary University of London, U.K., from 2011 to 2013. In 2014, he joined the School of Electrical Engineering/Electromagnetic Engineering at KTH Royal Institute of Technology, Sweden, where he is currently an associate professor and director of the Master Programme in Electromagnetics, Fusion and Space Engineering.

He has made scientific contributions in the fields of microstrip patch antennas, lens antennas, metasurfaces, higher symmetries, transformation optics, and high impedance surfaces. He has co-authored over 60 papers in international journals, over 120 at international conferences, and has received approval on 2 patents.