Ka-Band Low-Sidelobe-Level Slot Array Leaky-Wave Antenna Based on Substrate Integrated Nonradiative Dielectric Waveguide

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***Abstract*—This letter presents a leaky-wave antenna array in the substrate integrated nonradiative dielectric (SINRD) waveguide technology. Several radiating slots are etched on the copper foil of the SINRD guide and placed with opposing tilt angles to achieve a compact configuration. After investigating the characteristic of the complex propagation constant of an SINRD guide with slots, the low sidelobe level (SLL) of a leaky-wave antenna can be synthesized. Besides, this kind of antenna can be fabricated directly on the printed circuit board substrate, which means that it can be easily integrated with other kinds of planar circuits in the millimeter-wave band. As an example, a Ka-band prototype is designed and experimented, which has –18.1 dB SLL and 12.7 dBi gain at 29.4 GHz.**

***Index Terms*—Leaky-wave antenna, low sidelobe level (SLL), millimeter-wave, substrate integrated nonradiative dielectric (SINRD) waveguide.**

I. Introduction

THE nonradiative dielectric (NRD) guide [1] has been a promising technology for low-loss applications since its inception. To realize a NRD guide, a rectangular dielectric slab is sandwiched between two metallic plates. Considering the difficulties of integration and mechanical assembly, it is not an easy task to realize a millimeter-wave NRD guide circuit.

To convert an NRD guide into its planar version, a substrate integrated nonradiative dielectric (SINRD) guide is proposed in [2]–[4]. It also belongs to the family of substrate integrated circuits [5]–[9]. A material of the lower permittivity fills bilateral extents of the guiding channel. The original way of lowering permittivity in bilateral sides of the center guiding channel is the air hole perforation. This type of SINRD guide also needs additional metallic plates covered on both sides of the dielectric sheet. Thus, there exists potential air gap caused by mechanical assembly [10]. To overcome this weakness, a modified SINRD guide is developed in [11], which can be directly realized through the conventional printed circuit board (PCB) without employing mechanical assembly as usual.

Manuscript received September 3, 2017; revised October 5, 2017; accepted October 6, 2017. Date of publication October 10, 2017; date of current version November 8, 2017. This work was supported in part by the National Natural Science Foundation of China under Grant 61622105 and Grant 61631012, in part by the Foundation for the Author of National Excellent Doctoral Dissertation of PR China under Grant 201338, and in part by Fundamental Research Funds for the Central Universities under Grant ZYGX2014Z008. *(Corresponding author: Yu Jian Cheng.)*

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Digital Object Identifier 10.1109/LAWP.2017.2761780

Considering the inherent advantage of low loss, the SINRD guides can be effectively used to construct millimeter-wave antenna feeders or planar leaky-wave antennas [12], [13]. Therefore, in this letter, a leaky-wave antenna is implemented using this technology. The longitudinal-section-magnetic (LSM) mode and longitudinal-section-electric mode can be supported in an SINRD guide. Here, the selected operating mode is LSM_{11}. The electric field component of this mode is primarily parallel to the metallic plate and the field concentration is small in the region near the metallic plate. In this case, the conductor loss of the SINRD antenna is small. The overall loss is primarily determined by the dielectric loss. Several radiating slots are etched on the conductor surface of the SINRD guide with opposing tilt angles. After recognizing the characteristic of the slot versus its geometry, it is easy to control the sidelobe level (SLL) of the leaky-wave antenna by these slots. Compared with other SINRD guide antennas, these inclination slots barely influence the propagation constant of the SINRD guide [14]. In [10], the slot offset will change the leakage constant and the propagation constant at the same time. When the leakage constant is adjusted by the offset, the beam pointing will change as well. Additional design is required to keep the propagation constant close to a fixed value after suppressing the SLL. The design process is complex. Meanwhile, compared with other low-SLL planar leaky-wave antennas [15]–[27], the low-SLL antenna based on the SINRD guide has a smaller electrical length with the same gain. This is because a periodic leaky-wave antenna with a high dielectric constant has a smaller guide wavelength while the topology of slots is allowed to control the leakage constant twice within one guide wavelength.

In this letter, the design procedure of the SINRD guide slot array leaky-wave antenna is introduced at first. Then, a low-SLL Ka-band SINRD guide leaky-wave antenna is designed and fabricated through the normal PCB process.

II. SINRD Antenna Synthesis and Design

A. SINRD Guide Synthesis

To design an SINRD guide, the first step is to determine the dimension of the SINRD guide. An equilateral triangular lattice air hole arrangement is chosen here to effectively lower the effective permittivity of a dielectric region of interest. In this case, a dielectric channel is created in the dielectric substrate and constructs an SINRD guide as shown in Fig. 1. The effective dielectric constant of the air hole pattern can be approximated by [2]

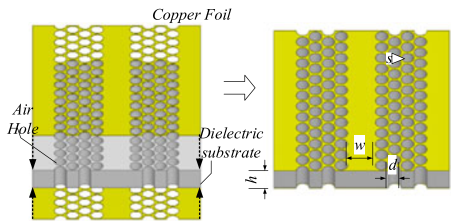


Fig. 1. Configuration of the SINRD guide by the normal PCB process.

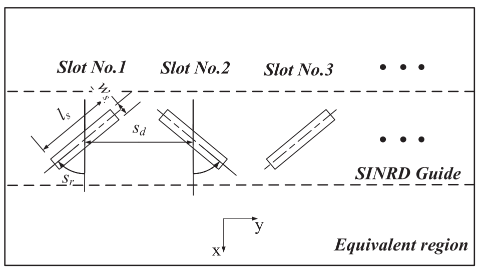


Fig. 2. Geometries of slots etched on the surface of the SINRD guide.

$$\varepsilon_{\text{eff}} = \varepsilon_r + \frac{(1-\varepsilon_r)\,\pi}{2\sqrt{3}}\left(\frac{d}{s}\right)^2. \tag{1}$$

In (1), ε_r is the dielectric constant of the substrate material, d is the diameter of the air hole, and s is the distance between adjacent holes. The relationship among the height h, the width w, and the effective dielectric constant ε_{eff} can be determined by the eigenfunctions of the corresponding modes [11]. The LSM_{12} mode and the LSM_{21} mode are high-order hybrid modes of an SINRD guide. There is a tiny coupling between the LSM_{12} mode and the LSM_{11} mode because of the symmetry of the SINRD guide, thus the LSM_{12} mode can be negligible to some extent, whereas the LSM_{21} mode needs to be cut off below the maximum operating frequency by selecting geometric parameters.

A 2.54 mm thick Taconic RF-10 substrate is employed. The measured relative permittivity is 10.8 at Ka-band by use of the resonator method. Based on this, the SINRD channel width is 3.06 mm, the diameter of the air hole is 1.35 mm, and the distance between adjacent holes is 1.61 mm.

B. SINRD Slot Array Antenna

As shown in Fig. 2, there is a series of inclination slots etched on the top copper foil of an SINRD guide. The inclination angle s_r is the angle between the slot and the x-axis. The slot is designed to operate at resonance. Its length is significantly affected by the dielectric permittivity of the guide. Through the full-wave simulation, the slot resonant length is 2.07 mm with a slot width of 0.26 mm at the center frequency of 29.4 GHz.

Because the array is composed of elements with opposing tilt angles, an additional phase shift π should be added to modify the conventional relationship between the beam direction and the distance between adjacent slots s_d. There is

$$\beta_{-1} = \beta_0 - \pi/s_d \tag{2}$$

$$\sin(\theta_m) = \beta_{-1}/k_0. \tag{3}$$

In (2) and (3), k_0 is the propagation constant in free space, β_0 is the phase constant in the SINRD, and β_{-1} is the phase constant of the first space harmonic. β_0 is 1366.2 rad/m at 29.4 GHz. In this design, the desired beam is $-23°$. Thus, the initial s_d can be calculated to be 1.95 mm.

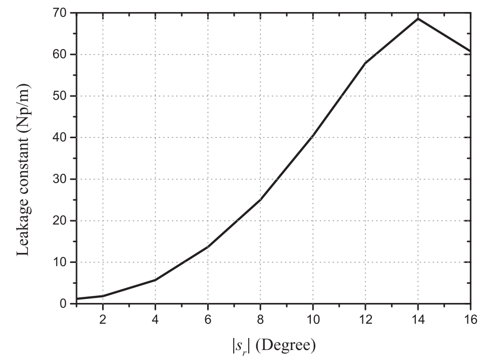


Fig. 3. Relationship between $|s_r|$ and the leakage constant.

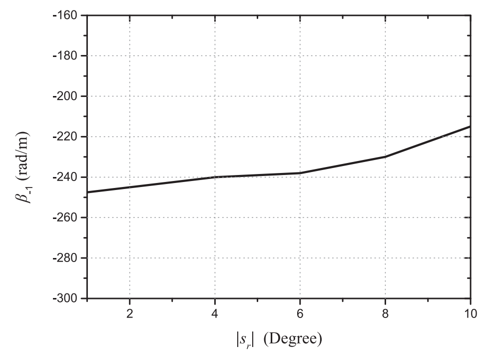


Fig. 4. Relationship between $|s_r|$ and β_{-1}.

In order to evaluate the leakage constant of the slot with different $|s_r|$, a full-wave model analysis of an SINRD guide composed by 26 slots with the same inclination angle from 1° to 16° is performed with Ansys HFSS. In this case, the effect of the coupling between slots is considered to obtain a more accurate leakage constant. It should be noted that elements with opposing tilt angles is a basic constraint in the design process. The conductor and dielectric material are set to be lossless. Then, the leakage constant can be extracted by the simulated *S*-parameters, whereas the phase constant can be extracted by calculating the phase change along the propagation direction. As shown in Fig. 3, when $|s_r|$ is below 14°, the leakage constant of the inclination slot array increases with $|s_r|$. Then, the leakage constant begins to decrease with the coupling between slots. As shown in Fig. 4, the absolute variation $\triangle\beta_{-1} / k_0$ is 0.06 when $|s_r|$ increases from 1° to 10°.

C. SINRD Leaky-Wave Antenna Design With Low SLL

Next, the SLL control of the leaky-wave antenna is discussed. The sidelobe behavior is poor for a leaky-wave antenna with slots having the same dimensions. It is noted that different inclination angles of slots only influence the leakage constant while keeping the propagation constant near to a constant, as shown in Fig. 4. It is very important in the design of a shaped-beam leaky-wave antenna. In this case, the aperture distribution and the beam direction can be controlled respectively. To suppress the SLL of a leaky-wave antenna, the practice is to vary the inclination angle slowly along the length in a specified way. The amplitude of the aperture distribution can be adjusted to yield the desired sidelobe performance. In fact, for fixed radiation efficiency, there is a tradeoff between the desired SLL and the

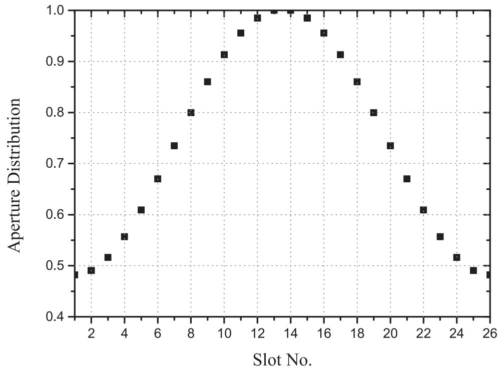


Fig. 5. Aperture distribution of the Taylor distribution with –22 dB SLL.

TABLE I
INCLINATION ANGLE OF EACH SLOT

Slot No.	1	2	3	4	5	6	7	8	9
$\|s_r\|$ (°)	1.3	1.3	1.65	2.1	2.8	3.6	4.4	5.1	5.6
Slot No.	10	11	12	13	14	15	16	17	18
$\|s_r\|$ (°)	6.1	6.6	7.1	7.7	8.3	9	9.5	9.8	10
Slot No.	19	20	21	22	23	24	25	26	
$\|s_r\|$ (°)	9.7	9	8	7.1	6.3	5.7	5.3	5.1	

array length. To achieve a lower SLL, the ratio of the maximum and minimum values of the required aperture distribution increases. A lower SLL may be not able to achieve at a fixed array length due to the limited radiation capacity of the slot. Although the required SLL determines the array aperture distribution, the absolute radiation requirements for each slot will decrease with the array length. Thus, a lower SLL can be achieved with the number of slots.

The experimental array with 26 elements is set to follow the Taylor distribution with –22 dB SLL. The required aperture distribution, A_m, for each slot is shown in Fig. 5. Then, the desired leakage constant of the mth slot can be expressed by [28]

$$\alpha_m = \frac{\frac{1}{2}|A_m|^2}{\frac{1}{1-R}\sum_{i=1}^{N}|A_i|^2 s_d - \sum_{i=1}^{m}|A_i|^2 s_d}. \tag{4}$$

In (4), R is the fraction of the input power absorbed by a load. Here, $R = 0.1$. Utilizing the relationship between the inclination angle of the slot and the leakage constant as shown in Fig. 3, the initial inclination angle of each slot can be obtained. After full-wave simulation and optimization implemented by the HFSS, the inclination angles of slots are listed in Table I. Here, the overall inclination is about 10°, which leads the phase change to be nonuniform along the propagation direction. In this case, the beamwidth is broadened a little.

III. RESULT

The prototype antenna is fabricated by the normal PCB process as shown in Fig. 6. The SINRD guide is placed at the middle of a WR-28 standard metallic waveguide to excite the LSM_{11} mode [13]. The substrate is tapered inside the waveguide to achieve a good matching. The simulated and measured *S*-parameters are presented in Fig. 7. The measured reflection coefficient is below –12 dB within 29.1–29.6 GHz.

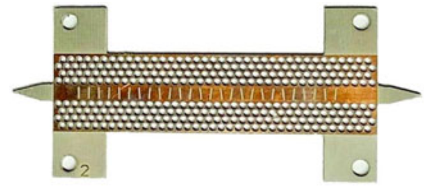


Fig. 6. Photograph of the fabricated SINRD guide leaky-wave antenna.

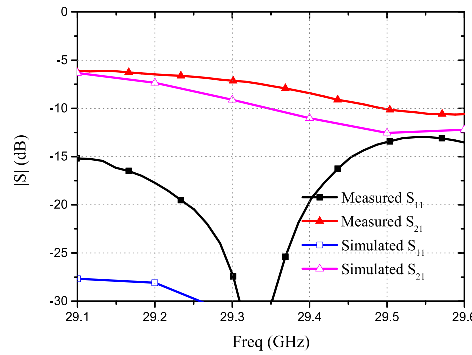


Fig. 7. *S*-parameters of the SINRD guide leaky-wave antenna.

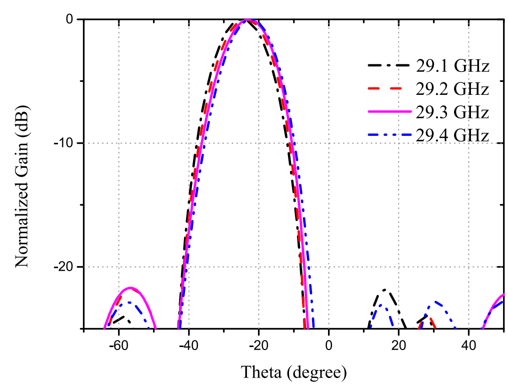


Fig. 8. Simulated patterns of the leaky-wave antenna at different frequencies.

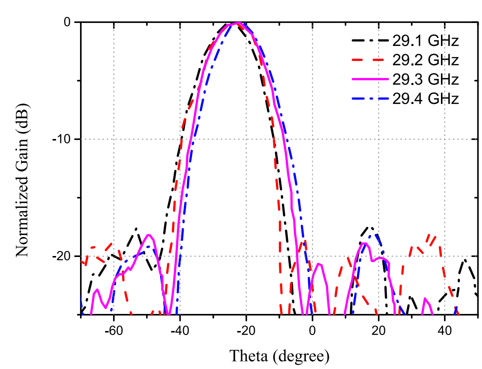
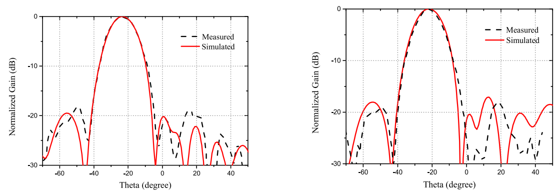


Fig. 9. Measured patterns of the leaky-wave antenna at different frequencies.

By using a waveguide-to-coaxial adapter, the output port of this leaky-wave antenna is terminated with a 50 Ω load. Figs. 8 and 9 show the simulated and measured E-plane radiation patterns. The gains are measured to be 11.6 , 12.0 , 12.4, 12.7 dBi, and the SLLs are measured to be –17.4, –17.9, –18.1, –18.1 dB at 29.1, 29.2, 29.3, and 29.4 GHz. With the increase of frequency, the beam is moved toward the propagation direction of the leaky wave. The beam direction of this antenna is changed from –24.9° to –22° in the frequency band of 29.1 to 29.4 GHz.



(a) (b)

Fig. 10. Measured pattern of the leaky-wave antenna and simulated pattern with position errors and screws. (a) At 29.3 GHz; (b) at 29.4 GHz.

TABLE II
COMPARISON OF DIFFERENT LEAKY-WAVE ANTENNAS

	Frequency (GHz)	Type of guide	L/λ_0	Gain (dBi)	SLL (dB)
[14]	9.5	NRD	7.9	9.6	–8.5
[10]	88	SINRD	10	7.59	–8.3
[16]	12.16	SIW	12.4	14.84	–20
[18]	15	SIW	6.8	11	–23
This work	29.4	SINRD	4.8	12.7	–18.1

Comparing the measured and simulated radiation patterns of the array, higher SLL in the measured patterns is caused by screws and position errors. Fig. 10 shows the simulated radiation pattern when the WR-28 standard feeding waveguide has a displacement of 0.1 mm. In practical application, this error can be eliminated when the microstrip line, slot line, coplanar waveguide, or substrate integrated waveguide (SIW) feedline is used to excite the antenna and fabricated together through the PCB process.

Compared performance between different NRD and SINRD leaky-wave antennas is listed in Table II. As listed in this table, our design is able to achieve low SLL in the millimeter-wave band with a smaller electrical length.

IV. CONCLUSION

Based on the low-loss SINRD guide, a Ka-band slot array leaky-wave antenna is investigated and designed. There are several radiating slots etched on the copper foil of the SINRD guide. They are placed with opposing tilt angles. The low SLL is achieved with carefully designing the geometry of each inclination slot. This kind of antenna can be fabricated directly through the normal PCB process to eliminate the integration problems. It has a smaller electrical length with the same gain compared with some other leaky-wave antennas.

REFERENCES

[1] T. Yoneyama and S. Nishida, "Non-radiative dielectric waveguide for millimeter-wave integrated circuits," *IEEE Trans. Microw. Theory Techn.*, vol. MTT-29, no. 11, pp. 1188–1192, Nov. 1981.

[2] N. Grigoropoulos and P. R. Young, "Low cost non radiative perforated dielectric waveguides," in *Proc. Eur. Microw. Conf.*, Munich, Germany, 2003, pp. 439–442.

[3] Y. Cassivi and K. Wu, "Substrate integrated non-radiative dielectric waveguide," *IEEE Microw. Wireless Compon. Lett.*, vol. 14, no. 3, pp. 89–91, Mar. 2004.

[4] Y. Cassivi and K. Wu, "Substrate integrated circuits concept applied to the nonradiative dielectric guide," *IEE Proc. Microw., Antennas Propag.*, vol. 152, no. 6, pp. 424–433, Dec. 2005.

[5] Y. J. Cheng, W. Hong, and K. Wu, "94 GHz substrate integrated monopulse antenna array," *IEEE Trans. Antennas Propag.*, vol. 60, no. 1, pp. 121–128, Jan. 2012.

[6] J. Wu, "A wideband high-gain high-efficiency hybrid integrated plate array antenna for V-band inter-satellite links," *IEEE Trans. Antennas Propag.*, vol. 63, no. 4, pp. 1225–1233, Apr. 2015.

[7] Y. J. Cheng and F. Xue, "Ka-band near-field-focused array antenna with variable focal point," *IEEE Trans. Antennas Propag.*, vol. 64, no. 5, pp. 1725–1732, May 2016.

[8] H. B. Wang, "Frequency selective surface with miniaturized elements based on quarter-mode substrate integrated waveguide cavity with two poles," *IEEE Trans. Antennas Propag.*, vol. 64, no. 3, pp. 914–922, Mar. 2016.

[9] Y. J. Cheng, Y. X. Guo, and Z. Q. Liu, "W-band large-scale high-gain planar integrated antenna array," *IEEE Trans. Antennas Propag.*, vol. 62, no. 6, pp. 3370–3373, Jun. 2014.

[10] P. Mondal and K. Wu, "A leaky-wave antenna in substrate integrated nonradiative dielectric (SINRD) waveguide with controllable scanning rate," *IEEE Trans. Antennas Propag.*, vol. 61, no. 4, pp. 2294–2297, Apr. 2013.

[11] F. Xu and K. Wu, "Substrate integrated nonradiative dielectric waveguide structures directly fabricated on printed circuits and metallized dielectric layers," *IEEE Trans. Microw. Theory Techn.*, vol. 59, no. 12, pp. 3076–3086, Dec. 2011.

[12] N. Ghassemi and K. Wu, "Planar dielectric rod antenna for gigabyte chip-to-chip communication," *IEEE Trans. Antennas Propag.*, vol. 60, no. 10, pp. 4924–4928, Oct. 2012.

[13] P. Mondal and K. Wu, "A leaky-wave antenna using periodic dielectric perforation for millimeter-wave applications," *IEEE Trans. Antennas Propag.*, vol. 64, no. 12, pp. 5492–5495, Dec. 2016.

[14] J. A. G. Malherbe, "The design of a slot array in non-radiating dielectric waveguide, Part II: Experiment," *IEEE Trans. Antennas Propag.*, vol. AP-32, no. 12, pp. 1335–1340, Dec. 1984.

[15] J. L. Gómez, A. Torre, D. Cañete, M. Gugliemi, and A. A. Melcón, "Design of tapered leaky-wave antennas in hybrid waveguide-planar technology for millimeter waveband applications," *IEEE Trans. Antennas Propag.*, vol. 53, no. 8, pp. 2563–2577, Aug. 2005.

[16] J. H. Liu. D. R. Jackson, Y. X. Li, C. Q. Zhang, and Y. L. Long, "Investigations of SIW leaky-wave antenna for endfire-radiation with narrow beam and sidelobe suppression," *IEEE Trans. Antennas Propag.*, vol. 62, no. 9, pp. 4489–4497, Sep. 2014.

[17] M. García-Vigueras, J. L. Gómez-Tornero, G. Goussetis, A. R. Weily, and Y. J. Guo, "Efficient synthesis of 1-D Fabry–Perot antennas with low sidelobe levels," *IEEE Antennas Wireless Propag. Lett.*, vol. 11, pp. 869–872, 2012.

[18] A. J. Martinez-Ros, J. L. Gomez-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, Jul. 2013.

[19] S. M. A. Nezhad and A. Mallahzadeh, "Periodic ridged leaky-wave antenna design based on SIW technology," *IEEE Antennas Wireless Propag. Lett.*, vol. 14, pp. 354–357, 2015.

[20] D. Comite, S. K. Podilchak, and P. Baccarelli, "A dual-layer planar leaky-wave antenna designed for linear scanning through broadside," *IEEE Antennas Wireless Propag. Lett.*, vol. 16, pp. 1106–1110, 2017.

[21] A. J. Martinez-Ros, J. Gómez-Tornero, and G. Goussetis, "Multifunctional angular bandpass filter SIW leaky-wave antenna," *IEEE Antennas Wireless Propag. Lett.*, vol. 16, pp. 936–939, 2017.

[22] J. H. Fu, A. Li, W. Chen, B. Lv, Z. J. Wang, and P. Li, "An electrically controlled CRLH-inspired circularly polarized leaky-wave antenna," *IEEE Antennas Wireless Propag. Lett.*, vol. 16, pp. 760–763, 2017.

[23] A. H. Dorrah and G. V. Eleftheriades, "Pencil-beam single-point-fed Dirac leaky-wave antenna on a transmission-line grid," *IEEE Antennas Wireless Propag. Lett.*, vol. 16, pp. 545–548, 2017.

[24] A. H. Panaretos and D. H. Werner, "Leaky-wave antennas based on capacitively tuned modulated reactance surfaces," *IEEE Antennas Wireless Propag. Lett.*, vol. 15, pp. 678–681, 2015.

[25] Y. J. Cheng, H. Xu, D. Ma, J. Wu, L. Wang, and Y. Fan, "Millimeter-wave shaped-beam substrate integrated conformal array antenna," *IEEE Trans. Antennas Propag.*, vol. 61, no. 9, pp. 4558–4566, Sep. 2013.

[26] R. Henry and M. Okoniewski, "A broadside scanning substrate integrated waveguide periodic phase-reversal leaky-wave antenna," *IEEE Antennas Wireless Propag. Lett.*, vol. 15, pp. 602–605, 2015.

[27] Y. Kushiyama, T. Arima, and T. Uno, "Differential-type CRLH leaky-wave antenna using stepped impedance resonators," *IEEE Antennas Wireless Propag. Lett.*, vol. 15, pp. 321–324, 2015.

[28] A. A. Oliner and D. R. Johnson, *Leaky-Wave Antennas, Antenna Engineering Handbook*, 4th ed. New York, NY, USA: McGraw-Hill, 2007, ch. 11.