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Circular Polarization Annular Leaky-Wave Antenna with Conical and Broadside Beams

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Abstract: In order to properly cover different scenarios, radiation patterns of antennas should be accordingly adjusted before fabrication. However, most antennas are unable to provide both broadside beam and designable conical beam which are usually-used radiation patterns for radio coverage. In this paper, a planar Circular Polarized (CP) annular Leaky-Wave Antenna (LWA) with conical beam is proposed, which is realized on annular Substrate-Integrated Waveguide (SIW). Broadside beam or conical beam could be easily obtained by fabricating the LWA with modified structural parameters. The central operating band is 5.8 GHz. The LWA allows only the -1th spatial harmonic to radiate, while the fundamental wave and other spatial harmonics are suppressed in slow wave mode. In order to validate the design effectiveness, two examples for broadside beam and conical beam radiation are fabricated and measured. The measurement results show good agreement with the simulation results. The proposed LWA presents a promising radiation performance and is a good candidate for wireless communication applications.

Keywords: annular leaky-wave antenna; conical and broadside beams; circular polarization

1. Introduction

Circularly polarized (CP) antennas have been studied for a long time due to its advantages of low polarization mismatch loss in applications. Among different kinds of CP antennas, CP conical beam antenna is one of important candidates for wireless communication applications. In [1], a low profile wideband CP conical beam antenna with arc-hook-shaped branches is proposed. In [2], a transmissive metasurface method for generating conical beam is put forward. In [3], an open-ended coaxial waveguide aperture antenna for conical beam radiation is proposed. In [4], a truncated circular cone slot antenna array with CP conical beam is designed, whose beam angle can be adjusted by changing the inclining angle of the cone surface. In [5], a modified crossed-wire antenna for wideband conical beam is proposed. In [6], a CP reconfigurable antenna equipped by a switchable feeding network for conical beam and broadside radiation is proposed. In [7], a CP wideband dual-cavity-backed crossed dipole antenna is proposed. In [8], a single-fed dual-slot broadband antenna generating CP broadside beam is proposed. In [9], a compact dual-band and dual CP stacked patch antenna generating broadside beam is put forward. In [10], a low-profile wideband circular patch antenna providing broadside beam and conical beam is proposed. In [11], a surface wave holographic antenna excited by a fundamental mode patch array for broadside radiation is proposed. However, most antennas are unable to provide both broadside beam and designable conical beam but generate either broadside beam or conical beam. Although a few works support to generate both broadside beam and conical beam, it is difficult to adjust the beam angle of the conical beam during design process. Thus, it is necessary to put forward new methods of antenna design for containing both broadside beam and designable conical beam.

Leaky-wave antenna (LWA), a popular type of antennas characterized by its flexible traveling-wave radiation property, has been researched for decades and on the hot-spot list today ever [12]-[15]. On the basis of LWA, all kinds of radiation properties have been realized e.g., linearly polarized (LP) and CP radiation on dual-band [12], wide forward [13] and low loss [14], dual-polarized fixed

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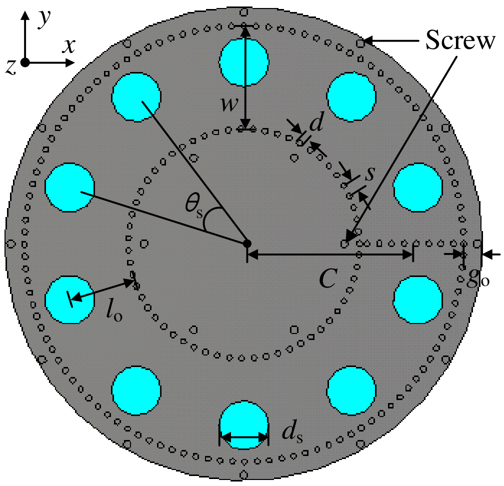
beam with high isolation and cross-polarization [15], etc. In our previous work, an annular LWA with rectangular slots is proposed [16], which can generate CP conical beam and broadside beam. In this paper, a planar annular LWA with circular slots based on SIW is proposed which contains the novelty and contribution of 1) using the mono radiation of the -1th harmonics in an annular LWA for more flexible beam adjustment in the design process, 2) arranging CP deviated circular slots in an annular SIW to guarantee CP radiation, 3) presenting two cases of antennas with broadside beam and conical beam separately to validate the antenna design method. By adjusting and optimizing the structure parameters, CP conical beam and broadside beam with higher gain can be obtained. Antenna structure is described in Section II. Analysis for impedance matching and radiation property is implemented in Section III. Antenna validation is presented in Section IV. Conclusions are given in Section V.

2. Antenna Structure

The structure of the proposed LWA is illustrated in Figure 1. It has two layers: the radiating layer and feeding layer. In the radiating layer, a series of circular slots with constant interval are etched in the top plane, and the locations of the slots are deviated away from the middle axis of the annular SIW. In the feeding layer, two arc-shaped feeding cavities proposed in previous work [16] are used. Two slots are etched in the bottom plane of the radiating SIW layer (also the top plane of feeding layer) for coupling energy from the feeding layer to radiating layer. To excite the cavities, two coaxial probes are welded at the bottom of the feeding layer, one for feeding energy into the LWA, and the other is terminated with a 50 Ohm matched load for absorbing the rest power. Both of the layers are designed on F4BM-2 substrates with εr = 3.2 (with the tolerance of ±2 %) and tanδ ≤ 0.002. The thicknesses of the two layers are both set to 4 mm. The operating frequency of the LWA is set to 5.8 GHz. To assemble the LWA compactly, plastic screws are used.



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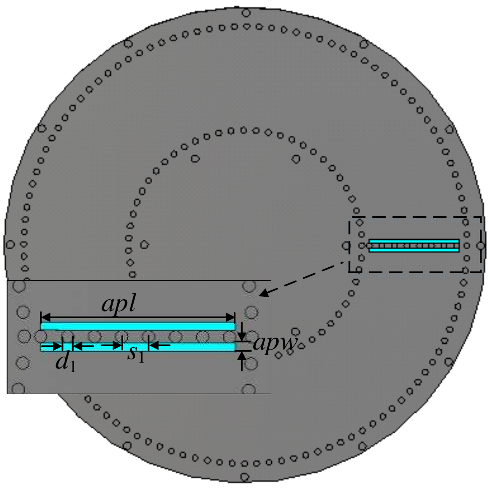

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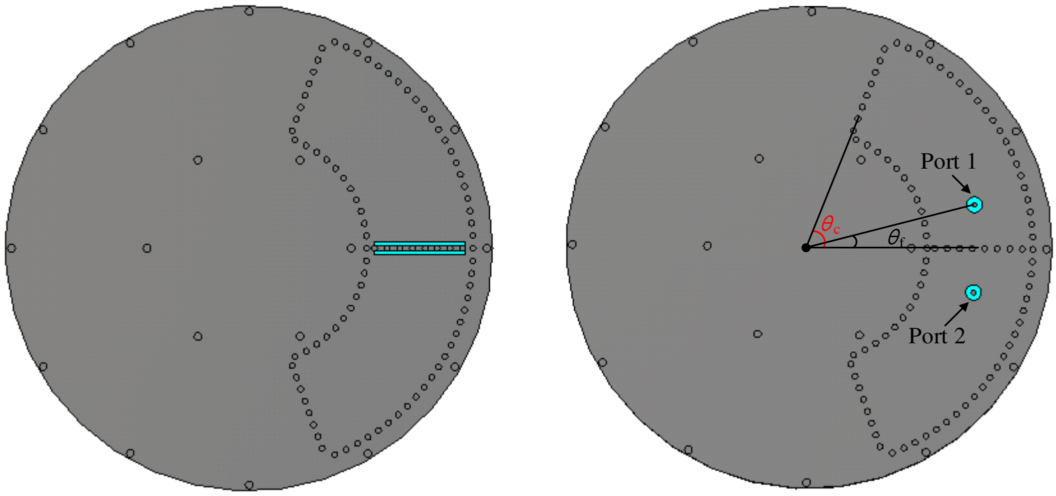


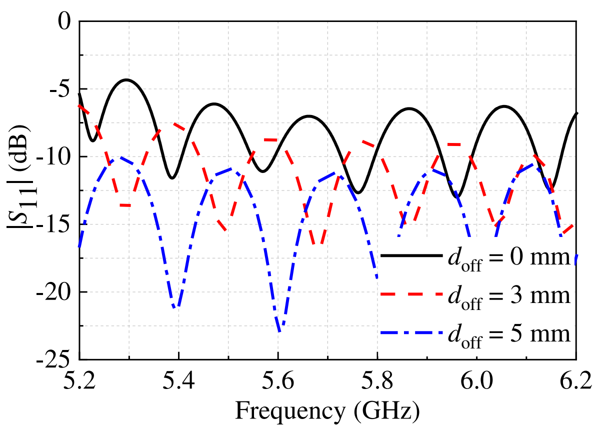
(c) (d)

Figure 1. Structure of the proposed LWA, (a) top view of the radiation layer, (b) back view of the radiation layer, (c) top view of the feeding layer, (d) back view of the feeding layer.

3. Parameter Analysis

3.1. Optimization of Impedance Matching

In order to achieve impedance matching, a series of variable analysis is carried out. First, the deviation distance of slots away from the middle axis of the SIW $d_{off} = w\text{-}l_0$ is studied. When $d_{off} = 0$, the slots are arranged in the middle axis of the SIW. As stated in [17], the transmission property of an annular SIW is almost identical to that of a straight SIW, and the electric field magnitude along the middle axis is the largest, so in case of $d_{off} = 0$ the wave travelling in the SIW is strongly perturbed by the slots. This will cause strong reflection in the SIW and the return loss will be high, as depicted in Figure 2(a). To reduce the return loss, a deviation distance of slots away from the middle axis should be set. However, if d_{off} is too large, the slots cannot effectively cut the surface current, and the radiation efficiency will be low. Therefore, d_{off} needs to be adequately determined for low return loss and high radiation efficiency. Second, the diameter of slots d_s is analyzed for impedance matching. Figure 2(b) shows the variation of return loss with d_s. If d_s is small, the return loss is low, but meanwhile the radiation efficiency will be low. If a large d_s is chosen, the return loss will increase obviously. So ds should also be selected properly. The analysis above is done based on the proposed LWA fed and terminated by perfect waveguide ports. Practically, an arc-shaped feeding cavity designed in [16], as mentioned in the last section, is used to feed the structure as sketched in Figure 1(d). θ_c is optimized to 70°to guarantee a half of guided wavelength inside the cavities for low return loss at the frequency of interest.



(a)

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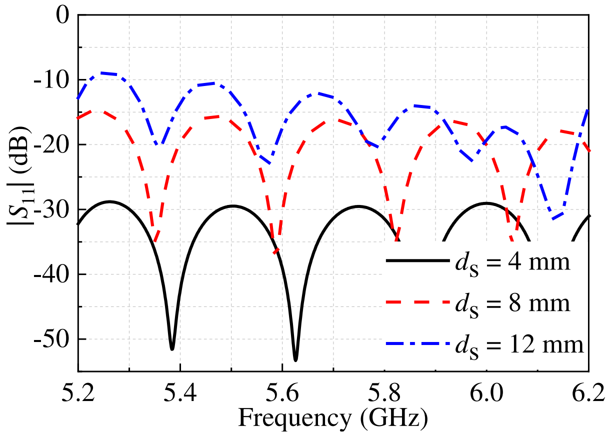


(**b**)

Figure 2. $|S_{11}|$ of the LWA as function of different variables, (a) d_{off}, (b) d_s, w = 27 mm and C = 43.5 mm.

3.2. Analysis of Radiation Property

The working mode in the proposed LWA is TE_{10}, whose electric distribution is illustrated in Figure 3. It can be observed that the wave mode is slightly disturbed due to the existence of deviated circular slots. Only -1th harmonic is allowed to be radiated, so the radiation condition of the proposed LWA can be expressed by

$$\beta_m / k_0 = \sqrt{\varepsilon_g} - m\lambda_0 / p \tag{1}$$

$$-1 < \sqrt{\varepsilon_g} - m\lambda_0 / p < 1 \tag{2}$$

$$\left|\sqrt{\varepsilon_g} + m\lambda_0 / p\right| > 1, m \neq -1 \tag{3}$$

where β_m is the propagation constant of the mth spatial harmonics, ε_g denotes the effective dielectric constant of SIW, and p is the arc-length period of slots. Figure 4 depicts the propagation and attenuation constants of the fundamental wave and -1th spatial harmonic in the proposed LWA, which are achieved by full-wave simulation. It is in Figure 4(a) that the fundamental wave operates in slow wave region ($\beta_0 > k_0$), and does not contribute to the radiation field. Radiation is generated by the -1th spatial harmonic, because β_{-1} is in the range of (-1, 1).

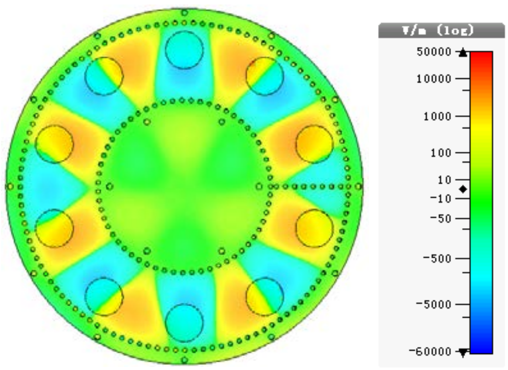
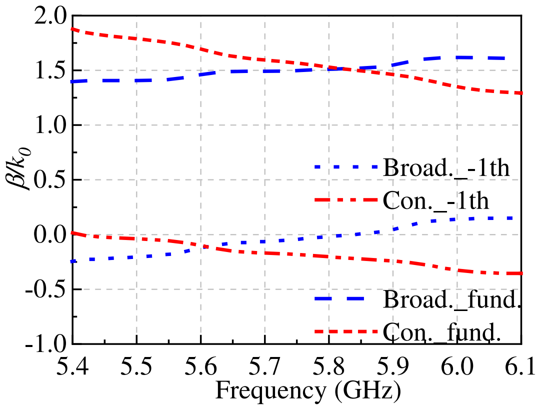


Figure 3. Transient electric field distribution of the proposed LWA. w = 27 mm, C = 43.5 mm, l_0 = 17.5 mm and θ_s = 36º.



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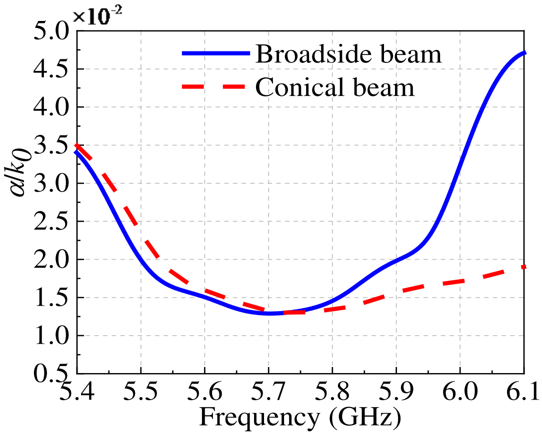

(**b**)

Figure 4. Dispersion curves of the LWA, (a) phase constant, (b) attenuation constant, θ_s = 40º and l_0 = 16.9 mm for broadside beam, θ_s = 36º and l_0 = 17.5 mm for conical beam, w = 27 mm and C = 43.5 mm.

As we know, for the radiation of -1th spatial harmonic, different slot intervals lead to different beam angles. To demonstrate the radiation property of the proposed LWA, three examples are given, one for broadside beam radiation (LWA 1) and two for conical beam radiation (LWA 2 and 3). Figure 5 presents the radiation patterns of the LWAs with different slot intervals (32.7 mm for LWA 1, 29.8 mm for LWA 2 and 25.8 mm for LWA 3). Figure 5(a) gives the radiation patterns for broadside beam and conical beams with different beam angles in *xoz*-plane. Specifically, the omnidirectivity of the conical beams is presented in Figure 5(b). Furthermore, in order to explain the CP property of the LWA, electric distribution of one single slot is demonstrated in Figure 6. It can be seen that two orthogonal electric components with 90º phase difference are excited, so that Left Hand Circular Polarization (LHCP) is generated by a single circular slot. This is attributed to the deviation of slots away from the middle axis of SIW. In addition, it should be noticed that the LWA is excited from port 1, and Port 2 is terminated with a 50 Ohm matched load, which means that the wave travelling in the SIW is anticlockwise. According to previous work [16], antenna working on fundamental mode radiation will generate RHCP radiation when excited by anticlockwise travelling wave. But for the -1th spatial harmonic, the propagation constant is below zero at 5.8 GHz as depicted in Figure 4(a), which means the LWA generates backward radiation. Hence, the anticlockwise travelling wave excites LHCP radiation. Figure 7 gives the axial ratio of the LWA 2 in azimuth plane with θ = 18º. In the whole azimuth plane, the conical beam generated by the proposed LWA presents the CP property.

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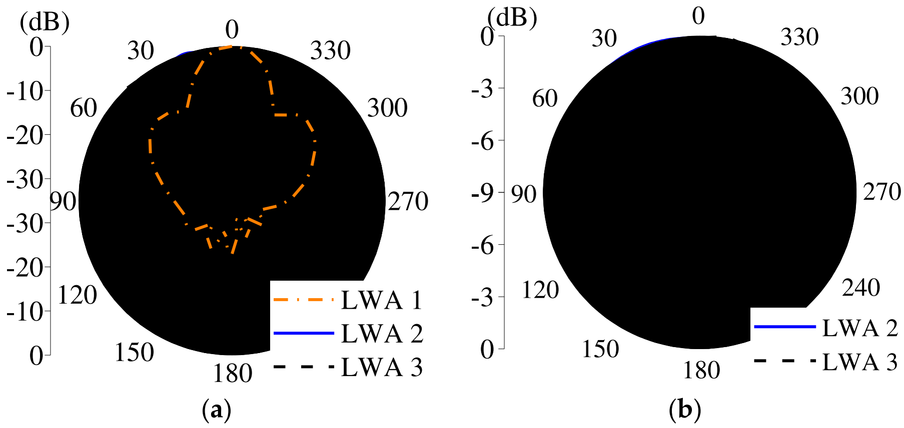

Figure 5. Normalized radiation patterns of the proposed antenna, (a) *xoz*-plane, (b) azimuth plane in the main beam directions (θ = 18º for LWA 2 and θ = 44º for LWA 3), w = 27 mm, C = 43.5 mm and l_0 = 17.5 mm.

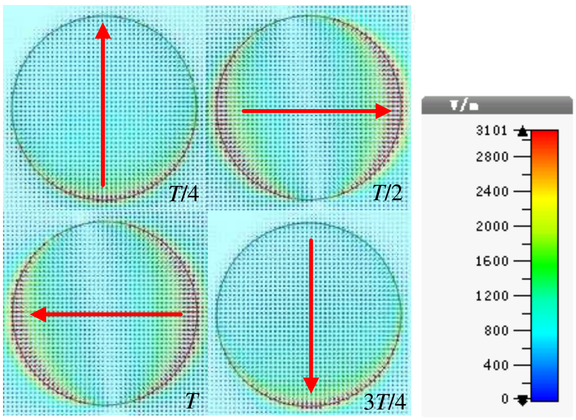

Figure 6. Electric field distributions of one single circular slot during a period T, w = 27 mm, C = 43.5 mm, l_0 = 17.5 mm and θ_s = 36º.

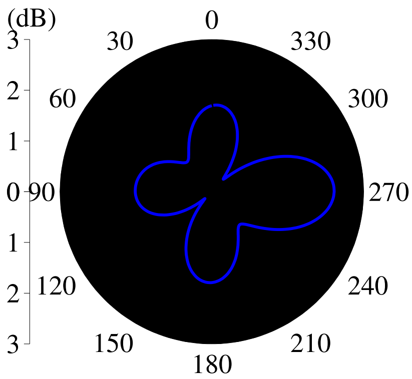

Figure 7. Axial ratio of the LWA 2 in azimuth plane of θ = 18º.

4. Experimental Validation

In order to validate the proposed LWA, two LWAs capable of generating different beam patterns, i.e. LWA 1 for broadside beam and LWA 2 for conical beam, are fabricated, as shown in Figure 8. Two axial probes are welded at the rear of the feeding structure. The depth of the probes inside the SIW is set to 3.5 mm. Structural parameters of the two LWAs are listed in Table 1. To conduct the experiments, Port 1s of the LWAs are the input ports that are excited and Port 2s of them are the output ports that are cascaded to 50 Ohm matched loads. The measurements are carried out

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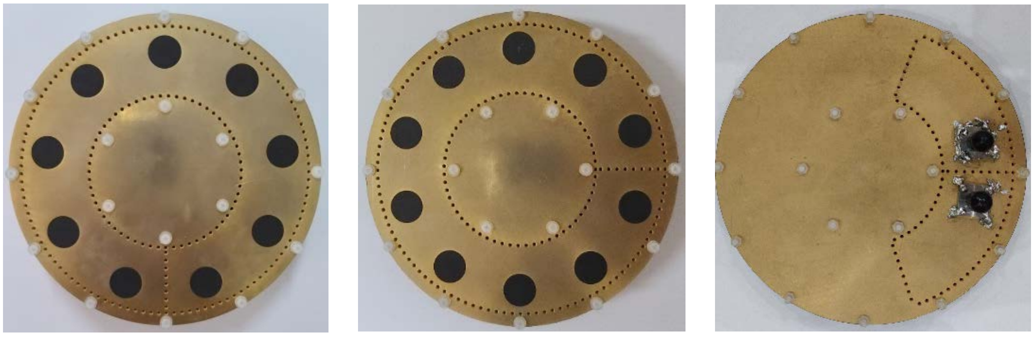
in a far-field anechoic chamber. As can be seen in Figure 9, LWA 1 is fixed on the antenna holder. For simplicity, the familiar picture of the measurement setup of LWA 2 is omitted here.



(**a**) (**b**) (**c**)

Figure 8. Axial ratio of the LWA 2 in azimuth plane of θ = 18º.

Figure 9. Illustration of LWA 1 measurement setup.

Table 1. Structural parameters of the LWAs.

LWA	l_o	θ_s			
1	16.9	40º			
2	17.5	36º			
d	s	d_s	C	g_o	θ_c
1.5	3.2	13	43.5	5	70º
apl	d_1	$s1$	apw	w	θ_f
23.1	1.5	3.2	1	27	15º

Figure 10 shows the S-parameters of the two LWAs. It can be observed that the measurement results are basically in good agreement with the simulation results. The difference between them is mainly caused by the fabrication tolerance, assembling error and the frequency deviation of the substrates.

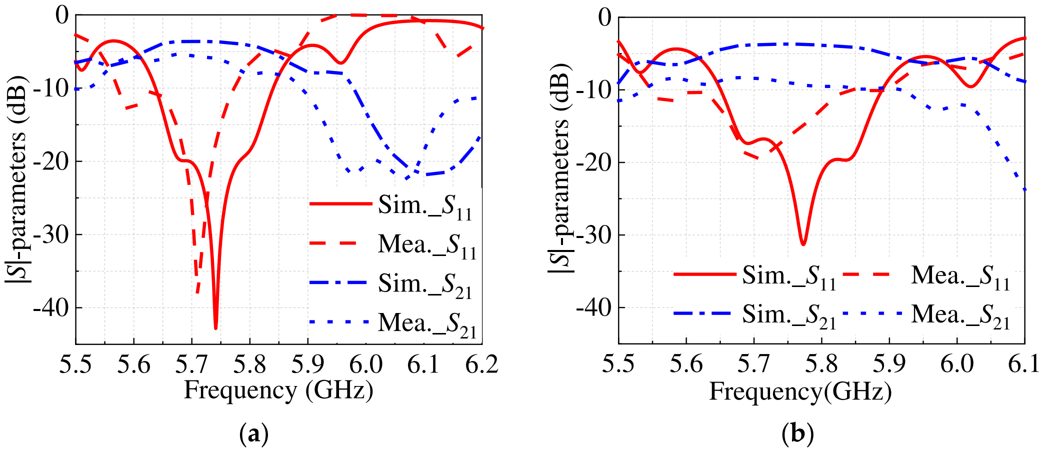


Figure 10. |*S*|-parameters of the proposed LWAs, (a) LWA 1, (b) LWA 2.

Figure 11 depicts the radiation patterns of the two LWAs. The measured results agree well with the counterpart in simulation. It is concluded that the proposed LWA acquires broadside beam and conical beam by changing the slot interval. The simulated realized gains of the LWA 1 and LWA 2 are 10.5 dBic and 7.16 dBic while the measured realized gains of them are 9.75 dBic and 7.93 dBic, respectively. Besides, the simulated efficiencies of LWA 1 and 2 are 43.27% and 43.14% respectively. The measured sidelobe levels (SLLs) of LWA 1 in *xoz*-plane and *yoz*-plane are -10.07 dB and -9.24 dB, respectively. And the measured SLLs of LWA 2 in *xoz*-plane and *yoz*-plane are -8.84 dB and -10.14 dB, respectively. The results show that the SLLs of the two LWAs are similar. And the sidelobes of the LWAs exist due to the relatively large distance (about 2.4 λ_0) between radiating slots in any one cut plane of the LWAs. In the final, from the measured and simulated axial ratios shown in Figure 12, we can see that the two LWAs both present expected CP property, which verifies the performance of the proposed LWA.

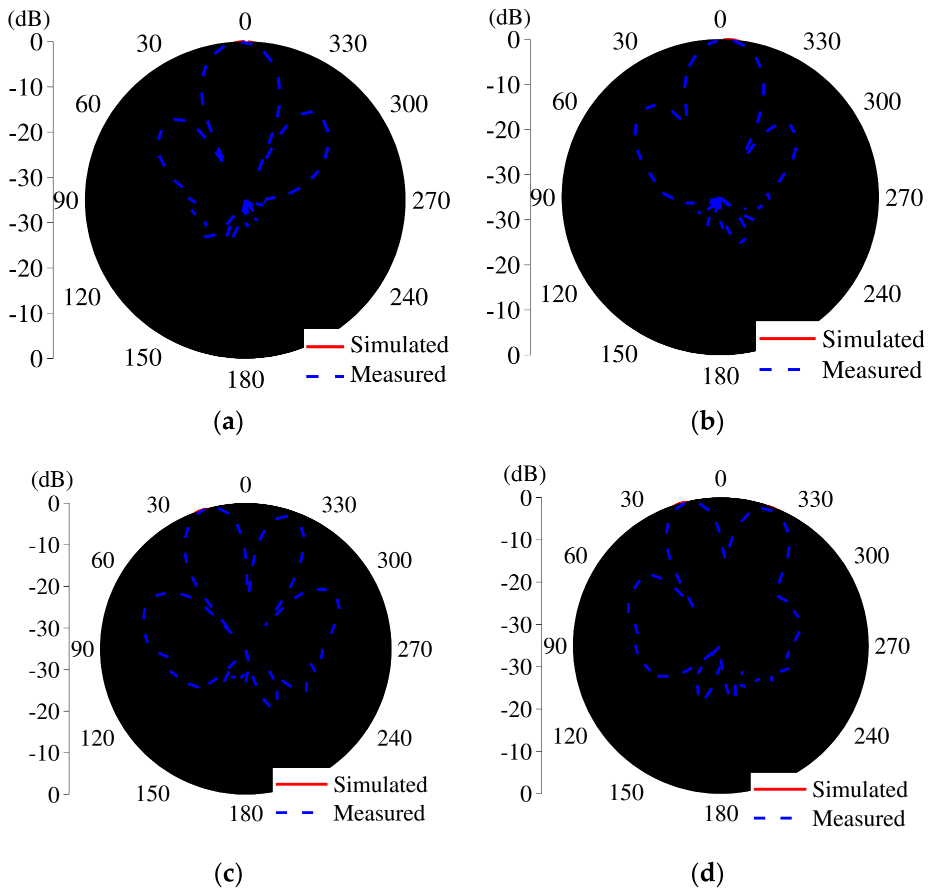
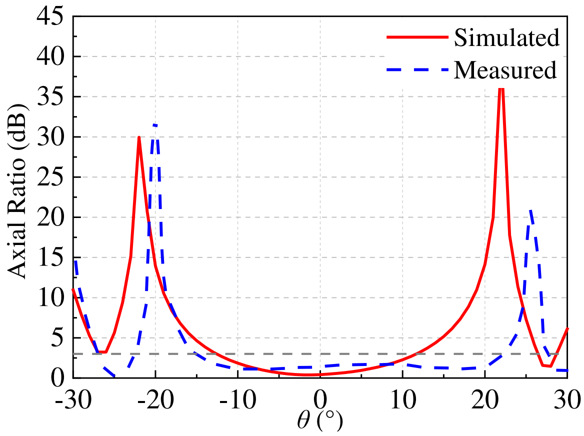


Figure 11. Radiation patterns of the proposed LWA, (a) *xoz*-plane of LWA 1 at 5.75 GHz, (b) *yoz*-plane of LWA 1 at 5.75 GHz, (c) *xoz*-plane of LWA 2 at 5.8 GHz, (d) *yoz*-plane of LWA 2 at 5.8 GHz.



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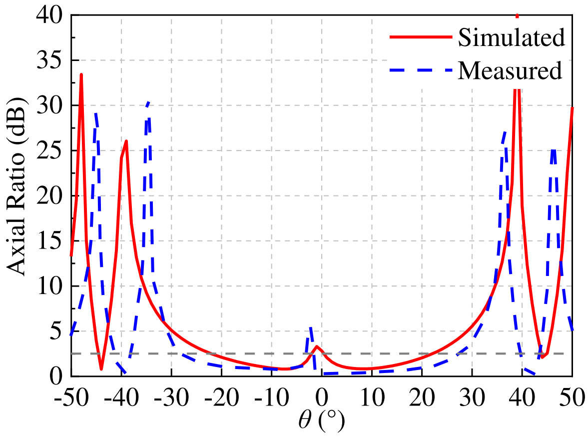

(**b**)

Figure 12. Axial ratios of the proposed LWAs in *xoz*-plane, (a) LWA 1 at 5.75 GHz, (b) LWA 2 at 5.8 GHz.

Tables 2 and 3 present the comparison of the proposed LWA and the existing works. Parameters of broadside beam antennas are listed in Table 2, while parameters of conical beam antennas are listed in Table 3. It can be concluded that the proposed antennas in this paper have relatively higher realized gains. The thickness of the proposed LWAs is medium i.e. 0.15 λ_0 compared with that of other antennas with similar bandwidth, gain i.e. 1.53 λ_0 in [1], 0.12 λ_0 in [6], 0.24 λ_0 in [7] and 0.024 λ_0 in [9]. It will be further improved in the future work. Thus, the proposed LWA shows good performance and can be a promising candidate for wireless communication applications.

Table 2. Performance comparison of broadside beam pattern.

Ref.	Center freq. (GHz)	Imp. BW (%)	Profile (λ_0 at center frequency)	Realized Gain (dBic)
[6]	2.5	2.17	$1.15\times1.15\times0.12\lambda_0$	8.5
[7]	3.0	7.8	$0.57\times0.57\times0.24\lambda_0$	9.7
[8]	6.5	79.4	$0.89\times1.41\times0.02\lambda_0$	7.3
[9]	1.6/2.5	9.1/5.1	$0.38\times0.38\times0.024\lambda_0$	3.3/4.2
[10]	1.85	27.3	$1.23\times1.23\times0.12\lambda_0$	9.5
Previous work [13]	5.8	7.7	$R=0.37\lambda_0$, $h=0.096\lambda_0$	3.71
This work (LWA 1)	5.8	3.5	$R=1.2\lambda_0$, $h=0.15\lambda_0$	9.75

Table 3. Performance comparison of conical beam pattern.

Ref.	Center freq. (GHz)	Imp. BW (%)	Profile (λ_0 at center frequency)	Realized Gain (dBic)	Beam angle controllable	Beam angle
[1]	10.0	6	R=1.6λ_0, h=1.53λ_0	11.9	√	18°
[2]	4.0	39.6	R=0.5λ_0, h=0.16λ_0	2.5	×	30°
[3]	10.4	52.6	R=5.21λ_0, h=0.35λ_0	7.1	×	28°
[4]	5.8	13.3	R=1.24λ_0, h=1λ_0	5.8	√	45°
[6]	2.5	2.17	1.15×1.15×0.12λ_0	5.8	×	30°
Previous work [13]	5.8	6.0	R=0.56λ_0, h=0.096λ_0	2.03	√	34°
This work (LWA 2)	5.8	6.1	R=1.2λ_0, h=0.15λ_0	7.93	√	13°

5. Conclusions

In this paper, CP annular LWAs at 5.8 GHz with conical beams and broadside radiation based on annular SIW are proposed, which compose of radiating layer and feeding layer. More flexible than the previous work, the proposed antenna works in -1th harmonic mode, which brings the merit of that by adjusting the slot interval broadside beam and conical beams with different conical angles can be obtained, not merely by adjusting the width of SIW. Furthermore, deviated circular slots are arranged in the annular SIW to guarantee CP radiation. It is concluded from the measurement results that the proposed LWA shows good performances in higher gain, flexible beam-angle changing and CP property. Additionally, the LWA is easy to be fabricated which is suitable for indoor or outdoor wireless communication applications.

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Conflicts of Interest: The authors declare that there is no conflict of interests regarding the publication of this paper.

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