

A wideband and low-cost square radial line slot array antenna for circularly polarized applications

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Abstract A circularly polarized radial line slot array with enhanced bandwidth is presented in this letter. The proposed antenna consists of two parallel plates, a monopole probe and a spiral slot array. The parallel plates form a radial cavity and is fed by the probe. Then, the spiral slot array etched on the upper substrate can be excited by the radially outward wave to provide broadside radiation. In this design, the side wall of the cavity is left open, which helps to obtain wideband operation and has little effect on radiation patterns. To enhance the bandwidth further, a square cavity is used here to substitute for an initial circular one. With such a structure, the antenna is wide in bandwidth and compact in size. The proposed antenna is designed and fabricated. Measured results reveal that the antenna can provide an impedance bandwidth of 37.2% (15.1–22.0 GHz) and an axial ratio bandwidth of 31.0% (15.0–20.5 GHz), respectively. Additionally, the measured maximum gain is 26.7 dBic at 17.5 GHz.

Keywords: wideband, high-gain antenna, low-profile antenna, circularly polarized antenna

Classification: Microwave and millimeter-wave devices, circuits, and modules

1. Introduction

Since the ruling of wideband technology by the Federal Communication Commission [1], the wideband antennas have drawn more attention for use in many applications such as modern high-speed wireless communication systems [2, 3, 4, 5]. For example, different types of wideband antennas with relatively good performance in published works [6, 7, 8, 9, 10, 11] have been developed. However, compared with circular polarized antennas [12, 13, 14, 15, 16, 17, 18], these wideband linearly polarized antennas are more likely to cause polarization mismatch. And these antennas have no enough bandwidth to support high data rate transmission. In addition, there are also many challenges in the design of such antennas, especially the contradiction between the bandwidth enhancement, size reduction, and the fabrication cost.

In the past two decades, radial line slot array (RLSA) antennas [19, 20, 21, 22, 23, 24] have attracted great attention due to their outstanding features of low profile, low cost, ease of installation. And a lot of efforts have been put into this research over the past years. In terms of the

DOI: 10.1587/elex.16.20190686 Received November 12, 2019 Accepted November 28, 2019 Publicized December 17, 2019 Copyedited January 10, 2020 polarization type, the RLSA antennas can be divided into two categories in summary. The first one is linearly polarized RLSA (LP-RLSA) antennas [25, 26, 27]. The slot pairs of these antennas here are all arranged in concentric. Different slow wave materials or phase tuning structures are also added to alleviate grating lobes in radiation patterns. And low return loss can be improved by introducing a set of reflection cancelling slots. The second one is circularly polarized RLSA (CP-RLSA) antennas [28, 29, 30]. For the CP-RLSA antennas, the slot pairs can be arrayed in spiral or concentric. Noted that, when the slot pairs are arranged spirally, the feeding structure is a concentric phase wave source. While the slots are placed concentrically, the feeding source should produce the rotational phase mode. Although the RLSA antennas mentioned above could provide good radiation properties, their limited bandwidths ($\leq 15\%$) are not conducive to highcapacity wireless communications.



Fig. 1. Geometry of the proposed antenna: (a) Top view; (b) Side view.

In this letter, a wideband and low-cost RLSA antenna for circularly polarized (CP) applications is proposed. No external feeding network is needed in this design. The antenna is simply fed by a monopole probe and can achieve a high gain property. Normally, RLSA antenna produces a narrow bandwidth characteristic. This research successfully enhances the antenna's bandwidth. With the side wall of the cavity left open, the impedance matching is improved. Further, by cutting the initial circular cavity into a square one, the antenna can obtain an enhanced bandwidth of 37.2%. Thus, the antenna is suitable for the wideband and high gain applications.

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2. Antenna geometry and design

Fig. 1 shows the geometry of the proposed antenna. The antenna can be divided into three parts, namely two lowcost parallel substrates (permittivity 2.2), a monopole probe and a spiral slot array. The parallel plates form a radial cavity which is fed by the probe. And detailed structure of the probe is shown in Fig. 1(b). Here, the spacing of two plates should be sufficiently small (less than one half waveguide wavelength, $\lambda_g/2$) to propagate the dominant mode of the radial waveguide. And the slot pairs used as radiators are etched spirally on the upper substrate. It is noted that each slot pair consists of two orthogonal slots. The radial spacing between them is $\lambda_g/4$, leading to a relative phase shift of $\pm \pi/2$. Thus, a circularly polarized radiation can be formed when two polarizations of one slot pair are equal in amplitude and quadrature in phase.

To design the spiral slot array in detail, Fig. 1(a) shows the positions of the first slot pair, namely ($\rho 1, \varphi 1$) and ($\rho 2, \varphi 2$). And $\psi 1$ and $\psi 2$ are the tilted angles with respect to radial line for two slots, respectively. In this design, the relation among these parameters can be expressed as:

$$\begin{cases} \rho_2 = \rho_1 + \lambda_g / 4 \\ \psi_2 = 180^\circ - \psi_1 \\ \varphi_2 - \varphi_1 = 2\psi_1 - 90^\circ \end{cases}$$
(1)

Here, the field phase can be obtained by moving the slots along the radial direction, while the field amplitude depends on the slot position, tilted angle and length. In addition, the radial distance S between two slot pairs should be one waveguide wavelength to ensure the desired amplitude and phase distribution. Finally, the input TEM coaxial mode is transitioned to an outgoing radial mode. Then, the spiral slot array are excited to create a directional and circularly polarized beam.



Fig. 2. Three improved prototypes of the proposed antenna.

For clarifying the improvement process of the bandwidth, three prototypes of the CP antenna are defined in Fig. 2 (Ants. 1–3). Ant. 1 is a conventional CP-RLSA antenna, each slot pair in which is a unit radiator of circular polarization. The radial waveguide is a circular one and the side wall of the cavity is shorted. Based on Ant. 1, the side wall is left open in Ant. 2. For the proposed antenna (Ant. 3), the circular cavity in Ant. 2 is cut into a square one. The VSWR and Axial Ratio (AR) of three antennas are depicted in Fig. 3 and Fig. 4, respectively. Ant. 1 has both narrow impedance bandwidth (IBW) and AR bandwidth (ARBW). However, a wider IBW of Ant. 2 can be obtained when the side wall of the cavity is left open. This is because the wave reflected by the wall disappears, which results in a good impedance matching and little effect on the radiation pattern. Besides, a capacitive-coupled circular loop is loaded at the center of the upper substrate, to some extent, to improve matching. The IBW of Ant. 3 is further increased to 37.2% (15.1–22.0 GHz). This is due to the declined quality factor of the open cavity. In addition, the asymmetric spiral slot array is modified into a square one, improving the CP amplitude and phase distributions in the far-field region, thus a wider AR bandwidth is achieved here. Finally, the detailed dimensions of the proposed antenna are demonstrated as follows.





Fig. 4. Simulated Axial Ratios for Ants. 1–3.

Table I. Dimensions of the proposed antenna

Parameter	Value	Parameter	Value	Parameter	Value
L	150 mm	R1	9.0 mm	R2	9.8 mm
R3	91.7 mm	S	16.8 mm	L1	7.3 mm
H0	3.7 mm	H1	0.5 mm	H2	0.5 mm
HF	3.3 mm	$\rho 1$	16.8 mm	W1	0.5 mm
ρ2	21.3 mm	D	0.4 mm	ψ1	45 deg
ψ2	121 deg	φ1	0 deg	φ2	14 deg

3. Parametric study

To characterize the proposed circularly polarized RLSA, a parametric study is carried out in this section. And the effects of vital parameters, such as L, HF, H0 and ρ 2, on the bandwidth and AR are discussed. In addition, all the other parameters not mentioned stay constant as shown in Table I during this process.

Fig. 5 demonstrates the simulated VSWR and AR of the proposed antenna with different L. Here, the variation of the L implies the extent to modify the circular cavity into the square one. It can be seen that the length of L has a critical effect on both the VSWR and AR. This may be due to the declined quality factor of the open cavity as mentioned above.



Fig. 5. Simulated VSWR and Axial Ratio of the proposed RLSA for different L.



Fig. 6. Simulated VSWR and Axial Ratio of the proposed RLSA for different HF.

Fig. 6 shows the simulated VSWR and AR of the proposed antenna with different HF. It is known that the variation of the height HF has greater effect on VSWR than AR for the antenna. This is because the height of the probe is more related to impedance matching than the AR. It suggests that the impedance matching can be accomplished by adjusting HF without affecting AR.



Fig. 7. Simulated VSWR and Axial Ratio of the proposed RLSA for different H0.

The simulated VSWR and AR of the proposed antenna with different H0 is shown in Fig. 7. As we known, the spacing of two plates should be approximate $\lambda_g/2$ to propagate the dominant mode of the radial waveguide. Hence, the greater effect on VSWR than AR for the antenna can be expected here.

Finally, the effect of the distance $\rho 2$ of the second slot is investigated as shown in Fig. 8. The variation of the $\rho 2$ implies the variation of radial spacing for the orthogonal



Fig. 8. Simulated VSWR and Axial Ratio of the proposed RLSA for different $\rho 2$.

slot pair. Here, the reason that CP properties get worse could be that the respective polarization purity of the two orthogonal modes gets deteriorated with the variation of position $\rho 2$.

In summary, the cavity dimensions (L) has great effects on both the input impedance and AR. And the probe height and cavity height (HF and H0) mainly affect the reflection coefficient, while the spacing of the slot pair (ρ 2) affects the AR only. Therefore, properties of these vital parameters can be used to greatly simplify the design process.

4. Experimental results and discussion

To verify the design, a prototype of the proposed antenna has been fabricated and measured. Fig. 9 shows a photograph of the fabricated antenna. Measurement on VSWR is accomplished by the Wiltron 37269A Network Analyzer, and the gains and radiation patterns are measured by the time-gating method.



Fig. 9. Photograph of the fabricated antenna prototype.

Fig. 10 show the simulated and measured VSWR and AR, and good agreement between them is obtained. In Fig. 6(a), the simulated and measured IBWs are 36.8% (15.3–22.2 GHz) and 37.2% (15.1–22.0 GHz), respectively. As shown in Fig. 6(b), the simulated and measured ARBWs are 31.5% (15.0–20.6 GHz) and 31.0% (15.0–20.5 GHz).

The measured radiation patterns in the xoz planes at 15 and 19 GHz are demonstrated in Fig. 11, respectively. The measured sidelobe level at two frequencies are -16.2 dB and -16.0 dB, respectively. And within the 3-dB beamwidths, the cross-polarizations at two frequencies are both lower than -20 dB. In Fig. 12, 3-dB gain bandwidth is 23.5% (15–19 GHz). The maximum measured right-hand CP gain is 26.7 dBic at 17.5 GHz. As a result, the aperture



Fig. 10. Measured VSWR and AR of the proposed antenna.



Fig. 11. Simulated and measured radiation patterns of the proposed antenna in the xoz planes at 15 GHz and 19 GHz.

efficiency is 50.9% for the antenna. In addition, the radiation efficiency decreases as the frequency increases. This is due to appearance of grating lobe in the upper frequency band.

Finally, a comparison of the proposed antenna with published referenced works is made in Table II. It can be concluded that the proposed antenna provides the widest IBW and ARBW. Nevertheless, the aperture efficiency is lower. And enhancement in efficiency is left for further study.



Fig. 12. Measured gain and radiation efficiency of the proposed antenna.

Table	II.	Comparison	of different	RLSA	antennas
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Ref.	Polarization	IBW	ARBW	Aperture efficiency
[28]	СР	4.0%	4.0%	~60.0%
[29]	СР	11.0%	18.0%	/
[30]	СР	5.0%	5.0%	62.7%
proposed	СР	37.2%	31.0%	50.9%

5. Conclusion

and fabricated in this letter. The measured results indicate that the proposed antenna has an impedance bandwidth of 37.2% and an axial ratio bandwidth of 31.0%. In addition, the antenna can achieve the measured maximum gain of 26.7 dBic and aperture efficiency of 50.9% at 17.5 GHz. With a simple feeding probe, the proposed antenna is wide in bandwidth and reduced in size. Based on these features, the antenna is suitable for high gain and CP applications at Ku-band in the future.tyles.

References

- Federal Communications Commission: "First report and order, revision of part 15 of commission's rule regarding ultra-wideband transmission systems," FCC 02-48 (2002).
- [2] A. Alarifi, et al.: "Ultra wideband indoor positioning technologies: Analysis and recent advances," Sensors 16 (2016) 707 (DOI: 10.3390/s16050707).
- [3] P. C. C. Cruz, *et al.*: "Hybrid UHF/UWB antenna for passive indoor identification and localization system," IEEE Trans. Antennas Propag. **61** (2013) 354 (DOI: 10.1109/TAP.2012. 2220112).
- [4] F. Elbahhar, *et al.*: "Indoor positioning system based on the ultrawideband for transport applications," IntechOpen (2012) (DOI: 10.5772/50017).
- M. S. Ellis, *et al.*: "Small planar monopole ultra-wideband antenna with reduced ground plane effect," IET Microw. Antennas Propag. 9 (2015) 1028 (DOI: 10.1049/iet-map.2014.0538).
- [6] L. L. Meng, *et al.*: "A novel wideband planar nquasi-Yagi antenna loading with parasitical patches and multiple reflectors," IEICE Electron. Express **14** (2017) 20170681 (DOI: 10.1587/elex.14. 20170681).
- [7] D. S. Woo and K. W. Kim: "A miniaturized broadband quasi-Yagi antenna for X- to Ku-band applications," IEICE Electron. Express 10 (2013) 20120828 (DOI: 10.1587/elex.10.20120828).
- [8] Y. S. Li, *et al.*: "Compact CPW-fed ultra-wideband antenna with dual band notched characteristics," IEICE Electron. Express 7 (2010) 1597 (DOI: 10.1587/elex.7.1597).
- [9] R. Bayderkhani and G. R. Dadashzadeh: "Printed wideband CPWfed slot antenna with high polarization purity," IEICE Electron. Express 10 (2013) 20120828 (DOI: 10.1587/elex.10.20120828).
- [10] M. S. Karoui, *et al.*: "A compact UWB elliptic antenna for indoor localization system," IEICE Electron. Express **16** (2019) 20190425 (DOI: 10.1587/elex.16.20190425).
- [11] D. Venkatachalam, *et al.*: "A miniaturized planar antenna with defective ground structure for UWB applications," IEICE Electron. Express 16 (2019) 20190242 (DOI: 10.1587/elex.16.20190242).
- [12] C. Y. Wang, *et al.*: "Single-feed circularly polarized rectangular dielectric resonator antenna coupled with dual mode slot-line square ring resonator," IEICE Electron. Express **16** (2019) 20190083 (DOI: 10.1587/elex.16.20190083).
- [13] H. Y. Zhang, *et al.*: "A low-profile and wideband crossed dipole antenna based on AMC reflector for circularly polarized applications," IEICE Electron. Express **15** (2018) 20180287 (DOI: 10. 1587/elex.15.20180287).
- [14] M. Matsunaga, *et al.*: "A cross shaped spiral antenna radiating omnidirectional circularly and linearly polarized waves," IEICE Electron. Express 9 (2012) 256 (DOI: 10.1587/elex.9.256).
- [15] K. Sato, *et al.*: "Coupling of a circularly polarized slot pair on a corrugated waveguide of finite length," IEICE Electron. Express 3 (2006) 424 (DOI: 10.1587/elex.3.424).
- [16] H. Kai, et al.: "Circularly polarized post-wall waveguide slotted arrays," IEICE Electron. Express 1 (2004) 7 (DOI: 10.1587/elex. 1.7).
- [17] J. D. Lin, *et al.*: "AMC-based planar antenna with low-profile and broad CP beamwidth," IEICE Electron. Express **14** (2017) 20170473 (DOI: 10.1587/elex.14.20170473).
- [18] C. Li, et al.: "A dual-band circularly polarized antenna with wide HPBWs for CNSS applications," IEICE Electron. Express 15 (2018) 20180409 (DOI: 10.1587/elex.15.20180409).

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- [19] J. I. Herranz, et al.: "New topologies of radial-line slot-dipole array antennas," IEEE EUCAP (2006) (DOI: 10.1109/EUCAP.2006. 4584589).
- [20] X.-Q. Li, et al.: "A GW level high-power radial line helical array antenna," IEEE Trans. Antennas Propag. 56 (2008) 2943 (DOI: 10.1109/TAP.2008.928781).
- [21] C. I. Paez and J. Cardenas: "Radial line slot array antenna for point to point applications using IEEE 802.11a," IEEE Latin America Trans. 14 (2016) 639 (DOI: 10.1109/TLA.2016.7437204).
- [22] M. Y. Shalaby, *et al.*: "Radial line slotted antenna for satellite communications in Ku-band," PIERS (2016) (DOI: 10.1109/PIERS. 2016.7735127).
- [23] T. Zhou, et al.: "The rotation mode feeding structure for concentric array radial line slot antenna," 2016 IEEE International Symposium on Antennas and Propagation (APSURSI). (2016) (10.1109/ APS.2016.7696438).
- [24] X.-Q. Li, *et al.*: "16-element single-layer rectangular radial line helical array antenna for high-power applications," IEEE Antennas Wireless Propag. Lett. 9 (2010) 708 (DOI: 10.1109/LAWP.2010. 2059371).
- [25] P. W. Davis and M. E. Bialkowski: "Experimental investigations into a linearly polarized radial slot antenna for DBS TV in Australia," IEEE Trans. Antennas Propag. 45 (1997) 1123 (DOI: 10.1109/8.596903).
- [26] S. R. Peng, *et al.*: "Linearly polarized radial line slot antenna for high-power microwave application," IET Microw. Antennas Propag. **11** (2017) 680 (DOI: 10.1049/iet-map.2016.0289).
- [27] M. Su, et al.: "A linearly polarized radial-line dielectric resonator antenna array," IEEE Antennas Wireless Propag. Lett. 16 (2016) 788 (DOI: 10.1109/LAWP.2016.2604287).
- [28] M. Takahashi, et al.: "Dual circularly polarized radial line slot antennas," IEEE Trans. Antennas Propag. 43 (1995) 874 (DOI: 10.1109/8.402208).
- [29] S. Bhardwaj, *et al.*: "Radial line slot array antenna with vertical waveguide feed for F-band communication," IET Microw. Antennas Propag. **9** (2015) 193 (DOI: 10.1049/iet-map.2014. 0212).
- [30] S. R. Peng, *et al.*: "Design of a concentric array radial line slot antenna for high-power microwave application," IEEE Trans. Plasma Sci. 43 (2015) 3527 (DOI: 10.1109/TPS.2015.2392097).