Second-Higher-Order Mode Microstrip Leaky-Wave Antenna with I-Shaped Slots for Single Main Beam Radiation in Cross Section

Peng Fei Zhang, *Student Member, IEEE*, Lei Zhu, *Fellow, IEEE*, and Sheng Sun, *Senior Member, IEEE*

Abstract— **This paper presents a second-higher-order mode microstrip leaky-wave antenna for single main beam radiation. Different from its conventional second-higher-order leaky-mode counterpart with two symmetric radiation beams, the proposed antenna with an array of I-shaped slots radiates only one main radiation beam at the cross-sectional center plane. By introducing a transversally-loaded slot array along the microstrip line, the cross polarization of the antenna can be largely enhanced, while a longitudinally-loaded slot array interrupts the current flow and thus effectively reduce the original two radiation beams. Subsequently, an array of I-shaped slots, including transversal- and longitudinal-slot portions, is etched on the strip conductor and its unique characteristics is then analyzed to obtain a single main radiation beam in the center plane. To validate this proposal, a prototype of single-main-beam leaky-wave antenna with second-higher-order mode is designed, implemented and fabricated. Due to larger leakage constant, the leaky-wave antenna presented in this paper radiate higher power within a shorter length in term of guided wavelength, resulting to a higher gain. The measured results show a beam-scanning capability from 20° to 55° as the frequency varies from 5.1 to 4.6 GHz, while the maximum gain of 14.6 dBi is achieved at 4.9 GHz.**

Index Terms— **Microstrip leaky wave antenna, second-higher-order mode, I-shaped slot array, single main beam radiation.**

I. Introduction

MICROSTRIP leaky-wave antenna (LWA) has attracted wide attentions due to its low profile, simple structure, high gain, wide bandwidth, as well as inherent beam-scanning capacity. Various technologies have been proposed to excite the radiation mode of the microstrip line, such as uniform or quasi uniform microstrip LWA based on higher order mode [1]-[21], periodic microstrip LWA based on the space harmonic of the fundamental mode [22]-[25], and quasi uniform LWAs based on the concept of metamaterials [26]-[31]. As a major part of the microstrip line LWA, the microstrip higher order mode has been widely utilized for leaky-wave radiation. In the 1970's, the initial researches on high order mode of microstrip line were intensively reported in [1]-[5]. In [1], [2], Ermert reported the propagation characteristics of the guided-wave modes and radiation in microstrip line and indicated a leaky-wave solution. Later on, Menzel experimentally demonstrated the radiation property of the first higher order EH_1-mode [3]. Then, Oliner and Lee show the radiation property in a leakage band with a complex propagation constant, i.e. a phase constant (β) and a leakage constant (α_r) [4], [5]. It is clear that the fast wave ($\beta < k_0$) is a condition for generating the leaky-wave radiation [6]-[8], while the fields of slow wave ($\beta > k_0$) are well confined inside the guided-wave structure with shorter wavelength.

Various excellent works have been conducted to design LWA based on EH_1-mode as well. To obtain a pure first-higher -order mode, the metallic vias were periodically loaded along the center of line, thus shortening the maximum electric field of the fundamental mode (EH_0-mode) [3], [9]. In [10], a half-width EH_1-mode LWA was proposed. Because of the existence of shorting wall, the EH_0-mode does not emerge and only EH_1 can be excited. Besides, the slotline, coplanar strip line, as well as wideband microstrip line balun were also inquired to effectively excite the EH_1-mode [11]-[13]. To further improve the performance, the odd-mode of coupled half-width topology was utilized to enhance leakage bandwidth [14], while the EH_1-mode LWA with shorting pins was demonstrated for enhancing the directivity and frequency sensitivity [15], [16]. In addition, the backward-to-forward scanning can also be realized [22], [23].

Different from the EH_1-mode, the second-higher-order mode (EH2-mode) has more variegated field distribution. Therefore, it has the potential to get a variety of different radiation characteristics through different forms of loading, rather than being limited to its dual-beam radiation. However, the researches based on the EH_2-mode has mainly focused on the excitation method so far, only limited researches have studied the radiation characteristic of the EH_2-mode. Due to the symmetric field distribution of the EH_2-mode, the two radiation beams of EH_2-mode were excited based on the backside

The manuscript submitted November 16, 2018.

This work was supported in part by National Natural Science Foundation of China (61721001, 61622106, 61571468), in part by University of Macau (MYRG2017-00007-FST, MYRG2018-00073-FST, CPG2017-00028-FST), and in part by Macao Science and Technology Development Fund (091/2016/A2). (*Corresponding Author: Sheng Sun*)

P. F. Zhang is with the School of Electronic Science and Engineering, University of Electronic Science and Technology of China, Chengdu 611731, China, and also with the Department of Electrical and Computer Engineering, Faculty of Science and Technology, University of Macau, Macau, China

L. Zhu is with the Department of Electrical and Computer Engineering, Faculty of Science and Technology, University of Macau, Macau, China (e-mail: LeiZhu@umac.mo).

S. Sun is with the with the School of Electronic Science and Engineering, University of Electronic Science and Technology of China, China (e-mail: sunsheng@ieee.org).

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TAP.2019.2920260, IEEE Transactions on Antennas and Propagation

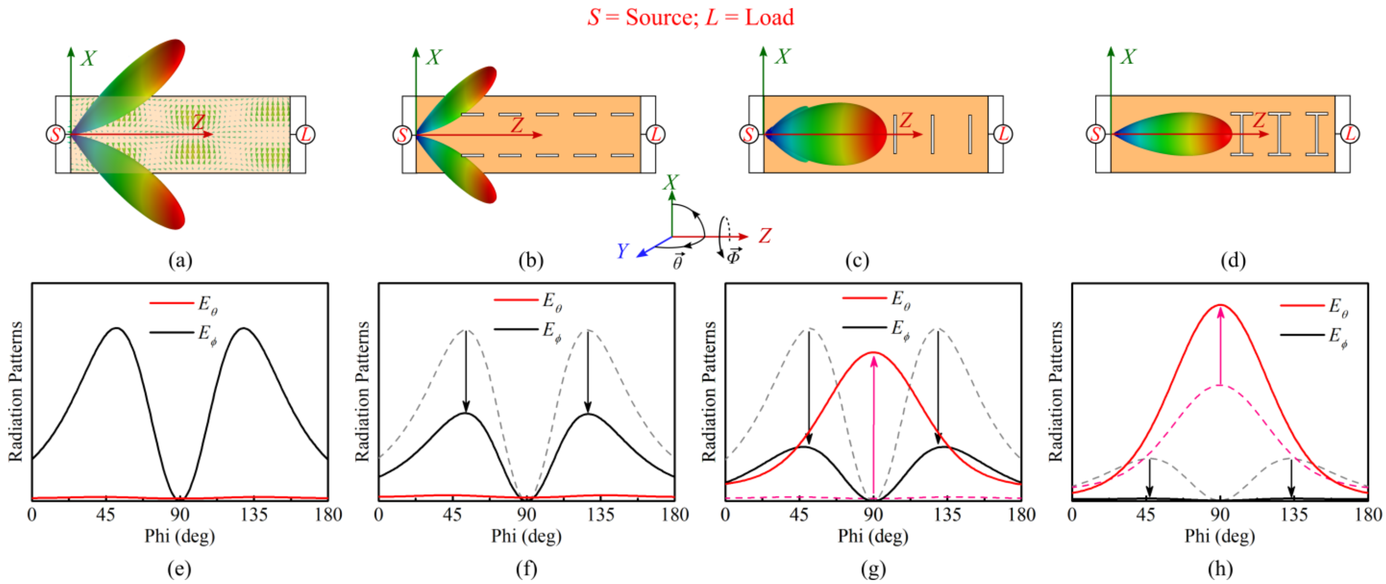


Fig. 1. Structure studied in this paper. (a) Original EH_2-mode. (b) EH_2-mode with longitudinal slots. (c) EH_2-mode with transversal slots. (d) EH_2-mode with I-shaped slots. And respective radiation patterns in an angular plane with $\theta = 45°$. (e)-(h).

coplanar waveguide (CPW) structure [17]. With two quarter-wavelength slots and two pins at the end of the microstrip, a microstrip-fed EH_2-mode LWA was proposed [18]. By employing multi-layer structure, an aperture-coupled EH_2-mode LWA was reported in [19]. To enhance the bandwidth, two rows of periodically metallic vias were loaded along the line, while a tapered feeding structure was employed to improve the impedance matching of EH_2-mode [20]. By utilizing a three-way power divider with pre-matched amplitudes and phases, the EH_2-mode was successfully excited with high radiation efficiency within a wide frequency range [21]. Moreover, a series of substrate integrated waveguide (SIW) based LWAs can realize various radiation patterns [32]-[37], such as single beam [32], [33], dual-beam [34], circularly polarized beam [35], polarization- flexible application [36], backward-to-forward scanning [37]. Notice that the EH_2-mode LWA with one main beam was studied by adding two parallel plates [38]. However, it neglects the polarization property and has high profile.

This paper presents a novel method to design a single beam LWA based on EH_2-mode. Therefore, the EH_2-mode can achieve two types of radiation patterns depending on whether the slot arrays are loaded, which has potential to design a reconfigurable antenna with flexible beam control. In this work, the I-shaped slots are periodically loaded on the strip conductor along the microstrip line to realize a single main beam in the cross-sectional center plane. The slots along the transversal direction can suppress the field of EH_0 mode and enhance cross polarization, while the slots along the longitudinal direction blocks the radiation of the original two ϕ-polarization beams of EH_2-mode. As a result, the single main radiation beam with θ-polarization is achieved in its cross section and thus provides more degree of freedom in design of a two-dimensional (2-D) LWA array consisting of several rows of transversally-arranged EH_2-mode LWA. To better understanding the leaky-wave characteristics, the numerical de-embedding technique with short-open calibration (SOC) is employed to extract the propagation parameters [39]. Compared with the quasi-uniform SIW-based LWAs with EH_1 mode, the EH_2-mode microstrip LWA can achieve higher radiation gain within a shorter length in term of guided wavelength. Finally, a prototype is fabricated and measured to validate the predicted performance of the proposed EH_2-mode LWA with single main beam in its cross-sectional plane.

II. Working Principle Through Slot Analysis

Fig. 1(a) shows the simulated current distribution of the microstrip line under the EH_2-mode excitation. One can observe that the longitudinal currents reach its maximum at the center of the line, while the transversal currents achieve its maximum at a quarter width away from the edge ends. In order to change the radiation pattern of the EH_2-mode, the loaded slots should disturb the current flow with maximum values. As shown in Fig. 1(b) and Fig. 1(c), two types of slot array are considered here, respectively, while their combination with I-shaped slot array is depicted in Fig. 1(d).

The original radiation pattern of microstrip EH_2-mode is shown in Fig. 1(e). Indeed, it has two symmetrical beams with ϕ-polarization and nearly zero θ-polarization. The dual radiation beams along ϕ-polarization is significantly reduced by cutting the longitudinal slots, while the single radiation beam along θ-polarization is significantly enhanced due to high cross-polarization by cutting the transversal slots and the beams along ϕ-polarization are obviously reduced, as shown in Fig. 1(f) and Fig. 1(g). By etching out longitudinal I-shaped slots on the strip conductor, the θ-polarized radiation can be further enhanced, while the ϕ-polarized field is keeping reduced, as shown in Fig. 1(h).

In this section, the radiation pattern variations of EH_2-mode under the loading of the transversal-, longitudinal- and I-shaped

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TAP.2019.2920260, IEEE Transactions on Antennas and Propagation

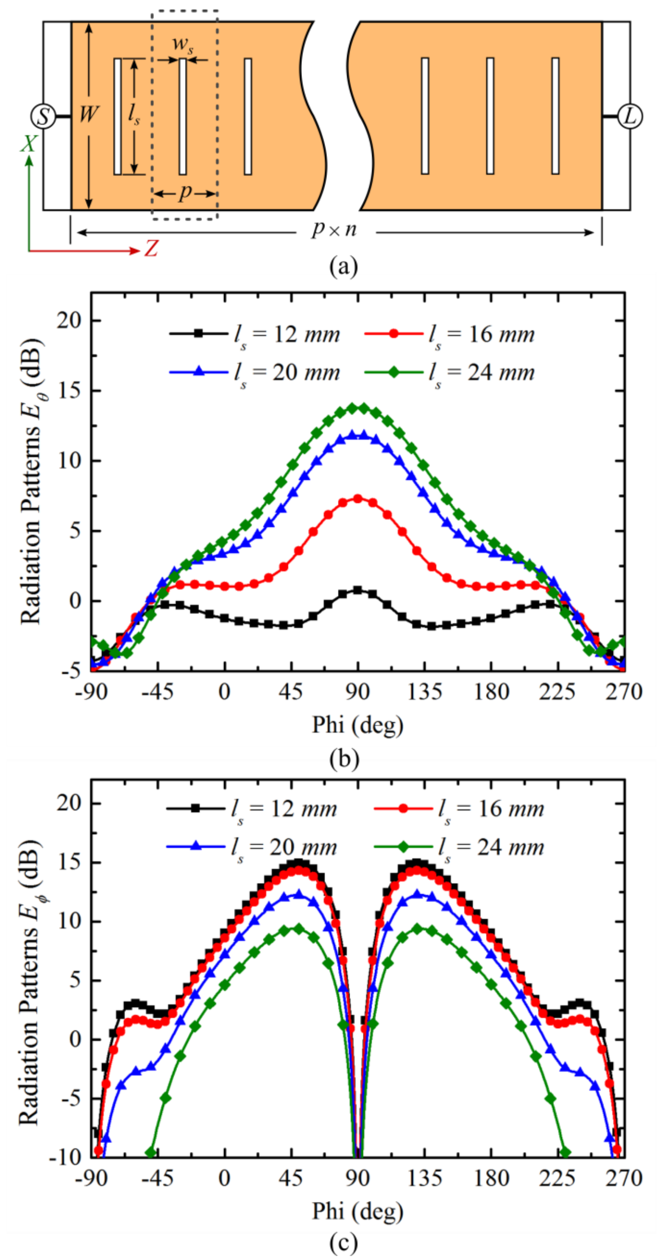


Fig. 2. (a) EH_2-mode LWA with transverse slots. (b) θ-polarization radiation patterns in H-plane with different l_s. (c) φ-polarization.

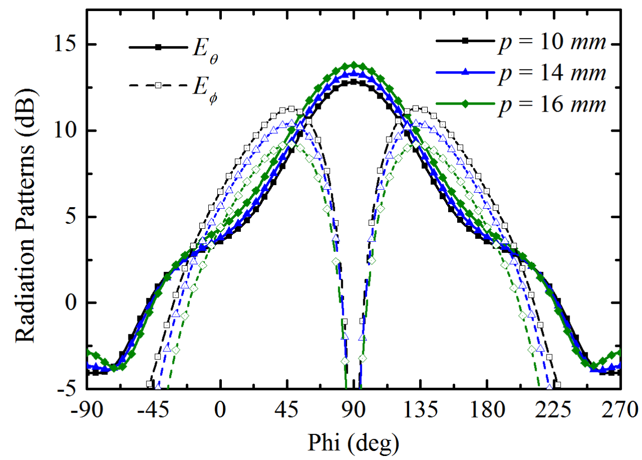


Fig. 3. Radiation patterns at H-plane with different periodicities.

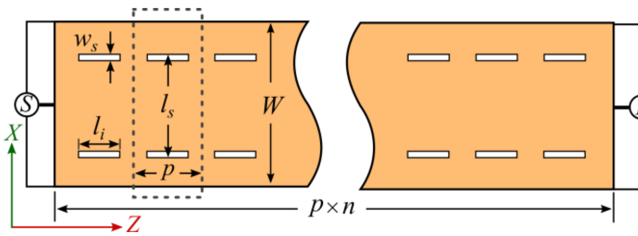


Fig. 4. EH_2-mode LWA with longitudinal slots.

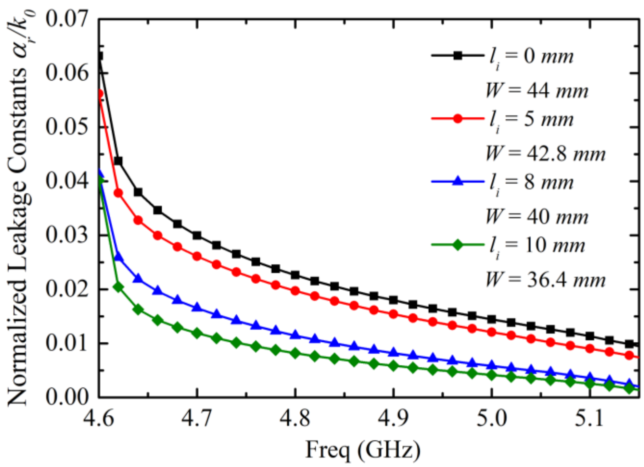
slots has been studied in detail. Notice that the EH_2-mode can be purely excited by a power divider with the pre-matched amplitudes and phase. The power divider is employed at both ends of the microstrip line, one is used as the source of the EH_2-mode and the other is used as a matched load. The feeding mechanism is explained at the end of this section, as also in the short-open calibration process.

A. Θ-Polarization Enhancement with Transversal Slots

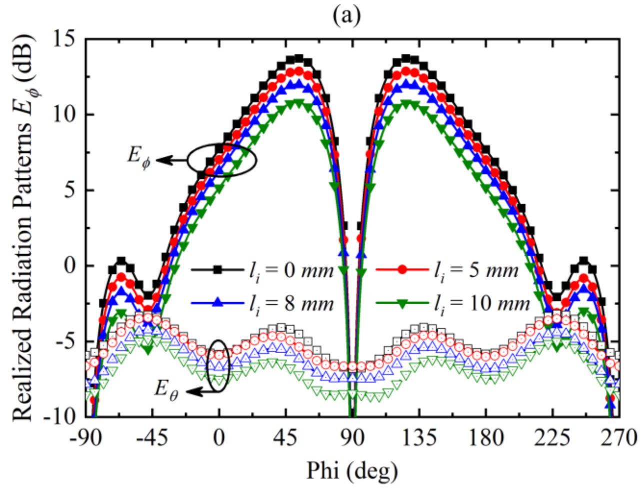
For the initial demonstration, the EH_2-mode LWA with transversal slot array is designed at 4.8 GHz, as shown in Fig. 2(a). Herein, a RT/Duroid 5880 substrate with a thickness of 0.787 *mm*, a relative permittivity of 2.2, and a loss tangent of 0.0009 is used. The strip width of the microstrip line is set with W = 44 *mm*, the length and width of the loaded slots are l_s and w_s = 1 *mm*, the periodicity of the slots is p, and the number of slots is n = 20. Hence, the total length of the microstrip LWA to be considered here is $p \times n$. Due to the loading of transversal slots, the fundamental mode, i.e., EH_0-mode, is strongly suppressed. The EH_1-mode does not exist when the feeding structure is even-symmetric. Meanwhile, EH_2-mode can be effectively excited by a suitable feeding structure with large rejection of EH_0-mode. Here, only EH_2-mode wave can propagate along the microstrip-line with pre-matched amplitudes and phase of the feeding structure [21] (The feeding mechanism is introduced at the end of this section). As the length of slots increases from 12 mm to 24 mm, the θ-polarized radiation field with one radiation beam is progressively enhanced due to the increased cross-polarization, and the maximum field at ϕ = 90° (z-direction) is increased from 0.75 dB to 13.78 dB, as illustrated in Fig. 2(b). Meanwhile, as depicted in Fig. 2(c), the ϕ-polarized radiation field with two symmetrical beams becomes weakened and the maximum fields at ϕ = 42° and ϕ = 133° are both reduced from 14.92 dB to 9.38 dB. As l_s is further increased beyond 24 *mm* (> $W_{eff}/2$), the θ-polarized radiation field gradually degrades because of enhanced interruption of reversely-oriented electric currents along the edges.

To ensure the antenna radiates from the dominant space harmonic [7], the periodicity of the slot array should be small enough with respect to the guided wavelength. The influence of different slot periodicities on radiation pattern is investigated and illustrated in Fig. 3. As the periodicity of the slots increases from 10 *mm* to 16 *mm*, the θ-polarized and ϕ-polarized

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TAP.2019.2920260, IEEE Transactions on Antennas and Propagation



(a)



(b)

Fig. 5. (a) Normalized leakage constants. (b) Realized radiation patterns with different lengths of longitudinal slots.

radiation fields have been further increased and reduced, respectively. Further increasing the slot periodicity would not contribute too much if the two-to-one beam conversion is realized. Due to this reason, the periodicity of slot array is fixed at 16 *mm* in the following sections.

B. Φ-Polarization Reduction with Longitudinal Slots

Fig. 4 depicts the geometrical configuration of the presented EH_2-mode microstrip LWA with longitudinal slots. The longitudinal slots are symmetrically mounted on the strip conductor to interrupt the transversal current of the EH_2-mode. As studied in [40], loading the longitudinal slots can effectively reduce the transverse strip width of the microstrip LWA. This technique is also workable for microstrip LWA to be presented herein. Then, it can reduce radiation power for the EH_2-mode LWA. The electric field inside the slots is pointing opposite direction to that at two sides of the microstrip line. Therefore, the resultant radiation pattern with two beams in the far-field region becomes weakened due to the field cancellation.

As shown in Fig. 5(a), the normalized leakage constants are extracted by virtue of the numerical short-open calibration (SOC) technique [39] (the SOC process is introduced at the end of this section). As the length of the slots l_i increases, the leakage constant becomes lower in the concerned frequency range or leakage band. It means that the radiation power becomes less, while the realized ϕ-polarized radiation is reduced, as shown in Fig. 5(b). Although the loading of longitudinal slots helps reduction in strip width, further increasing their length l_i may damage the current distribution of EH_2-mode and block the wave propagation as inquired.

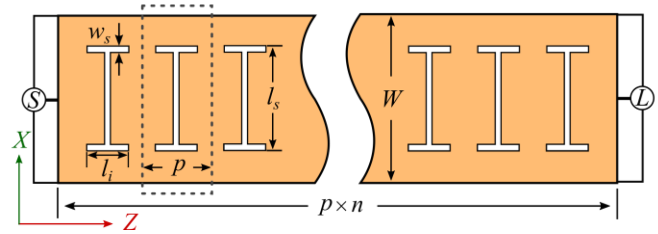


Fig. 6. EH_2-mode microstrip LWA with an array of I-shaped slots.

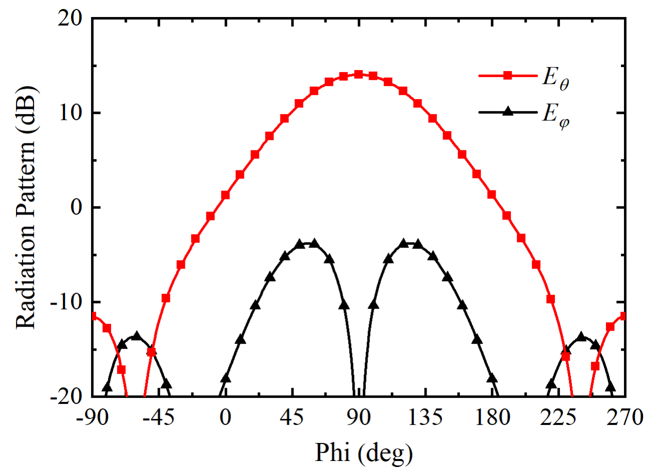


Fig. 7. Radiation patterns in H-plane of EH_2-mode microstrip LWA with an array of I-shaped slots at 4.8 GHz.

C. Proposed I-shaped Slots

To make effective use of both aforementioned advantages of the loading transversal and longitudinal slots, the I-shaped slots in Fig. 6 are comprised in final. The dimensions in the unit of *mm* are chosen with W = 36.4, w_s = 1, p = 16, l_s = 20.2, and l_i =10. Fig. 7 shows the resultant radiation field of the proposed EH_2-mode LWA with periodic I-shaped slots. It is interesting to notice that the θ-polarized field with single radiation beam in cross section reaches 16.07 dB, while the ϕ-polarized field with two radiation beams are fully suppressed below 0 dB. Hence, the resultant I-shaped slot configuration on strip conductor of the microstrip line can effectively suppress the symmetric beams and obtain a single main radiation beam in cross section.

Furthermore, the normalized dispersion diagram of the EH_2-mode propagation is numerically extracted based on the SOC technique [39]. As shown in Fig. 8, the leakage region is ranged between 4.5 GHz and 5.1 GHz. Because 4.5 GHz approaches its cutoff frequency, the operating band can be estimated to work in the range of 4.6 - 5.1 GHz. Compared to the original EH_2-mode without loaded slots, the normalized attenuation constant (α/k_0) in the leakage band (beyond the

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TAP.2019.2920260, IEEE Transactions on Antennas and Propagation

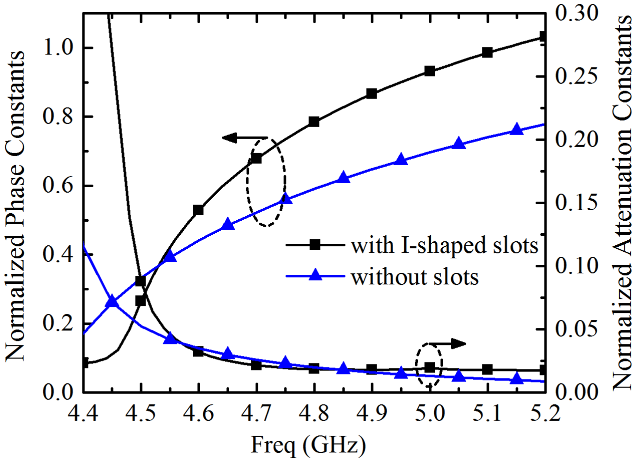


Fig. 8. Extracted normalized propagation constant α/k_0 and β/k_0 of the EH_2-mode LWAs with and without I-shaped slots.

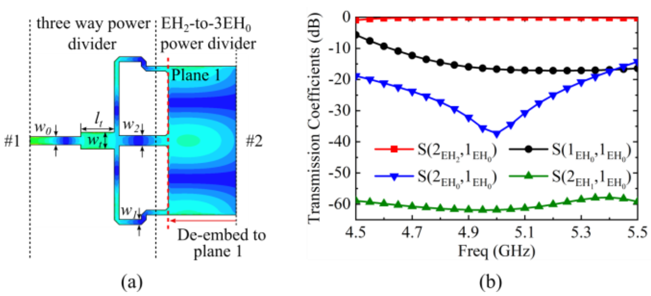


Fig. 9. (a) Configuration of the EH_0-to-EH_2 mode converter. (b) Transmission coefficients of the mode converter.

cross point of α/k_0 and β/k_0) has been indeed enlarged by periodically loading an array of I-shaped slots. Meanwhile, the slope of normalized phase constant (β/k_0) rises up in a range below the cutoff frequency, thus resulting in an enhanced frequency sensitivity in terms of radiation beam.

D. Feeding Mechanism and SOC Process

In order to ensure that only EH_2-mode is propagating in the microstrip line, the feeding structure should directly excite EH_2-mode and strongly suppress the other modes. As studied in [21], if EH_2-mode can be transferred into EH_0-mode with high efficiency, as the transformation is reversible, EH_0-mode can be transferred to EH_2-mode naturally. According to this idea, the EH_2-mode is divided into three ways of EH_0-mode as shown in Fig. 9(a). And then, a three-way power divider is used to combine them together. In order to ensure good mode conversion efficiency, the power ratio and phase distribution of the three-way power divider needs to be unchanged with the counterpart of the EH_2-to-$3EH_0$ power divider. Therefore, the three-way power ratio is set as 1:1.59:1 with the three phases 0°, 180° and 0°. Finally, a high-efficiency mode converter from EH_0-mode to EH_2-mode is obtained. As shown in Fig. 9(b), the transfer efficiency is about 94%, while the EH_0- and EH_1-mode are both highly suppressed.

Fig. 10 shows the schematic for full-wave modeling of the microstrip line with EH_2-mode feeding structure. The entire layout is classified into three distinctive sections, i.e., two

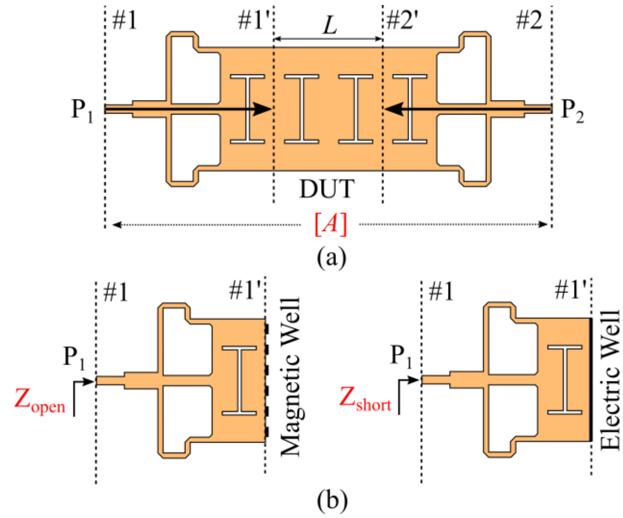


Fig. 10. (a) Schematic of EM modeling for SOC de-embedding procedure. (b) Two calibration standards in SOC.

TABLE I
DIMENSIONAL PARAMETERS OF EH_2-MODE SLOTTED MICROSTRIP LWA

Parameter	w_0	w_t	l_t	w_1	w_2
Value(mm)	2.38	4.9	1.59	1.5	3
Parameter	W	w_s	l_s	l_i	p
Value(mm)	36.4	1	20.2	10	16

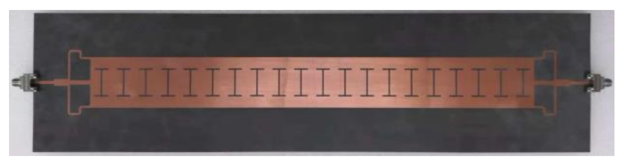


Fig. 11. Photograph of the design EH_2-mode LWA with I-shaped slots.

feeding structures in the regions of #1 - #1' and #2 - #2', and the core section with finite length (L) referred as to a DUT (DUT: device under test). P_1 and P_2 indicate the port locations, whereas #1' and #2' stand for the reference planes.

The matrix [A] ([A] = [e_1,e_2;e_3,e_4]) represents the overall ABCD matrix and it can be obtained by simulating the entire layout in Fig. 10(a). Meanwhile, the calibration standards in SOC, namely, Z_{open} and Z_{short} can be simulated by terminated electric and magnetic wells as shown in Fig. 10(b). Therefore, the complex propagation constant of DUT can be explicitly calculated in terms of the [A], Z_{open} and Z_{short} as follows:

$$\cosh(\gamma L) = \frac{(Z_{open} + Z_{short})(e_1 + e_4) - 2Z_{open}Z_{short}e_3 - 2e_2}{2(Z_{open} - Z_{short})}$$

where γ is the complex propagation constant, including the attenuation and phase constants, α and β.

III. ANTENNA DESIGN, FABRICATION AND MEASUREMENT

In order to validate the proposed LWA, a three-way power dividing structure with pre-matched amplitudes and phases is designed and then employed to excite the pure EH_2-mode along the radiating strip conductor. To effectively absorb the

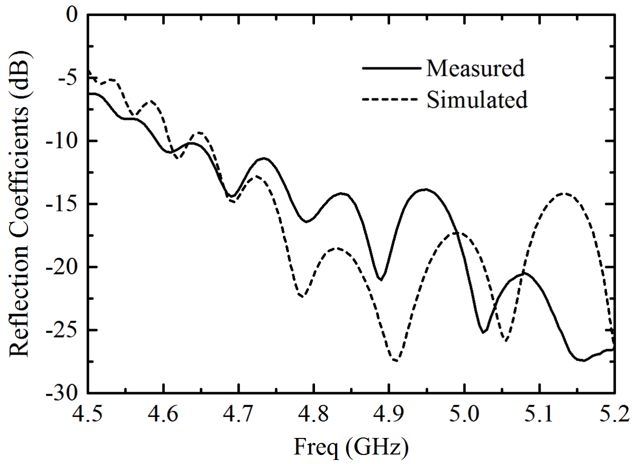


Fig. 12. Reflection coefficients of the designed EH_2-mode LWA.

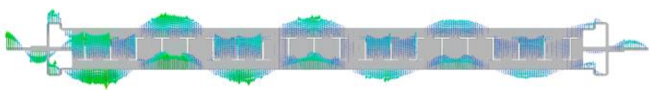


Fig. 13. Simulated electric-field distribution of the proposed EH_2-mode LWA with I-shaped slots at 4.8 GHz.

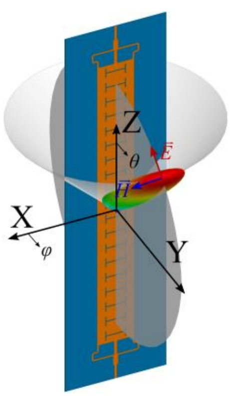


Fig. 14. Illustration of the LWA alignment in the coordinates.

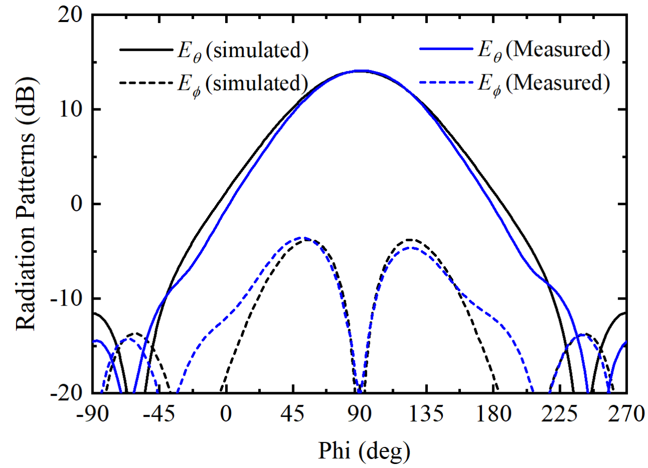


Fig. 15. Measured and simulated radiation patterns in H-plane at 4.8GHz.

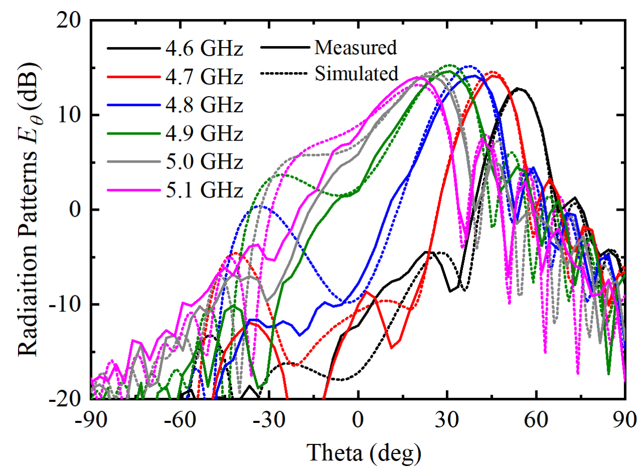


Fig. 16. Measured and simulated radiation patterns in E-plane.

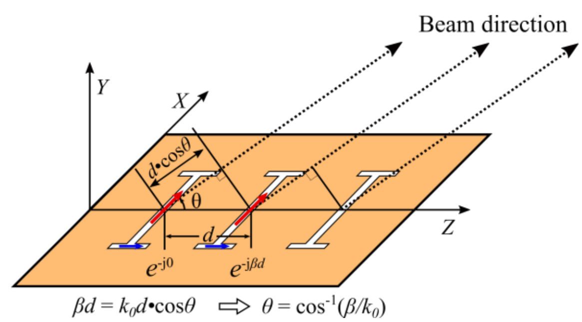


Fig. 17. A brief explanation of the beam direction of leaky wave antenna.

remaining power at the end of the LWA, the above feeding structure is installed and connected to a matching load. Fig. 11 shows the photograph of the fabricated EH_2-mode LWA with I-shaped slots. The detailed dimensional parameters are provided in Table I.

As shown in Fig. 12, the simulated and measured reflection coefficients of the designed LWA are found in reasonable agreement with each other. The measured reflection coefficient below -10 dB is ranged from 4.59 to 5.10 GHz, which means that the obtained leakage band is consistent with that of the normalized dispersion diagram as displayed in Fig. 8. Fig. 13 shows the simulated E-field distribution at 4.8 GHz. It reveals that the designed LWA is indeed working at EH_2-mode, where the E-field vector at the center is always opposite to the field vectors at two sides.

Fig. 15 and Fig. 16 depict the radiation patterns in H-plane and E-plane of the proposed LWA, respectively. The antenna under test is placed along Z-axis on XZ-plane, as shown in Fig. 14. Here, the *H*-plane is referred as to an angular region with $\theta = 40°$, while *E*-plane is defined at the center plane with $\phi = 90°$. At 4.8 GHz, the measured θ-polarized radiation pattern in H-plane achieves 14.5 dB at peak, while the ϕ-polarized far-fields are all below 0-dB over all the leakage band. As the frequency varies from 5.1 to 4.6 GHz in the leakage band, the single-main-radiation beam of proposed LWA exhibits an attractive beam scanning capability from 20° to 55° at E-plane as usually demanded. The achieved maximum gain is about 14.6 dBi at 4.9 GHz. The simulated and measured gain flatness are 2.4 dB and 2.1 dB over the leakage band, respectively.

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TAP.2019.2920260, IEEE Transactions on Antennas and Propagation

TABLE II
COMPARISON WITH QUASI-UNIFORM SIW-BASED LWA AT CENTER FREQUENCY

Reference	Slotted based on	ε_r	Antenna Size (Without fed part)	Measured Gain (Maximum)	Leaky Regain Bandwidth	Normalized Leakage Constant	Radiated Power	Radiation Efficiency (HFSS)
[32]	SIW	2.25	$1.5\lambda_0 \times 9.7\lambda_0$	9 dBi	16.2%	0.009	66%	59%
[33]	SIW	2.2	$1.5\lambda_0 \times 9.9\lambda_0$	10.5 dBi	16.2%	—	—	—
This paper	EH_2-mode	2.2	$1.6\lambda_0 \times 5.2\lambda_0$	14.6 dBi	14%	0.020	72%	91%

Notice that the beam direction is determined by the normalized phase constants, as shown in Fig. 17. Two adjacent radiation unit with distance d has a phase difference βd, and it produces a beam point to $\theta = \cos^{-1}(\beta/k_0)$. Moreover, it implies that the radiation angles of the transversal and longitudinal slots is the same.

Table II tabulates the comparison between the proposed EH_2-mode LWA and traditional quasi-uniform SIW-based LWA [32] [33]. It can be found that the proposed LWA achieve higher radiation gain with a shorter antenna length. This is mainly attributed to the role of the loaded slots with enlarged length. As shown in Table II, the leakage constant could be effectively increased, resulting to raise the radiation power and radiation efficiency along the slotted strip conductor. On the contrast, the leakage constant of θ-polarized field for the traditional quasi-uniform SIW-based LWA is relatively small, thus requiring a longer antenna length under the same requirement of radiation efficiency. In other words, the proposed EH_2-mode LWA can achieve a higher gain under the same length in total.

IV. CONCLUSION

This paper presents a novel EH_2-mode LWA with periodic I-shaped slots towards single main beam radiation in its transverse cross section. After the effects of transversal and longitudinal slots along the strip conductor are analyzed, the I-shaped slots have been finally formed up. It has been well revealed that the transversal slots mainly contribute to the enhancement of θ-polarized single-main-beam radiation, while the longitudinal slots effectively reduce the radiation intensity of two ϕ-polarized beams. As a result, the proposed EH_2-mode LWA with I-shaped slots have successfully accomplished the radiation pattern reconstruction from two beams to single main beam in its cross section. Over all the leakage band, the designed LWA have exhibited an attractive beam-scanning capability along the E-plane as well.

REFERENCES

[1] H. Ermert, “Guided modes and radiation characteristics of covered microstrip lines,” *Arch. Elektron. Uebertrag. Tech.*, vol. 30, no. 2, pp. 65-70, 1976.
[2] H. Ermert, “Guiding and radiation characteristics of planar waveguides,” *IEE J. Microw. Opt. Acoust.*, vol. 3, no. 2, pp. 59-62, Mar. 1979.
[3] W. Menzel, “A new travelling wave antenna in microstrip,” *Arch. Elektron. Uebertrag. Tech.*, vol. 33, no. 4, pp. 137-140, Apr. 1979.
[4] A. Oliner and K. Lee, “The nature of the leakage from higher modes on microstrip line,” in *IEEE MTT-S Int. Microw. Symp. Dig.*, Baltimore, MD, Jun. 1986, pp. 57-60.
[5] A. Oliner and K. Lee, “Microstrip leaky wave strip antennas,” in *IEEE Int. Antennas Propag. Symp. Dig.*, Philadelphia, PA, Jun. 1986, pp. 443-446.
[6] A. A. Oliner and D. R. Jackson, “Leaky-wave antennas,” in *Antenna Engineering Handbook*, J. L. Volakis, Ed. New York, NY, USA: McGraw-Hill, 2007, ch. 11.
[7] C. Caloz, D. R. Jackson, and T. Itoh, “Leaky-wave antennas,” in *Frontiers in Antennas*, F. B. Gross, Ed. New York, NY, USA: McGraw-Hill, 2011, ch. 9.
[8] F. Xu and K. Wu, “Understanding leaky-wave structures: a special form of guided-wave structure,” *IEEE Microwave Magazine*, vol. 14, no. 5, pp. 87-96, July-Aug. 2013.
[9] J. Liu, Y. Li, and Y. Long, “Design of periodic shorting-vias for suppressing the fundamental mode in microstrip leaky-wave antennas,” *IEEE Trans. Antennas Propag.*, vol. 63, no. 10, pp. 4297-4304, Oct. 2015.
[10] G. Zelinski, G. Thiele, M. Hastriter, M. Havrilla, and A. Terzuoli, “Half width leaky wave antennas,” *IET Microw. Antennas Propag.*, vol. 1, no. 2, pp. 341-348, Apr. 2007.
[11] Y. Lin, J. Sheen, and C. Tzuang, “Analysis and design of feeding structures for microstrip leaky-wave antenna,” *IEEE Trans. Microw. Theory Tech.*, vol. 44, no. 9, pp. 1540-1547, Sep. 1996.
[12] Y. Qian, B. Chang, T. Itoh, K. Chen, and C. Tzuang, “High efficiency and broadband excitation of leaky mode in microstrip structures,” in Proc. *IEEE Microw. Theory Tech. Dig.*, vol. 4, Anaheim, CA, Jun. 1999, pp. 1419-1422.
[13] W. Hong, T. Chen, C. Chang, J. Sheen, and Y. Lin, “Broadband tapered microstrip leaky-wave antenna,” *IEEE Trans. Antennas Propag.*, vol. 51, no. 8, pp. 1922-1928, Aug. 2003.
[14] G.-F. Cheng and C.-K. C. Tzuang, “A differentially excited coupled half-width microstrip leaky EH_1-mode antenna,” *IEEE Trans. Antennas Propag.*, vol. 61, no. 12, pp. 5885-5892, Dec. 2013.
[15] D. Xie, L. Zhu, X. Zhang, and N. W. Liu, “Gain-enhanced EH_1-mode microstrip leaky wave antenna with periodical loading of shorting pins,” *IET Microw. Antennas Propag.*, vol. 12, no. 2, pp. 230-236, Jan. 2018.
[16] D. Xie and L. Zhu, “Microstrip leaky-wave antennas with non-uniform periodical loading of shorting pins for enhanced frequency sensitivity,” *IEEE Trans. Antennas Propag.*, vol. 66, no. 7, pp. 3337-3335, Jul 2018.
[17] Y. Lin, P. Chi, and T. Chen, “Design of the feeding structures for the excitation of the microstrip line second higher order mode leaky wave antenna,” in *Proc. IEEE Antennas Propag. Soc. Int. Symp. Dig.*, Jul. 1997, pp. 1142-1145.
[18] T. Chen, Y. Lin, and J. Sheen, “Microstrip-fed microstrip second higher order leaky-mode antenna,” *IEEE Trans. Antennas Propag.*, vol. 49, no. 6, pp. 855-857, Jun. 2001.
[19] T. Chen and Y. Lin, “Aperture-coupled microstrip second higher order leaky-mode antenna,” in *Proc. Asia Pacific Microw. Conf.*, Aug. 2001, pp. 1060-1063.
[20] D. Karmokar, K. Esselle, and T. Bird, “Wideband microstrip leaky-wave antennas with two symmetrical side beams for simultaneous dual-beam scanning,” *IEEE Trans. Antennas Propag.*, vol. 64, no. 4, pp. 1262-1269, Apr. 2016.
[21] P. F. Zhang and S. Sun, “A novel feeding structure for second higher order mode excitation of microstrip leaky wave antenna,” in *Proc. IEEE Antennas Propag. Soc. Int. Symp. Dig.* Jul. 2017, pp. 291-292.
[22] D. K. Karmokar and K. P. Esselle, “Periodic U-slot-loaded dual-band half-width microstrip leaky-wave antennas for forward and backward beam scanning,” *IEEE Trans. Antennas Propag.*, vol. 63, no. 12, pp. 5372–5381, Dec. 2015.
[23] M. H. Rahmani and D. Deslandes, “Backward to forward scanning periodic leaky-wave antenna with wide scanning range,” *IEEE Trans. Antennas Propag.*, vol. 65, no. 7, pp. 3326-3335, Jul. 2017.
[24] Y. -L. Lyu, F. -Y. Meng, G. -H. Yang, P. -Y. Wang, Q. Wu and K. Wu, “Periodic leaky-wave antenna based on complementary pair of radiation elements,” *IEEE Trans. Antennas Propag.*, vol. 66, no. 9, pp. 4503–4515, Sep. 2018.

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TAP.2019.2920260, IEEE Transactions on Antennas and Propagation

[25] A. Al-Bassam, S. Otto, D. Heberling, and C. Caloz, "Broadside dual-channel orthogonal-polarization radiation using a double-asymmetric periodic leaky-wave antenna," *IEEE Trans. Antennas Propag.*, vol. 65, no. 6, pp. 2855–2864, Jun. 2017.

[26] S. Lim, C. Caloz, and T. Itoh, "Metamaterial-based electronically controlled transmission-Line structure as a novel leaky-wave antenna with tunable radiation angle and beamwidth," *IEEE Trans. Microw. Theory Tech.*, vol. 53, no. 1, pp. 161-173, Jan. 2005.

[27] S. Paulotto, P. Baccarelli, F. Frezza, and D. R. Jackson, "Full-wave modal dispersion analysis and broadside optimization for a class of microstrip CRLH leaky-wave antennas," *IEEE Trans. Microw. Theory Tech.*, pp. 2826–2837, Dec. 2008.

[28] A. Grbic, and G. V. Eleftheriades, "Leaky CPW-based slot antenna arrays for millimeter-wave applications," *IEEE Trans. Antennas Propag.*, vol. 50, no. 11, pp. 1494–1504, Jun. 2002.

[29] D. R. Smith, O. Yurduseven, L. P. Mancera and P. Bowen, "Analysis of a waveguide-fed metasurface anatenna," *Phys. Rev. Appl.*, vol. 8, no. 5, 2017, Art. no. 054048.

[30] 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, Jan. 2015.

[31] L. M. Pulido-Mancera, T. Zvolensky, F. Imani, P. T. Bowen, M. Valayil and D. R. Smith, "Discrete dipole approximation applied to highly directive slotted waveguide antennas," *IEEE Antennas Wireless Propag. Lett.*, vol. 15, pp. 1823–1826, 2016.

[32] J. Liu, D. R. Jackson, and Y. Long, "Substrate integrated waveguide (SIW) leaky-wave antenna with transverse slots," *IEEE Trans. Antennas Propag.*, vol. 60, no. 1, pp. 20–29, Jan. 2012.

[33] Y. Mohtashami and J. Rashed-Mohassel, "A butterfly substrate integrated waveguide leaky-wave antenna," *IEEE Trans. Antennas Propag.*, vol. 62, no. 6, pp. 3384–3388, Jun. 2014.

[34] 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, Feb. 2010.

[35] Y. L. Lyu, F. Y. Meng, G. H. Yang, D. Erni, Q. Wu, and K. Wu, "Periodic SIW leaky-wave antenna with large circularly polarized beam scanning range," *IEEE Antennas Wireless Propag. Lett.*, vol. 16, pp. 2493–2496, 2017.

[36] Y. Dong and T. Itoh, "Substrate integrated composite right-/left-handed leaky-wave structure for polarization-flexible antenna application," *IEEE Trans. Antennas Propag.*, vol. 60, no. 2, pp. 760–771, Feb. 2012.

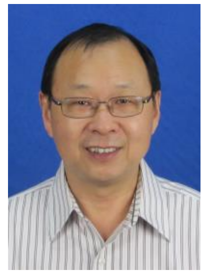
[37] J. Liu, W. Zhou, and Y. Long, "A simple technique for open stop-band suppression in periodic leaky-wave antennas using two nonidentical elements per unit cell," *IEEE Trans. Antennas Propag.*, vol. 66, no. 6, pp. 2741-2751, Jun. 2018.

[38] J. L. Gomez-Tornero, D. Caete-Rebenaque, and A. Alvarez-Melcon, "Microstrip leaky wave antenna with control of leakage rate and only one main beam in the azimuth plane," *IEEE Trans. Antennas Propag.*, vol. 56, no. 2, pp. 335-344, Feb. 2008.

[39] Z. Liu, L. Zhu, G. Xiao, and Q. -S. Wu, "An effective approach to deembed the complex propagation constant of half-mode SIW and its application," *IEEE Trans. Compon., Packag., Manuf. Technol.*, vol. 6, no. 1, pp. 109–116, Jan. 2016.

[40] X. Zhang, L. Zhu, and Q. -S. Wu, "Sidelobe-reduced and gain-enhanced square patch antennas with adjustable beamwidth under TM_{03} mode operation," *IEEE Trans. Antennas Propag.*, vol. 66, no. 4, pp. 1704–1713, Apr. 2018.

Peng-fei Zhang (S'15) received the B.Eng. degree from the University of Electronic Science and Technology of China, Chengdu, China, in 2015, where he is currently pursuing the Ph.D. degree in electromagnetics and microwave technology. His research interests include planer leaky-wave antennas and array antenna.



Lei Zhu (S'91–M'93–SM'00–F'12) received the B.Eng. and M.Eng. Degrees in radio engineering from the Nanjing Institute of Technology (now Southeast University), Nanjing, China, in 1985 and 1988, respectively, and the Ph.D. Degree in electronic engineering from the University of Electro-Communications, Tokyo, Japan, in 1993.

From 1993 to 1996, he was a Research Engineer with Matsushita-Kotobuki Electronics Industries Ltd., Tokyo, Japan. From 1996 to 2000, he was a Research Fellow with the École Polytechnique de Montréal, Montréal, QC, Canada. From 2000 to 2013, he was an Associate Professor with the School of Electrical and Electronic Engineering, Nanyang Technological University, Singapore. He joined the Faculty of Science and Technology, University of Macau, Macau, China, as a Full Professor in August 2013, and has been a Distinguished Professor since December 2016. From August 2014 to August 2017, he served as the Head of Department of Electrical and Computer Engineering, University of Macau. So far, he has authored or coauthored more than 480 papers in international journals and conference proceedings. His papers have been cited more than 6100 times with the H-index of 41 (source: ISI Web of Science). His research interests include microwave circuits, periodic structures, planar antennas, and computational electromagnetic techniques.

Dr. Zhu was the Associate Editors for the IEEE TRANSACTIONS ON MICROWAVE THEORY AND TECHNIQUES (2010-2013) and IEEE MICROWAVE AND WIRELESS COMPONENTS LETTERS (2006-2012). He served as a General Chair of the 2008 IEEE MTT-S International Microwave Workshop Series on the Art of Miniaturizing RF and Microwave Passive Components, Chengdu, China, and a Technical Program Committee Co-Chair of the 2009 Asia–Pacific Microwave Conference, Singapore. He served as the member of IEEE MTT-S Fellow Evaluation Committee (2013-2015), and has been serving as the member of IEEE AP-S Fellows Committee (2015-2017). He was the recipient of the 1997 Asia–Pacific Microwave Prize Award, the 1996 Silver Award of Excellent Invention from Matsushita-Kotobuki Electronics Industries Ltd., and the 1993 First-Order Achievement Award in Science and Technology from the National Education Committee, China.

Sheng Sun (S'02–M'07–SM'12) received the B.Eng. degree in information engineering from Xi'an Jiaotong University, Xi'an, China, in 2001, and the Ph.D. degree in electrical and electronic engineering from Nanyang Technological University (NTU), Singapore, in 2006.

From 2005 to 2006, he was with the Institute of Microelectronics, Singapore. From 2006 to 2008, he was a Post-Doctoral Research Fellow with NTU. From 2008 to 2010, he was a Humboldt Research Fellow with the Institute of Microwave Techniques, University of Ulm, Ulm, Germany. From 2010 to 2015, he was a Research Assistant Professor with The University of Hong Kong, Hong Kong. Since 2015, he has been a Full Professor with the

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TAP.2019.2920260, IEEE Transactions on Antennas and Propagation

University of Electronic Science and Technology of China, Chengdu, China. He has authored or co-authored 1 book and 2 book chapters, and over 160 journal and conference publications. His current research interests include electromagnetic theory, computational mathematics, multiphysics, numerical modeling of planar circuits and antennas, microwave passive and active devices, and the microwave- and millimeter-wave communication systems.

Dr. Sun was a recipient of the ISAP Young Scientist Travel Grant, Japan, in 2004, the Hildegard Maier Research Fellowship of the Alexander Von Humboldt Foundation, Germany, in 2008, the Outstanding Reviewer Award of the IEEE MICROWAVE AND WIRELESS COMPONENTS LETTERS in 2010, and the General Assembly Young Scientists Award from the International Union of Radio Science in 2014. He was a co-recipient of the several Best Student Paper Awards of international conferences. He was an Associate Editor of the *IEICE Transactions on Electronics* from 2010 to 2014 and a Guest Associate Editor of the *Applied Computational Electromagnetics Society Journal* in 2017. Dr. Sun is currently a member of the Editor Board of the *International Journal of RF and Microwave Computer Aided Engineering* and serves as an Associate Editor for IEEE MICROWAVE AND WIRELESS COMPONENTS LETTERS.