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# A Leaky-Wave Antenna Array With Beam-Formed Radiation Pattern for Application in a Confined Space

**YUNJIE GENG, JUNHONG WANG, (Senior Member, IEEE), ZHENG LI, (Member, IEEE), YUJIAN LI, (Member, IEEE), MEIE CHEN, AND ZHAN ZHANG**

Key Laboratory of All Optical Network and Advanced Telecommunication Network of MOE, Beijing Jiaotong University, Beijing 100044, China
Institute of Lightwave Technology, Beijing Jiaotong University, Beijing 100044, China

Corresponding author: Junhong Wang (wangjunh@bjtu.edu.cn)

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**ABSTRACT** A substrate integrated waveguide (SIW) leaky-wave antenna (LWA) array with beam-formed radiation pattern is investigated in this paper. The array is composed of two LWA elements with different parameters of slots. For each LWA, the period of slots is selected first within the scope of only $n = -1$ space harmonic radiation to ensure the beam radiate in the desired direction. Then, the length of the slots is tapered according to the binomial aperture distribution to get the wide beam. Finally, the width of the slots is adjusted to get the desired radiation field strength. By superposing two wide beams from two elements in a weighting way, a cosecant-squared-like beam-formed radiation pattern is realized, which is preferable for the application of uniform radio wave coverage in a long straight confined space. The array is fabricated and measured, and the measured results are consistent with the simulated results.

**INDEX TERMS** Antenna array, beam-formed radiation pattern, confined space, leaky-wave antenna (LWA), substrate integrated waveguide (SIW).

## I. INTRODUCTION

Leaky-wave antennas (LWAs) have attracted much attentions due to their features of high gain, simple feeding network and frequency scanning capability [1], [2]. Substrate integrated waveguide (SIW) technology was proposed for its advantages of low profile and easy to be integrated with planar circuits [3]–[5]. It's well known that the radiation patterns of LWAs can be synthesized by controlling the leakage constant and phase constant along the structure, such as side lobe level (SLL) suppression [6], [7], radiation nulls generation [8], [9], and desired shapes beamforming [9]–[11]. Therefore, SIW LWAs are the good candidates for many applications of communication systems.

Traditionally, the antennas used in a confined space have omnidirectional radiation patterns, so the radio wave coverage in the confined space attenuates fast [12], [13], especially for the long straight confined space, such as tunnels and corridors. Therefore, if the uniform radio wave coverage is expected, antenna with beam-formed radiation pattern should be studied. For a long straight confined space, the ideal e-filed radiation pattern should meet a cosecant-squared distribution, as shown in Fig. 1.

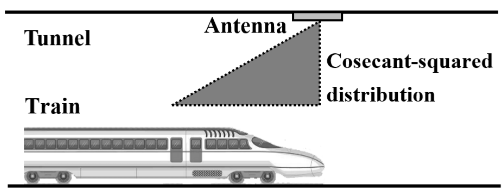


**FIGURE 1.** Diagram of the beam-formed antenna with cosecant-squared radiation pattern mounted in a tunnel.

In our previous works, the idea of superposing radiations from the $n = -1$ space harmonics of different periodic leaky-wave structures was proposed [14], a LWA array with broad-beam pattern [15] and a beam-formed LWA with the composite cosine-shaped slot [16] were designed based on this idea. In this paper, utilizing the same idea, a periodic

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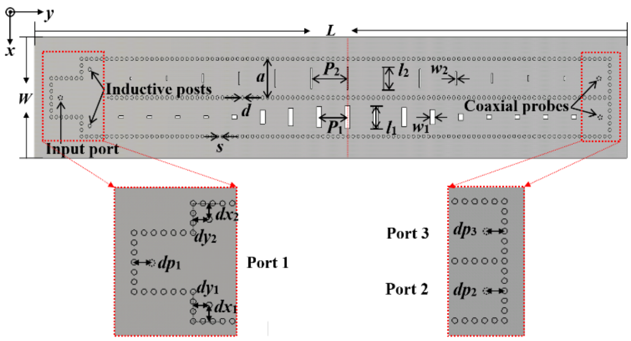


**FIGURE 2.** Geometry of the beam-formed SIW LWA array: $L = 188$ mm, $W = 30$ mm, $a = 9.6$ mm, $d = 0.9$ mm, $s = 1.6$ mm, $dp_1 = dp_2 = dp_3 = 3$ mm, $dx_1 = dx_2 = dy_1 = dy_2 = 2.6$ mm (Not in scale).

slotted SIW LWA array with beam-formed radiation pattern is investigated for the application of uniform radio wave coverage in a long straight confined space. Compared with the beam-formed LWA with composite cosine-shaped slot proposed in [16], this array not only has the simpler design procedures, but also realizes a wider coverage area combined by only two beams, which are widened by tuning the length of slots according to the binomial aperture distribution. The design procedures of the array are given in Section II. The simulated and measured results are shown in Section III. The conclusions are drawn in Section IV.

## II. ANTENNA GEOMETRY AND DESIGN

Fig. 2 demonstrates the geometry of the proposed beam-formed array, which is composed of two SIW LWA elements and a two-way SIW power divider with two inductive posts in the bends. There are totally three ports (port 1, 2 and 3) in the array, all of them are connected by the coaxial probes with impedance of 50 Ω. Port 1 is in the beginning of the array and is used as the input port, port 2 and 3 are in the end of the array and are terminated with matching loads. The operating frequency is 15 GHz. The length and width of the whole array are $L = 188$ mm and $W = 30$ mm, respectively. The substrate is Rogers RO3003 with thickness of $h = 1.524$ mm and dielectric constant of $\varepsilon_r = 3$. The width of SIW is $a = 9.6$ mm, the diameter of metallic via is $d = 0.9$ mm and the spacing between adjacent vias is $s = 1.6$ mm. Both two elements have the same waveguide configuration, but the parameters of transverse slots etched on their top walls are different. The period, length and width of their slots are denoted by $P_n$, $l_n$ and $w_n$, respectively, where $n = 1, 2$, representing the number of two elements, as shown in Fig. 2.

### A. PERIOD OF SLOTS

According to the application requirements considered in this paper, the radiation field of antenna is expected to uniformly cover the long straight confined space. Fig. 3(a) gives the ideal cosecant-squared distribution as stated above, where $\theta$ is the wide angle of radio wave covered region, $E$ is the normalized e-field in a certain direction (e-field in the broadside direction is selected as the reference value). Fig. 3(b) shows the cosecant-squared-like beam-formed E-pattern based on the idea of superposing two wide beams with different directions ($\theta_1 = -45°$, $\theta_2 = -15°$) from two LWAs in a weighting way. As we can see, the radiation pattern is formed by two wide beams (by tapering the length of slots $l_n$), pointing to different directions $\theta_n$ (by selecting the period of slots $P_n$), and with different e-field strengths $E_n$ (by adjusting the width of slots $w_n$).

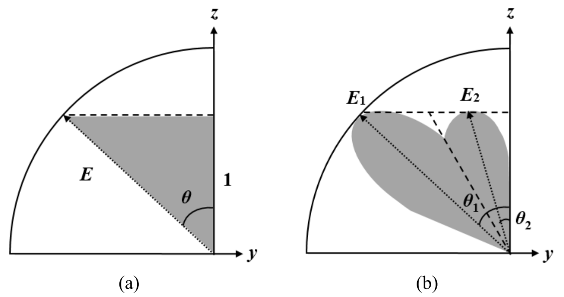


**FIGURE 3.** (a) Ideal cosecant-squared distribution, (b) beam-formed cosecant-squared-like E-pattern.

As we know that, a periodic structure can generate infinite space harmonics, and only those with smaller propagation constant (compared with that in free space) can leak away from the structure [17]. In this design, the $n = -1$ space harmonic is designed to radiate, and the beam direction can be changed by varying the period of slots within the scope of mono-harmonic radiation. Therefore, the conditions of slots periods $P_n$ that both two LWAs are working on only $n = -1$ space harmonic radiation mode, and with different beam directions $\theta_n$, are calculated by [17]:

$$\lambda_0/\left(\sqrt{\varepsilon_g}+1\right) < P < 2\lambda_0/\left(\sqrt{\varepsilon_g}+1\right) \tag{1}$$

$$\theta_{-1} = \sin^{-1}\left(\sqrt{\varepsilon_g} - \lambda_0/P\right) \tag{2}$$

where $\lambda_0$ is the wavelength in free space, and $\varepsilon_g$ is the equivalent dielectric constant of the leaky structure, which can be approximately expressed by [17]:

$$\varepsilon_g \approx \varepsilon_r - (\lambda_0/\lambda_c)^2 \approx \varepsilon_r - \left(\lambda_0/2w_{eff}\right)^2 \tag{3}$$

where $\lambda_c$ is the cut off wavelength of $TE_{10}$ mode in the closed waveguide and $w_{eff}$ is the effective width of SIW which can be obtained by the expression given in [5]. After many times of simulated optimizations, the periods of slots are finally selected to be $P_1 = 9$ mm and $P_2 = 11.5$ mm, respectively.

### B. LENGTH OF SLOTS

In this subsection, the length of each slot of the two LWAs is designed to make the aperture amplitude distribution to satisfy a binomial distribution $A(y)$, which can generate the radiation pattern with wide beam. The design steps for two elements are the same. The number of transverse slots $N_n$ ($n = 1, 2$) is calculated first in terms of waveguide length and the period of slots, so we get: $N_1 = 17$ and $N_2 = 13$. Then the curve of aperture distribution $A_n(y)$ can be fitted based

**TABLE 1.** The length of each slot for the first LWA ($n = 1$).

| $N_1$ | 1st | 2nd | 3rd | 4th | 5th | 6th | 7th |
|---|---|---|---|---|---|---|---|
| $l_1$(mm) | 0.50 | 0.50 | 0.50 | 0.50 | 1.03 | 3.43 | 4.45 |
| $N_1$ | 8th | 9th | 10th | 11th | 12th | 13th | 14th |
| $l_1$(mm) | 5.29 | 5.71 | 5.53 | 4.77 | 3.67 | 1.70 | 1.00 |
| $N_1$ | 15th | 16th | 17th | | | | |
| $l_1$(mm) | 1.00 | 1.00 | 1.00 | | | | |

**TABLE 2.** The length of each slot for the second LWA ($n = 2$).

| $N_2$ | 1st | 2nd | 3rd | 4th | 5th | 6th | 7th |
|---|---|---|---|---|---|---|---|
| $l_2$(mm) | 0.50 | 1.22 | 2.22 | 3.22 | 4.40 | 5.22 | 5.61 |
| $N_2$ | 8th | 9th | 10th | 11th | 12th | 13th | |
| $l_2$(mm) | 5.42 | 4.65 | 3.46 | 2.46 | 1.46 | 1.00 | |

on the normalized binomial coefficients [15] and the leakage constant $\alpha_n(y)$ can be calculated from [1]:

$$\alpha(y) = \frac{0.5 \times \left|A(y)^2\right|}{\frac{1}{\eta}\int_{-L/2}^{L/2}\left|A(\zeta)^2\right|d\zeta - \int_{-L/2}^{y}\left|A(\zeta)^2\right|d\zeta} \quad (4)$$

Usually, the leakage constant is physically determined by the parameters of slots. Here, in order to figure out the relationship between the leakage constant and the length of slots, a series of LWAs with different slot length are simulated first, and other parameters of slots are fixed. After the simulations, the results of leakage constant $\alpha_n(l)$ versus the length of slots $l_n$ are obtained. Finally using this relationship, the length of each slot $l_n$ at different position $y_n$ can be easily acquired by the leakage constant required at this position. For the two LWAs, the length of each slot at different position along the propagation direction is given in Table 1 and Table 2, respectively.

### C. WIDTH OF SLOTS

The width of slots $w_n$ can be adjusted to get the desired e-field strength $E_n$, so it can be used as a weighting factor (depends on the beam-formed radiation pattern) in the superposition of radiation beams from the two LWAs. First, we need to find the relationship between $w_n$ and $E_n$, so another series of LWAs with the selected slot period and the tapered slot length, but different slot width are simulated for both two elements. Then, by taking the Fourier transform of the aperture amplitude distribution, we can find the Fourier coefficient of $n = -1$ space harmonic $A^n_{-1}$, which reflects the e-field strength $E_n$ directly. Consequently, the relationships between $A^n_{-1}$ and $w_n$ for the two LWAs can be obtained, which are plotted in Fig. 4.

As can be seen from Fig. 3(b), for the two beams, the ratio between the beam direction $\theta_n$ and corresponding e-field strength $E_n$ is:

$$E_1 : E_2 = \sec\theta_1 : \sec\theta_2 \quad (5)$$

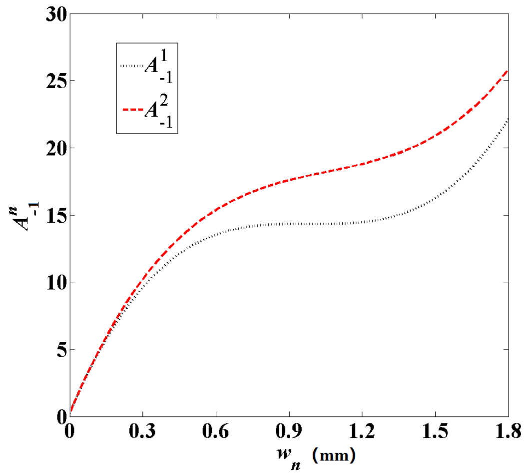


**FIGURE 4.** Variatios of the Fourier coefficients of the $n = -1$ space harmonic $A^n_{-1}$ as functios of slot width $w_n$ for the two LWAs ($n = 1, 2$).

Due to the proportional relationship between $E_n$ and $A^n_{-1}$, formula (5) can be rewritten as:

$$A^1_{-1} : A^2_{-1} = \sec\theta_1 : \sec\theta_2 \quad (6)$$

Combining formula (6) and Fig. 4, the width of slots $w_n$ can be easily acquired, in other words, the weighting factor of two beams can be found. As we know, larger slot width will generate stronger radiation, but the impedance matching will get worse. Therefore, we finally get: $w_1 = 1.52$ mm and $w_2 = 0.35$ mm, which are the optimized results after many times of simulation in consideration of the impedance matching and radiation efficiency.

## III. RESULTS AND DISCUSSION

Two SIW LWAs with slot period of $P_1 = 9$ mm and $P_2 = 11.5$ mm, tapered slot length as given in Table 1 and 2, and same slots widths $w_1 = w_2 = 1$ mm, are first simulated respectively. The other two SIW LWAs with the uniform slot length $l_1 = l_2 = 5$ mm (other structure parameters are same as the above two antennas) are also simulated for comparison. The E-plane normalized gain patterns at 15GHz of the first and second LWA are given in Fig. 5(a) and (b) respectively. It is obvious to see that, two LWAs have different beam directions, which are caused by the selection of slot period. Moreover, by tuning the length of slots in a tapered way, both beams have been widened and the SLLs have been suppressed, so it can provide a wider radio wave coverage compared with the uniform slotted LWAs.

Fig. 6 shows the photographs of fabricated beam-formed SIW LWA array. Simulated and measured $S$-parameters of the proposed beam-formed LWA array are plotted in Fig. 7 (a) and (b), respectively. As we can see that, there are some discrepancies between the simulated and measured results, especially for reflection coefficient. Due to the errors caused by the process of coaxial probe feeding structure soldering and measurement, the measured return los is not as good as the simulated result. The measured $|S_{11}|$ surpassed

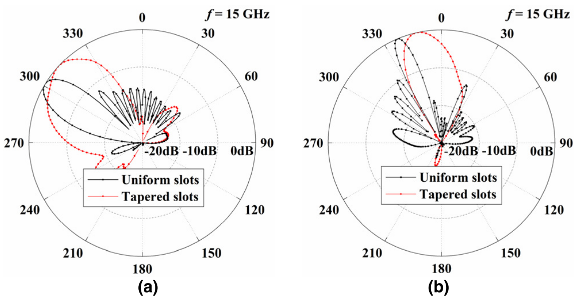


**FIGURE 5.** Simulated *E*-plane normalized gain patterns of the two SIW LWAs with uniform slots and tapered slots respectively (f = 15GHz): (a) the first LWA (*n* = 1), (b) the second LWA (*n* = 2).

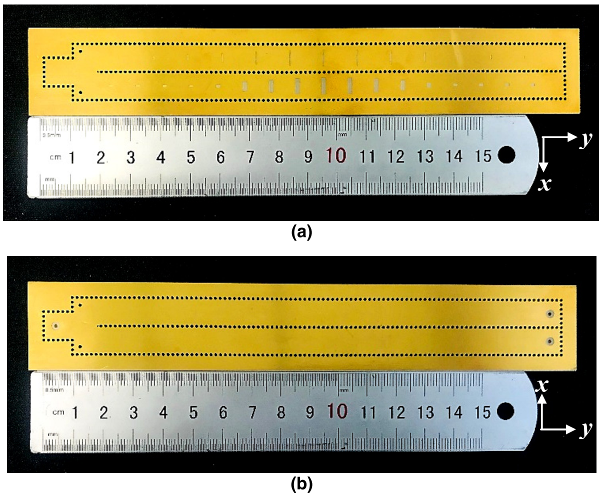


**FIGURE 6.** Photographs of the fabricated beam-formed SIW LWA array: (a) top view, (b) back view.

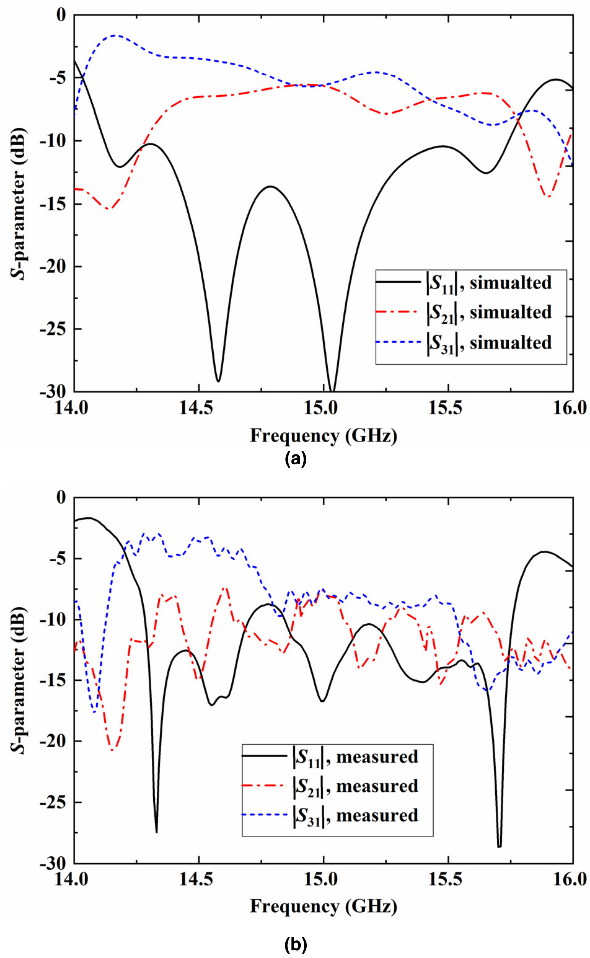


**FIGURE 7.** *S*-parameters of the beam-formed SIW LWA array: (a) simulated results, (b) measured results.

−10dB at around 14.75GHz, which breaks the frequency into two bands. This would be avoided by the fine-tuning of fabricated feed structure.

Fig. 8 plots the simulated and measured radiation patterns of this array at the operating frequency of 15 GHz. Fig. 8 (a) shows the simulated e-filed radiation pattern in E-plane, from which we can see that, the distribution of e-field is close to the ideal cosecant-squared pattern, we can call it the cosecant-squared-like beam-formed pattern. The simulated and measured normalized co-pol and cross-pol gain patterns in E-plane are shown in Fig. 8(b) and (c) respectively. It should be noted that, there are some ripples in the measured curve, which are probably caused by the weak receiving signal and environment noise injection, some discrepancies between the simulated and measured results. Except for the fabrication tolerances in structure parameter and the test errors in measurement process, the main beams of simulated and measured patterns are in reasonable consistency. Fig. 8(d) gives the simulated normalized co-pol and cross-pol gain patterns in H-plane (passing through the maximum radiation direction). Since only two LWA elements in $x$ direction is used to shape the pattern in E-plane, the array has the typical fan-like beam pattern in H-plane as indicated in [1].

Due to the frequency-scanning capability of LWAs, when the frequency changes, the beam direction and beam width of the two elements will change too, so that the beam-formed pattern will deteriorate accordingly and deviate from the desired design. Fig. 9 shows the simulated and measured E-plane radiation patterns of the beam-formed SIW LWA array at different frequencies. As can be observed, when the frequency changes from 14.8 GHz to 15.5GHz, corresponding to the beam angle scans from −53° to −40°, the array maintains the cosecant-squared-like beam-formed pattern basically, so the pattern bandwidth of this array is about 4.7%. This demonstrates that the proposed antenna array with beam-formed radiation pattern is only suitable for narrow band application in a confined space.

Fig. 10 summaries the simulated and measured peak gain and efficiency of the beam-formed SIW LWA array at different frequencies. Due to the discrepancies between the simulated and measured results of *S*-parameters as we stated above, the measured gain is lower than the simulation as shown in Fig. 10(a). Due to the limit of our experimental conditions, the radiation efficiency is not easy to be measured accurately, so only the simulated radiation efficiency $\eta_{rad}$.(corresponding to the "Tot. Efficiency" in the

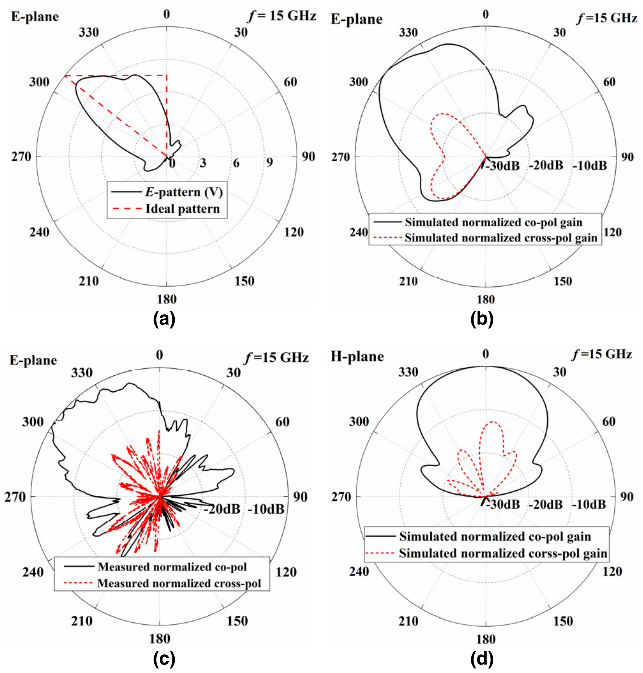


**FIGURE 8.** Simulated and measured radiation patterns of the beam-formed SIW LWA array at 15 GHz: (a) simulated e-field radiation pattern in E-plane, (b) simulated normalized co-pol and cross-pol gain patterns in E-plane, (c) measured normalized co-pol and cross-pol gain patterns in E-plane, (d) simulated normalized co-pol and cross-pol gain patterns in H-plane (passing through the maximum radiation direction).

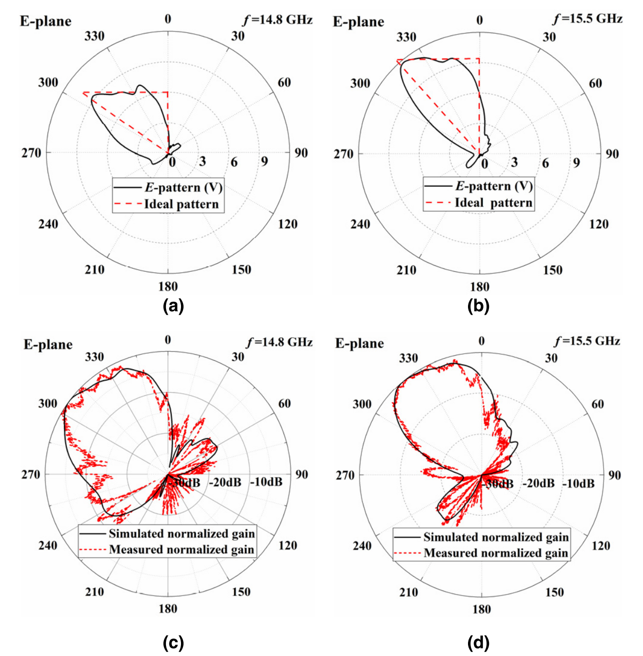


**FIGURE 9.** Simulated and measured radiation patterns in E-plane of the beam-formed SIW LWA array at different frequencies: (a) simulated e-field radiation pattern at 14.8 GHz, (b) simulated e-field radiation pattern at 15.5 GHz, (c) simulated and measured normalized gain patterns at 14.8 GHz, (d) simulated and measured normalized gain patterns at 15.5 GHz.

CST Microwave Studio) is given in Fig. 10(b). Meanwhile, the simulated and measured total power ratio for dissipation and radiation $\eta_{total} = 1-|S_{11}|^2-|S_{21}|^2-|S_{31}|^2$, is also given

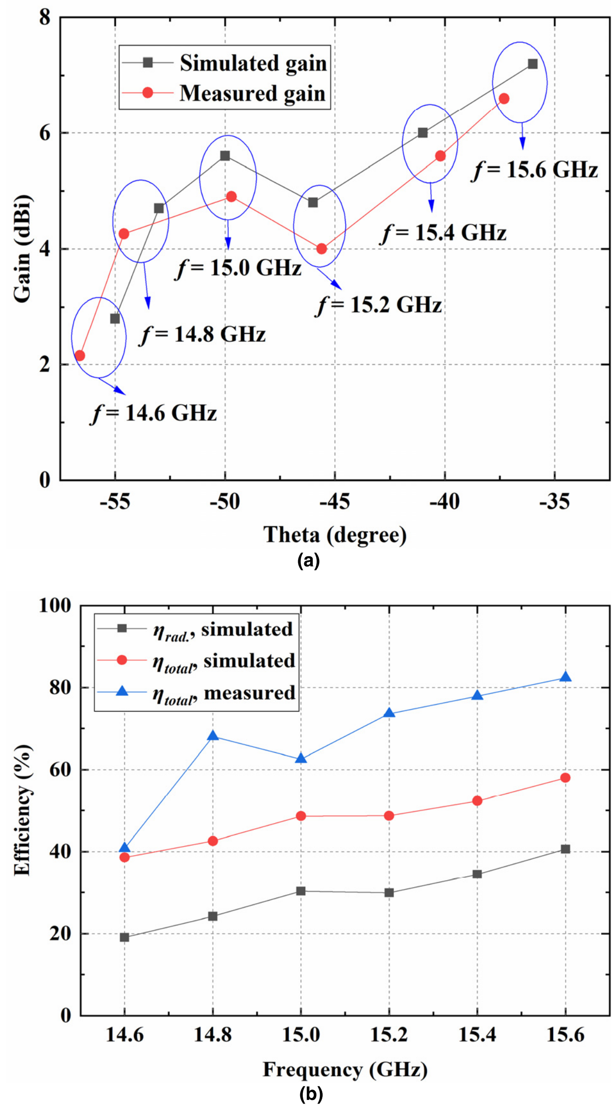


**FIGURE 10.** Simulated and measured peak gain and efficiency of the beam-formed SIW LWA array at different frequencies: (a) peak gain, (b) efficiency.

for comparison. As can be seen, the measured $\eta_{total}$ is higher than the simulated one, this is mainly because of the coaxial probe feeding connectors, which cause additional losses in the measurement, so the measured transmission coefficients $|S_{21}|$ and $|S_{31}|$ are lower than the simulated results, as shown in Fig. 7(b).

## IV. CONCLUSION

A SIW LWA array with cosecant-squared-like beam-formed radiation pattern for application in a confined space is designed, fabricated and measured. The beam-formed pattern is realized by superposing radiations from the $n = -1$ space harmonics of two LWA elements in a weighting way. First by selecting different slot periods of two LWAs, the two beams are oriented in different directions, and then they are broadened by tapering the slot lengths, finally radiated with different e-field strengths by adjusting the slot widths.

The simulated and measured results are in reasonable agreements, which validate the effectiveness of the proposed method. Moreover, the beam-formed method used in this paper is more clear and simple compared with the traditional data-driven method. However, this method still has some limitations, for example, the radiation pattern doesn't perfectly match the ideal distribution because the mutual coupling between the two beams are not considered, which needs to be further studied in the future works.

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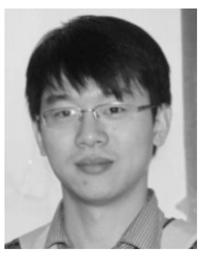
**YUNJIE GENG** was born in Hebei, China, in 1992. She received the B.S. degree in communications engineering from Beijing Jiaotong University, Beijing, China, in 2015, where she is currently pursuing the Ph.D. degree in electrical engineering.

From 2018 to 2019, she was a Visiting Student with the Poly-Grames Research Center, Polytechnique Montréal (University of Montreal), QC, Canada. Her current research interest includes leaky-wave antennas and arrays. She has served as a Reviewer for the IEEE Antennas and Wireless Propagation Letters, IEEE Access, and the *International Journal of Antennas and Propagation*.

**JUNHONG WANG** (M'02–SM'03) was born in Jiangsu, China, in 1965. He received the B.S. and M.S. degrees in electrical engineering from the University of Electronic Science and Technology of China, Chengdu, China, in 1988 and 1991, respectively, and the Ph.D. degree in electrical engineering from Southwest Jiaotong University, Chengdu, China, in 1994. In 1995, he joined the Beijing Jiaotong University, Beijing, China, where he became a Professor, in 1999. From 1999 to 2000, he was a Research Associate with the Department of Electric Engineering, City University of Hong Kong, Kowloon Tong, Hong Kong. From 2002 to 2003, he was a Research Scientist with Temasek Laboratories, National University of Singapore, Singapore. He is currently with the Key Laboratory of all Optical Network and Advanced Telecommunication Network, Ministry of Education of China, Beijing Jiaotong Univeristy, and also with the Institute of Lightwave Technology, Beijing Jiaotong University. His research interests include numerical methods, antennas, scattering, and leaky wave structures.

**ZHENG LI** (M'15) received the B.S. degree in physics and the Ph.D. degree in electrical engineering from Beijing Jiaotong University, Beijing, China, in 2006 and 2012, respectively.

From 2008 to 2009, he was a Visiting Student with Pennsylvania State University, Pennsylvania, USA. From 2017 to 2018, he was a Visiting Professor with the Global Big Data Technologies Centre, University of Technology Sydney, Australia. In 2012, he joined the faculty of the Department of Electrical Engineering, Beijing Jiaotong University, where he became an Associate Professor, in 2015. His research interests include electrically beam scanning antennas and leaky-wave antennas.



**YUJIAN LI** (S'12-M'15) was born in Hunan, China, in 1987. He received the B.S. and M.S. degrees in communications engineering from Beijing Jiaotong University, Beijing, China, in 2009 and 2012, respectively, and the Ph.D. degree in electronic engineering from the City University of Hong Kong, in 2015.

He joined the Institute of Lightwave Technology, Beijing Jiaotong University, in 2015, as an Associate Professor. His current research interests include millimeter wave antennas, base station antennas, and leaky wave structures. He received the Outstanding Research Thesis Award from the City University of Hong Kong, in 2015. He received the Best Paper Award at the 2015 IEEE Asia-Pacific Conference on Antennas and Propagation (APCAP), the Best Student Paper at 2013 National Conference on Antennas, and the Best Student Paper Award (Second Prize) at the 2013 IEEE International Workshop on Electromagnetics (iWEM). He was selected as a Finalist in the Student Paper Contest of 2015 IEEE AP-S Symposium on Antennas and Propagation (APS). He has served as a Reviewer for the IEEE Transactions on Antennas and Propagation, the IEEE Antennas and Wireless Propagation Letters, and the *IET Microwaves, Antennas and Propagation*.

**MEIE CHEN** received the B.S. degree in information and telecommunication engineering and the Ph.D. degree in electromagnetic and microwave technology from Beijing Jiaotong University, Beijing, China, in 2003 and 2009, respectively.

She is currently a Lecturer with the Institute of Lightwave Technology, Beijing Jiaotong University. Her research interests include antenna theory and technology, metasurface, and RCS reduction technique.

**ZHAN ZHANG** received the B.S. degree in electronics and communications engineering from Jilin University, China, in 2002, and the Ph.D. degree in electrical engineering from Nanyang Technological University, Singapore, in 2010. She joined the faculty of School of Electronics and Information Engineering, Beijing Jiaotong University, Beijing, China, in 2010, where she is currently an Associate Professor. Her current research interests include metamaterial-based antenna design and transformation optics.