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Compact High Gain Leaky-Wave Antennas Based on Substrate Integrated Waveguide TE_{220} Mode

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ABSTRACT In this paper, novel compact high gain broadband leaky-wave antenna (LWA) using TE_{220} high-order mode is proposed. The high-order mode antenna not only possesses more compact structure with higher gain, but also simplifies the feeding network of the antenna array and relaxes processing tolerance. The radiation element consists of an SIW cavity etched with 2×2 slot array on the top surface, which is excited by a microstrip-slot coupling structure. Microstrip spoof surface plasmon polariton (SPP) is worked as a slow-wave transmission line (TL) to increase the beam scanning range of a four elements periodic array antenna. The antenna was simulated, optimized and fabricated, which verified theoretical analysis. Experimental results show that the linearly polarized (LP) beam scanning antenna has a bandwidth of 53.5% (from 12.6 GHz to 21.8 GHz) with beam scanning range from $-24°$ to $+32°$ and gain in the range of 10.2 dBi to 12.4 dBi. Then a linear-to-circular polarization converter is loaded to implement a circular polarization (CP) beam scanning antenna. The proposed antenna has the features of compact size, low profile, high gain, large beam scanning range and flexible polarization conversion.

INDEX TERMS Beam scanning antenna, spoof surface plasmon polariton, high gain, high-order mode.

I. INTRODUCTION

With the rapid development of satellite communication and wireless communication, beam scanning antenna with compact size, low profile, high gain and wide scanning range has been widely used [1]. As a basic type of beam steering antenna, leaky-wave antenna (LWA) has attracted more attention because of its low profile, compact size, low cost and easy integration with planar circuits [2]–[6]. However, the LWA has an inherent disadvantage that radiation efficiency is not high, resulting in low gain. Traditional methods of increasing gain include increasing element number or loading lenses. However, it results in the increase of antenna size and profile thickness, which is not desirable [1], [7].

Wide scanning range is required for beam scanning antennas. For traditional right-handed (RH) LWAs, they only have an ability of forward scanning with limited scanning range. Then composite right/left-handed (CRLH) transmission line (TL) was investigated to realize beam steering from backward directions to forward directions [8]–[10]. Furthermore, a bending structure can also be used to enhance the phase shift and increase the beam scanning range by increasing the length of TLs between adjacent radiating elements [7], [11]. In addition, another way to increase the beam scanning range is to use slow-wave TLs feeding structure [12]–[15]. The TL structure with slow-wave dispersion characteristics can produce larger phase difference between adjacent radiation elements within the same frequency band, thus enlarging the beam scanning range. In recent years, spoof surface plasmon polariton (SPP) slow-wave TL that can excite electromagnetic wave generated by the coupling of free electrons and light waves have received more research.

However, all traditional frequency beam scanning antennas mentioned above are designed based on low-order modes (fundamental modes) element antennas. The higher-order modes antenna not only possesses more compact structure with higher gain, but also simplifies the feeding network of the antenna array and relaxes processing tolerance.

In standard printed circuit board (PCB) technology, the radius and spacing of metallized vias of substrate integrated waveguide (SIW) become electrically large at high frequencies. The higher the frequency, the more difficult in

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processing [16]. For this reason, high-order modes in SIW provide a good solution to this problem because the simplified structure reduces the number of metallized vias and relaxes processing tolerance [17]–[20]. In addition, the high-order modes in SIW possess higher gain than fundamental ones with the same size. In [17], a left hand circular polarization (LHCP) antenna fed by TE_{220} mode is proposed with simple feeding network can achieve a maximum gain of 11 dBi. A 3×3 slot cavity antenna based on TE_{330} mode with maximum gain about 13.8 dBi is obtained in [18]. Furthermore, a low-profile CP SIW cavity antenna is designed on TE_{440} mode with an antenna gain of about 16dBi in [19]. Therefore, we consider using the high-order modes in SIW with slots etched on top surface as radiation elements to design LWA with high gain performance.

A novel compact high gain broadband beam scanning antenna is proposed based on TE_{220} mode in SIW technology in this paper. The antenna is excited by a microstrip-slot coupling structure and electromagnetic wave is coupled out of SIW cavity with 2×2 slot array etched on the top surface. Spoof SPP slow-wave TL is worked as a feeding structure to increase the beam scanning range of the four elements periodic array structure. Then a polarization converter is loaded to generate CP property. The following sections will give the detailed design steps and theoretical analysis of the antenna.

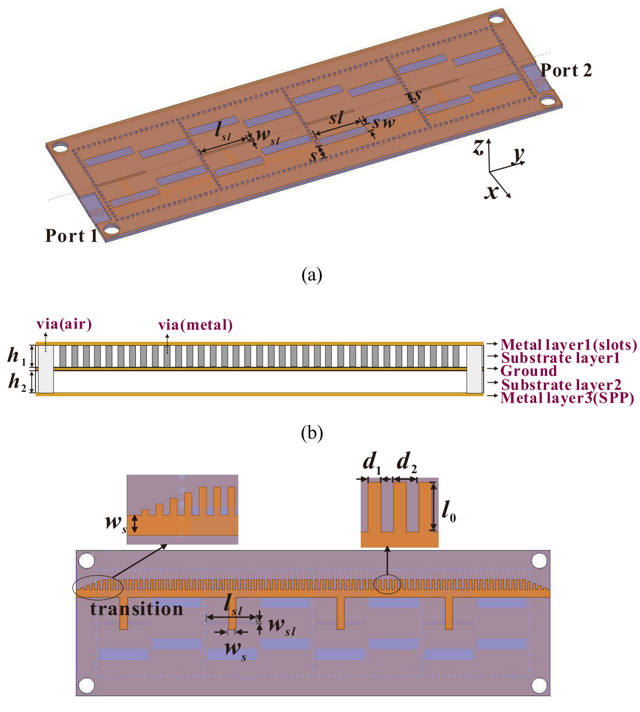
II. LINEARLY POLARIZED BEAM SCANNING ANTENNA

Fig. 1 shows the structure diagram of the proposed linear polarization (LP) beam scanning antenna. It consists of two substrates made by F4BM PCB ($\varepsilon_r = 2.2$, $\tan\delta = 0.001$). The up layer is a mode excitation structure. And the bottom layer is worked as the feeding layer. As shown in Fig. 1 (c), spoof SPP TL is etched on the back of the bottom layer as feeding structure. Both dielectric slabs own thickness of 0.508mm.

A. RADIATING ELEMENT

Fig. 2 shows the electric field and surface current distribution of a TE_{220} mode inside an SIW cavity. Ideally, 2 × 2 standing waves should be equally spaced in a square SIW cavity. The TE_{220} mode SIW can be equivalent to two parallel fundamental mode waveguides, and each two adjacent modes have the same amplitude but opposite phase [16]. Configuration of the radiation element is shown in Fig. 3. Corresponding to the 2 × 2 standing wave in the cavity, the 2 × 2 slot array is etched on the surface of the SIW cavity and thus a slotted radiator is formed. The longitudinally adjacent radiating slots are spaced at half-waveguide wavelength, which result in 180° phase difference, and are alternately placed on either side of the centerline to introduce another 180° phase difference. Therefore, adjacent radiating slots are fed in phase, and the radiating element obtains a broadside radiating pattern.

Excitation schemes for the SIW high-order modes were proposed in [16]–[19]. There are basically two feeding types. One type is a coaxial probe. But it is difficult to tune the location of the feed point and the bandwidth is usually limited. Another type is the microstrip-slot coupling type, which



(a)
(b)
(c)

FIGURE 1. Configuration of LP beam scanning antenna: (a) perspective view; (b) side view; (c) bottom layer.

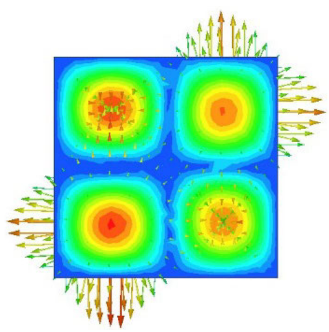


FIGURE 2. Distributions of the E-field and J_{surf} of the SIW TE_{20} mode.

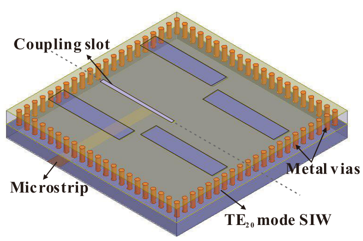


FIGURE 3. Configuration of the proposed radiation element.

possesses wider impedance bandwidth. As shown in Fig. 3, a coupling slot is employed along the central axis of the SIW cavity to excite the TE_{220} mode. The length and width of coupling slot are l_{sl} and w_{sl}, respectively. The radiation element consists of two substrates and three copper layers.

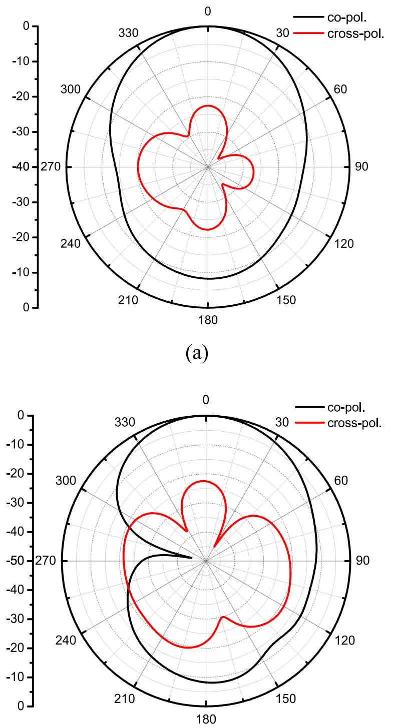


FIGURE 4. Radiation patterns of the proposed antenna element at 14.5 GHz: (a) *xoz*-plane; (b) *yoz*-plane.

2 × 2 slot array is etched on the top copper layer to radiate electromagnetic waves. The length and width of radiating slots are *sl* and *sw*, respectively. And an offset of each radiating slot with respect to the longitudinal center line is *s*. The coupling slot is etched on the middle copper layer, which is the metallic ground. And the microstrip line is printed on the bottom copper layer. The SIW is formed by a metal wall consisting of periodically arranged metallized vias between the top and middle copper layers. So the energy is fed by microstrip-slot coupling structure and TE_{220} mode is formed in SIW.

TABLE 1. Parameters of the proposed antenna (unit: mm).

sl	*sw*	*s*	*dl*	*dw*	p_0	*dr*	*α*	*lc*
9.2	2	3	6.4	2.2	1.02	0.5	45°	20
p	***h***	l_{sl}	w_{sl}	w_s	d_1	d_2	l_0	dl_0
20.4	2	9.2	0.4	1.4	0.5	1	2	4

The overall volume of the radiation element is $1\lambda_0 \times 1\lambda_0 \times 0.05\lambda_0$. Table 1 gives the specific parameters of the unit antenna. Radiation patterns in *xoz*-plane and *yoz*-plane at 14.5GHz are depicted in Fig. 4 (a) and (b), respectively. As shown, the antenna element realizes broadside radiation. At the same time, the antenna has low cross polarization on both planes, which are lower than −22dB.

B. THE FEEDING TL AND LINEARLY POLARIZED (LP) BEAM SCANNING ANTENNA

In order to realize beam scanning antenna, cascaded four radiation elements are introduced and fed in phase at the central frequency f_0. As shown in Fig. 1 (c), the spoof SPP TL is etched on the bottom copper layer of the antenna. It consists of microstrip line and metal strips arranged periodically on one side of it. In order to match a feeding port of 50Ω better, the width of the microstrip line is set as $w_s = 1.4$mm. The width and length of the metallic strips are d_1 and l_0, respectively. The periodic of spoof SPP structure is d_2.

Simulated dispersion characteristics of spoof SPP unit and microstrip line unit are described in Fig. 5. The dispersion curves of both TLs are in slow-wave region, and spoof SPP has larger phase difference property than microstrip line within the same frequency band. Therefore, compared with microstrip line, adjacent radiation units fed by spoof SPP TL can possess a larger phase difference, thus improving the beam scanning range.

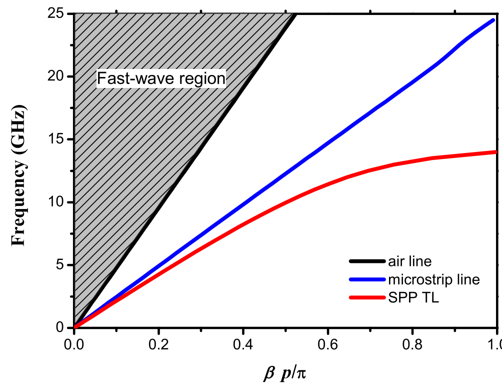


FIGURE 5. Dispersion curves of the spoof SPP unit and microstrip line.

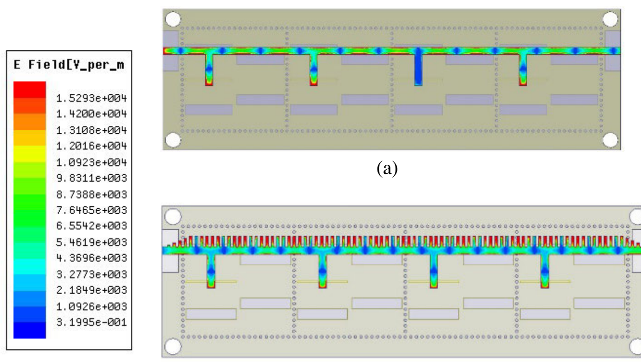
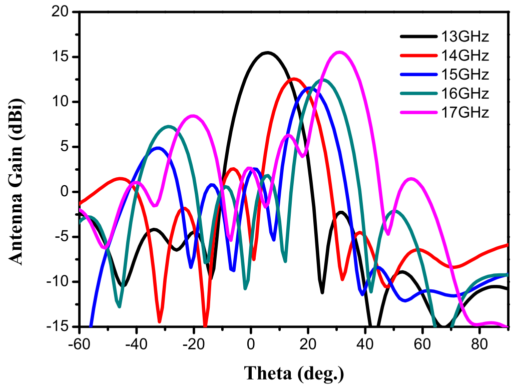
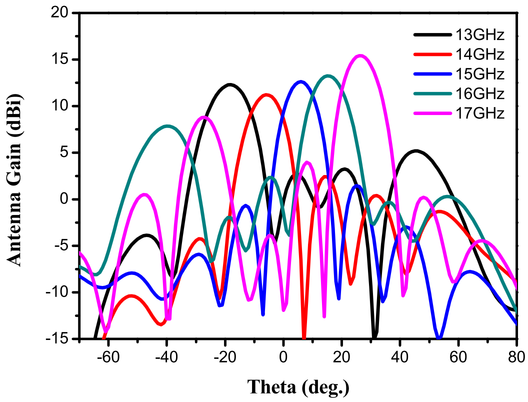


FIGURE 6. Electric-field distributions at 14.5 GHz: (a) microstrip line; (b) spoof SPP TL.

As shown in Fig. 6, the simulation results of electric field distribution at 14.5 GHz for two TLs are presented. Because of the slow-wave characteristic, the wavelength of the spoof SPP TL is significant reduced in comparison with that of the microstrip line. It can be seen that the radiation units are

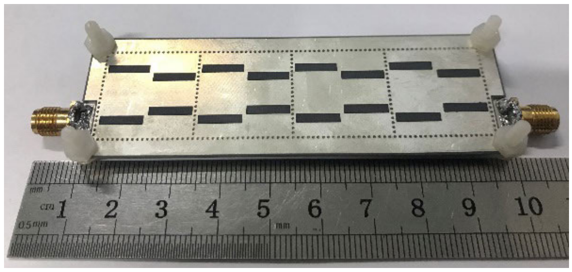


(a)

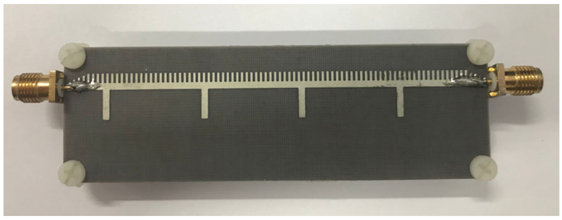


(b)

FIGURE 7. **Comparison of radiation patterns for LP LWA fed by (a) microstrip line and (b) spoof SPP TL.**



(a)



(b)

FIGURE 8. **Prototype of the fabricated LP beam scanning antenna: (a) forward side; (b) back side.**

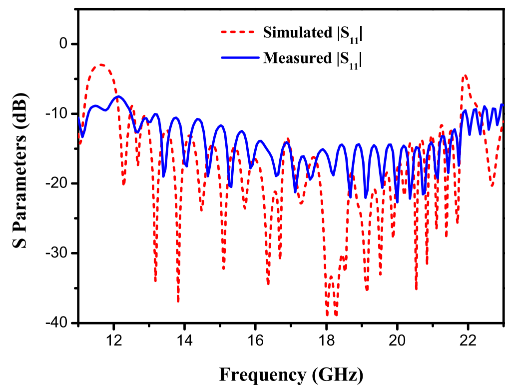


FIGURE 9. **Simulated and experimental S11 of the proposed LP LWA.**

fed in phase of the spoof SPP TL. The simulated radiation patterns in *yoz*-plane of the structure fed by two TLs are compared in Fig. 7. Fig. 7 shows that the antenna fed by spoof SPP possesses a beam scanning range from −19° to +32° within the operating band from 13 GHz to 17 GHz, while the scanning range of the microstrip line fed antenna is scanned from +6° to +33°. Comparison of simulation results show that the scanning range is increased about two times by using the spoof SPP TL.

C. EXPERIMENTAL VERIFICATION

The proposed LP beam scanning antenna was simulated, optimized and fabricated to verify theoretical analysis. Fig. 8 shows the prototype of the fabricated LP LWA. The antenna has compact structure and low profile characteristics. The two layers are fabricated individually. Plastic screws are used to fix them.

Fig. 9 exhibits the simulated and experimental S_{11} of the LP LWA. It shows that the two curves are in good agreement. A slight difference between the two curves may be caused by fabrication inaccuracy. The measured impedance bandwidth of -10dB is from 12.6 GHz to 21.8 GHz (53.5%).

The simulated and experimental radiation patterns in *yoz*-plane are shown in Fig. 10. The curves are in good agreement with scanning range from −24° to +32°. Compared with the simulated maximum gains of the radiation patterns vary from 11.4 dBi to 13.5 dBi, the experimental ones vary from 10.2 dBi to 12.4 dBi. The results are acceptable within the range of fabrication errors.

The major contribution of this paper is to realize the beam scanning antenna with compact size, low profile, high gain and wide angle by using a TE_{220} high-order cavity mode as radiation elements. Comparisons of experimental results between the proposed antenna and the former designs are shown in Table 2. The antenna size is described by the electrical size. The antennas designed in [4] and [6] are basic LWA, which etch orthogonal slot pairs on the surface of SIW to generate continuous beam scanning. However, the design of this paper achieves higher gain with a more compact size by using a TE_{220} high-order cavity mode as radiation elements. The unit cell of [8] and [10] consists of orthogonal interdigital slots, which provides a CRLH property and also effectively reduce the size of the structure. But the design of

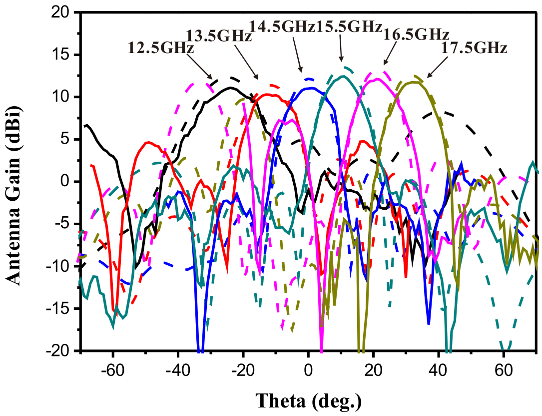


FIGURE 10. Simulated (dashed line) and experimental (solid line) radiation patterns of the proposed LP LWA.

TABLE 2. Comparisons between the proposed antenna and the former ones.

Ref.	Frequency range (GHz)	Max gain (dBi)	Beam scanning range	Number of unit cells	Antenna size: L*W (λ_0)
[4]	9-14(43.4%)	12	-40°-+35°	19	7.6*0.76
[6]	15.4-19(20.9%)	12.3	+35°-+47°	22	6.8*0.6
[8]	4.2-4.85(14.4%)	2.5	-25°-+26°	5	5.0*0.4
[10]	7.35-10.15(32%)	8.95	-19°-+84°	14	5.6*0.8
[15]	12-16.5(31.6%)	9.5	-5°-+37°	8	5.2*0.8
proposed	12.6-21.8(53.5%)	12.4	-24°-+32°	4	4.0*1.0

this paper achieves higher gain than the former design in a more compact antenna size. Moreover, the design achieves a wider impedance bandwidth by using microstrip-slot coupling structure. The design principle in [15] is similar to ours, cascaded antenna elements are fed in-phase at central frequency to achieve beam scanning. Through the comparison we can get that the proposed antenna has higher gain with smaller electrical size. At the same time, it possesses wider impedance bandwidth and certain beam scanning range.

III. CIRCULARLY POLARIZED BEAM SCANNING ANTENNA

A. ANTENNA CONFIGURATION

Compared with LP beam scanning antenna, CP antenna has the ability to reduce the influence of multipath reflection and rain fog interference, but its design is more complex.

However, the above LP beam scanning antenna can be easily converted into CP by loading a layer of polarization converter above it, which is separated by an air layer ($h = 2$mm), as shown in Fig. 11. The polarization converter is composed of microstrip dipole arrays with the same number of radiation slots. The microstrip dipole rotates at an angle of α from the y-axis relative to the radiation slot. The length and width of the dipole are dl and dw, respectively. The dipole array is etched on the same substrate mentioned above with thickness $h_3 = 0.508$mm ($\varepsilon_r = 2.2$, tan$\delta = 0.001$).

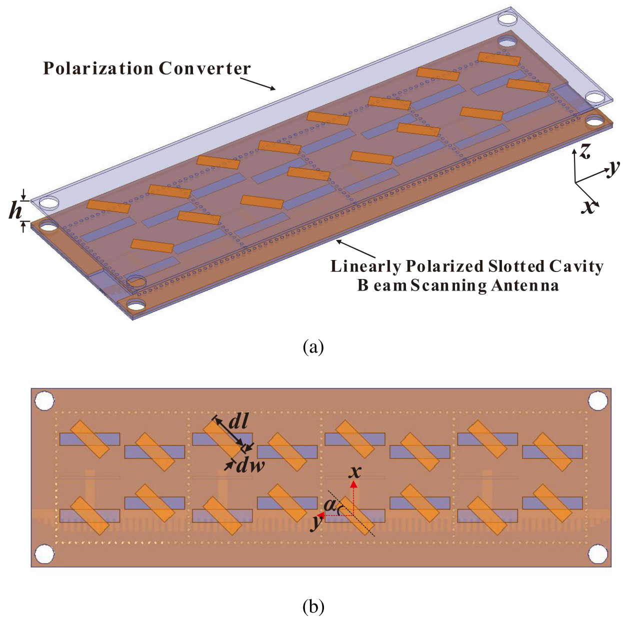


FIGURE 11. Configuration of the CP beam steering antenna: (a) perspective view; (b) top view.

A parametric study has been made to investigate the effect of some significant parameters of the polarization converter. Loading height h and dipole length dl have great influence on the axis ratio (AR) but little effect on the impedance matching. By optimizing the parameters of polarization converter, the widest 3dB AR bandwidth can be obtained. At the same time, we need to re-optimize the parameters of LP beam scanning antenna to maintain the 10dB return loss bandwidth. Final optimized parameters are listed in Table 1.

B. EXPERIMENTAL VERIFICATION

The proposed CP beam steering antenna was simulated, optimized and fabricated to verify theoretical analysis. The prototype of the fabricated antenna is shown in Fig. 12. The three layers are fabricated individually. Plastic screws are used to fix the lower two layers and keep 2mm spacing between the LP beam scanning antenna and the converter.

Fig. 13 shows the simulated (dashed line) and experimental (solid line) S_{11} of the CP beam scanning antenna. And the two curves are in good agreement with each other. A slight discrepancy between the two curves may be caused by fabrication inaccuracy. The experimental impedance bandwidth of -10dB is from 12.2 GHz to 22 GHz (about 57.3%).

Fig. 14 compared the simulated and experimental radiation patterns in yoz-plane. The curves are in good agreement with beam scanning range from $-31°$ to $+37°$ within the frequency range from 12 to 18 GHz. The experimental peak gains of the radiation patterns reach up to 9.9 dBic to 12.7 dBic, while the simulated ones vary from 11.6 dBic to 14.2 dBic. The results are acceptable within the range of fabrication and measurement errors. Compared with the former unloaded LP antenna, the beam scanning range of this design increases slightly and the gain is almost unchanged.

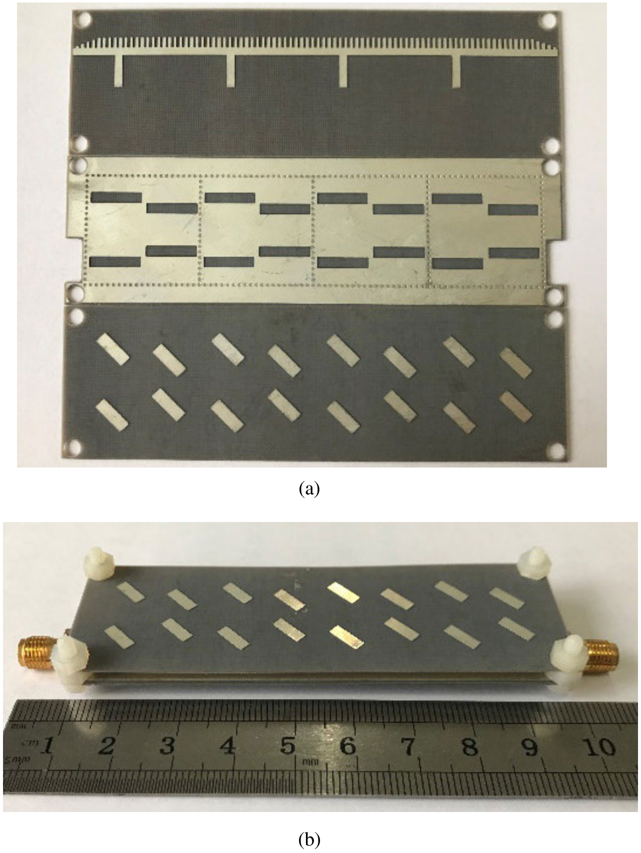


FIGURE 12. Prototype of the fabricated CP antenna: (a) top view of the three layers; (b) side view.

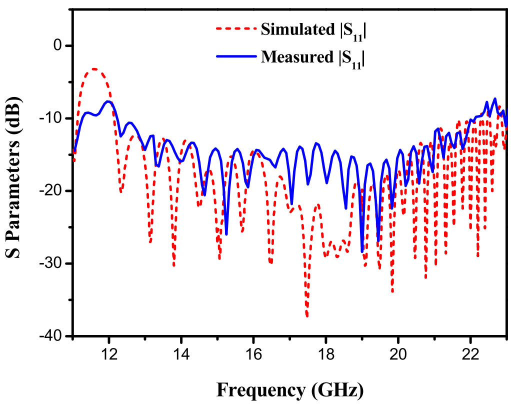


FIGURE 13. Simulated and experimental S11 of the proposed CP beam scanning antenna.

As shown in Fig. 15, the simulated and experimental axial ratios (ARs) curves have a fairly high identical. The measured results show that it can achieve 3dB AR bandwidth of 10.3% (from 14.5 to 16 GHz). Although the CP bandwidth of the design is not particularly good, but the proposed structure has the ability to transform into three kinds of polarization: LP, RHCP or LHCP flexibly. It hinges on whether the polarization converter is introduced and the direction of the dipole in the polarization converter.

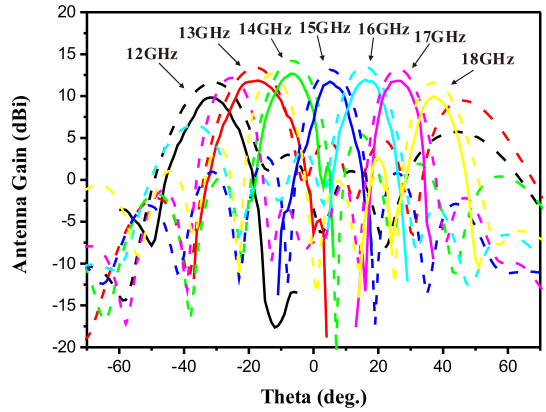


FIGURE 14. Simulated (dashed line) and experimental (solid line) radiation patterns of the CP antenna.

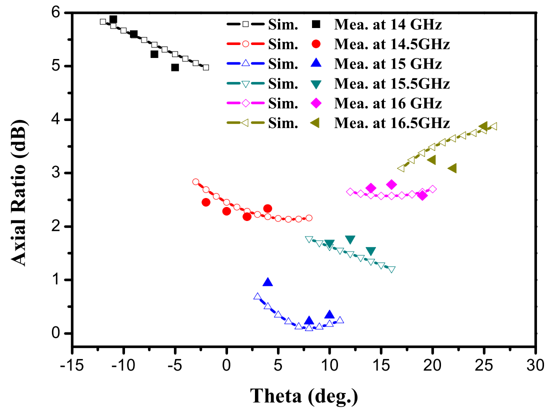


FIGURE 15. Simulated and measured ARs of the CP antenna.

IV. CONCLUSION

Compact high gain beam scanning antennas are proposed in this paper. Firstly, an LP slotted cavity SIW element antenna is designed based on TE_{220} mode. It is excited by microstrip-slot coupling structure and electromagnetic wave is coupled out of SIW cavity by 2×2 slot array etched on the top surface. Spoof SPP slow-wave TL is worked as a feeding structure to increase the beam scanning range of the four elements periodic array. Then a linear-to-circular polarization converter is introduced to generate CP. The proposed antenna has the features of compact size, low profile, high gain, and large beam scanning range. What's more, the proposed beam scanning antenna has the ability to transform into three kinds of polarization: LP, RHCP or LHCP flexibly. It hinges on whether the polarization converter is introduced and the direction of the dipole in the polarization converter.

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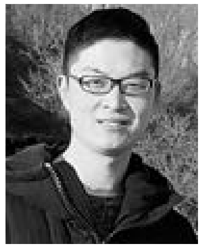

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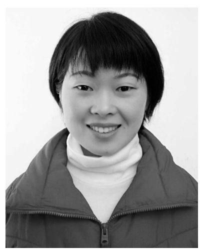

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