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Circularly Polarized SIW Antenna Array Based on Sequential Rotation Feeding

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Abstract—A right-handed circularly polarized (CP) substrate integrated waveguide (SIW)-based square ring-slot antenna array is proposed in this study. The array is composed of four elements and is based on a sequential rotation feeding technique to achieve wideband circularly polarization performance and high polarization purity. The feeding network for the array adopts SIW power divider having phase delay characteristic. In order to validate our design method, the antenna array is fabricated and measured. The measured impedance and axial ratio (AR) bandwidths are 8.5% (VSWR < 2) and 6.1% (AR < 3 dB), respectively, whereas the impedance and AR bandwidths for the element are 6.5% and 1.5%. It can be observed that this technique has significantly enhanced the AR bandwidth. Moreover, the antenna has a stable CP peak gain more than 12 dBi from 9.15 GHz to 9.5 GHz.

1. INTRODUCTION

Circularly polarized (CP) antennas have an ability to solve problems in wireless channels such as polarization mismatch with the result of Faraday Effect and interference generated by the multi-path effect. CP antennas are extensively used in space applications such as satellite communication, radar systems, etc. Among many kinds of CP antennas, printed slot CP antenna can achieve large bandwidth, low profile and excellent CP characteristic and bidirectional radiation. Thus a reflector board located at a distance of a quarter of wavelength at the centre frequency from the bottom of the antenna must be used to achieve a unidirectional CP radiation wave. It will certainly add to the height of the entire antenna. Substrate integrated waveguide (SIW) transmission structure [1], using metallic via arrays on low loss dielectric substrate to replace the side walls as metallic rectangular waveguide through printed circuit board (PCB) fabrication process, holds the advantage of low profile, low cost, high power handling capacity and low radiation loss characteristic. A SIW-based CP antenna can improve the radiation efficiency because of its low loss characteristic. It can also achieve a unidirectional radiation with its SIW structure.

Up to now, numerous SIW-based slot antennas and arrays have been reported in literature [2–10]. A 16-element top wall SIW slot antenna [2] proposed two-compounded slot pairs to obtain CP wave centred at 16 GHz, the usable bandwidth is just 2.3%. In [3], the authors proposed an X-band cavity backed crossed-slot antenna fed by a single grounded coplanar waveguide. Both of these antennas had the same problems: a narrow impedance bandwidth of less than 3% and a narrow axial ratio bandwidth about 1% for AR less then 3 dB. In [4], a circular ring-slot antenna embedded in a single-layered SIW with a microstrip-to-SIW transition was presented. The antenna had a wider AR bandwidth of 2.3% and a wide impedance bandwidth of 18.74% than the cavity backed crossed-slot antenna [2, 3]; however, its gain was less than 6 dBi, and the antenna had a high level of cross-polarization. In short, the aforementioned SIW antennas suffer from the same problem: narrow AR bandwidth. The feeding

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topology of a CP antenna array is an effective solution to improve the AR bandwidth. One type is series feed, and the other is parallel feed, such as the sequential rotation phase feeding method [11–18]. In [11–18], the microstrip line with different length in feeding network is utilized to achieve phase 0°, 90°, 180°, 270° for four ports of four-element array.

In this study, to increase the AR bandwidth and antenna gain, a four-element sequential rotation feeding array is proposed. The feeding network also employs SIW power divider with a delay line to compensate the spatial phase difference and provide equal amplitude to the four elements. The element for the array adopts a square ring-slot antenna with the AR bandwidth of 1.5% (AR < 3 dB). Finally, the AR bandwidth for array is improved to 6.1%, and the measured antenna gain is 13.1 dBi at 9.3 GHz in the boresight direction.

2. ANTENNA DESIGN AND DISCUSSION

2.1. Antenna Element Design

A single SIW-based antenna at the X-band is used as the element of the array which is shown in Fig. 1 to Fig. 3. Fig. 1 shows the geometrical configuration with side and top views, and the overall size of the SIW antenna is 34 mm × 34 mm. It is composed of three parts: SIW-based rectangular waveguide, square ring-slot with two shorted strips, and a coax feeding probe. Its design parameters are given in Fig. 1.

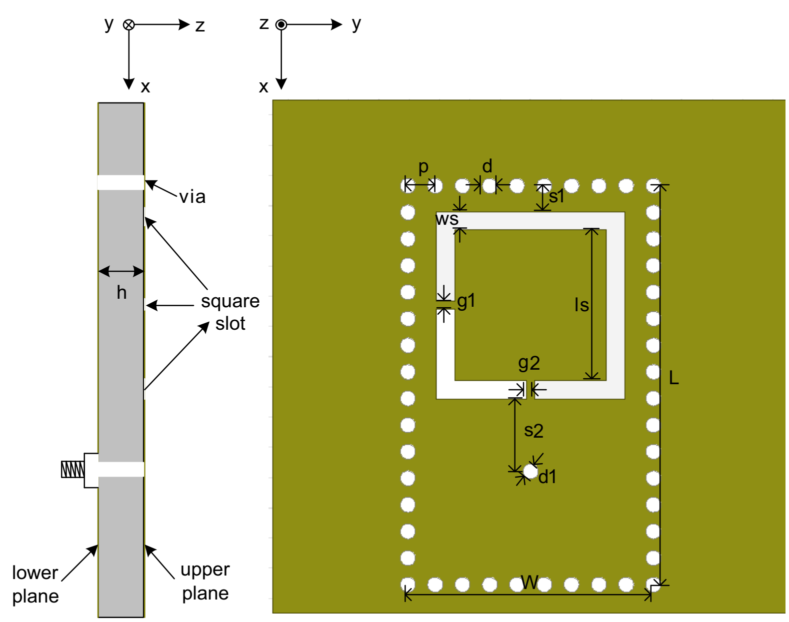


Figure 1. Configuration for the SIW-based element (side and top views).

To obtain a Right-Handed Circular Polarization (RHCP) wave, the location of the two shorting strips with widths $g1$ and $g2$ are important parameters to achieve the best CP performance. The parameters ls, $g1$, $g2$ also influence the impedance matching characteristic of the antenna. The final optimized parameter values are shown in Table 1 for the best impedance matching and AR characteristic. The proposed antenna is designed with the aid of HFSS (ANSYS Inc., USA) based on a finite element method (FED).

A dielectric substrate named Taconic TLX-8 with a relative permittivity of 2.55, a loss tangent of 0.0019, and a height of 1.52 mm is used for the element. The measured and simulated VSWRs are shown in Fig. 2. It can be observed that the bandwidth with VSWR less than 2 is 6.5% (9.04 GHz to 9.64 GHz), and the simulated and measured impedance bandwidths are in good agreement. The measured gain and AR are given in Fig. 3. The measured maximum gain in the boresight direction is 8.1 dBi at 9.2 GHz, and the measured AR bandwidth below 3 dB is 1.5%.

Table 1. The value for the simulated design parameters (Unit: mm).

W	16.2	d	1
L	26.4	$g1$	0.5
ls	1.2	$g2$	0.5
ws	1.2	$s1$	1.7
p	1.8	$s2$	4.8
$d1$	1.4		

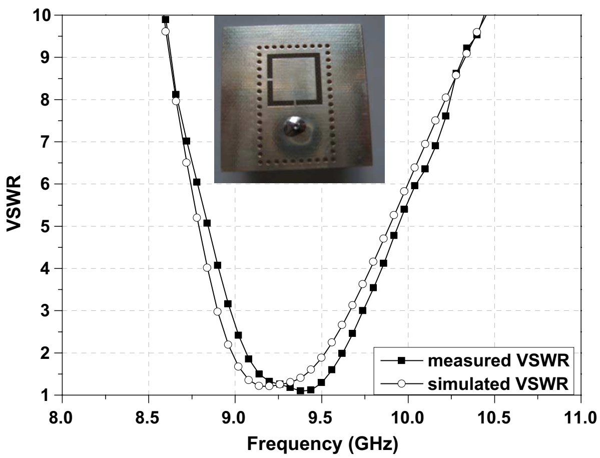


Figure 2. Simulated and measured VSWRs versus frequency.

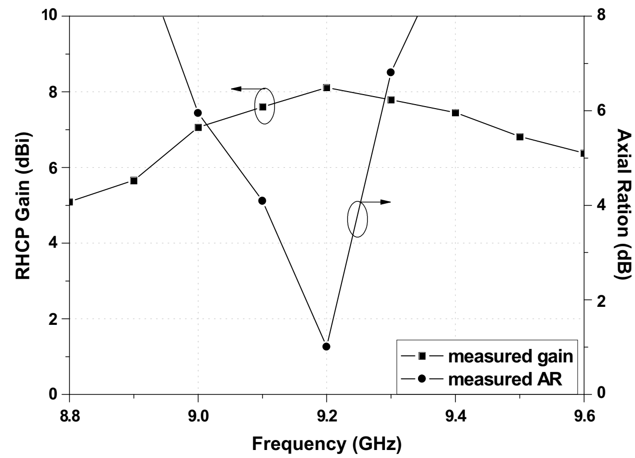


Figure 3. Measured gain and AR versus frequency.

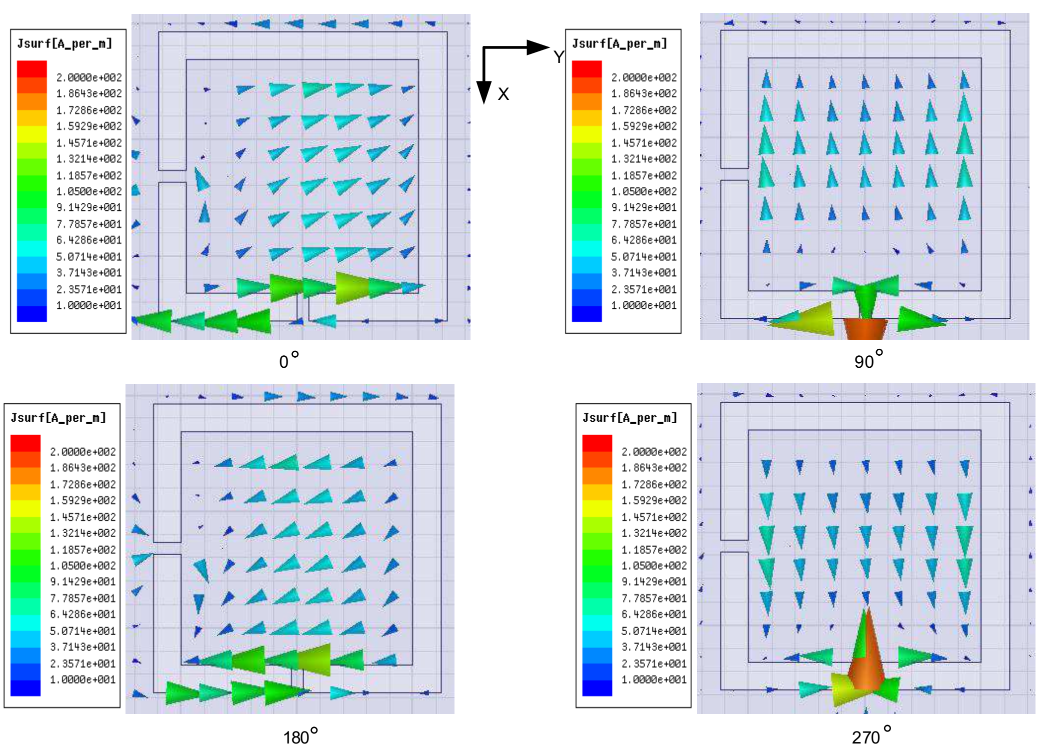


Figure 4. Distribution of the vector surface current on the square ring-slot of the proposed antenna at 9.2 GHz in 0°, 90°, 180°, 270° phase.

Fig. 4 shows the simulated vector surface current distribution of the proposed antenna at 9.2 GHz. It is observed that the vector surface current distributions in 180° and 270° are equal in magnitude and opposite in phases 0° and 90°. With the phase change, it can also be observed that the maximum currents located at the azimuth angle turn in the anti-clockwise direction and the currents turn the x axis into y axis like a RHCP wave.

2.2. Array Design Method

The sequential rotation technique is the most useful way to improve the bandwidth and polarization purity of circularly-polarized antennas if the four elements, each being a narrowband circularly-polarized element, are arranged sequentially in orientation and in phases. The four elements here are phased at 0°, 90°, 180°, and 270° in an attempt to achieve radiation symmetry, to cancel undesirable higher-order modes, and to obtain purer polarization and wideband CP bandwidth [11, 12]. In this paper, a four-element array is obtained based on the SIW-based element. And the four elements are located through the above mentioned sequential rotation feeding technique. The feed network for the array also adopts SIW power divider with a radial configuration to improve radiation efficiency and enables easy fabrication. The array employs two substrates with the same permittivity of 2.55, loss tangent of 0.0019, and height of 1.52 mm. The antenna element is etched on the top substrate, and SIW power divider is etched on the bottom substrate. The two substrates can then be glued together after fabrication. Figs. 5(a) and (b) show the top and bottom layers of the array. In Fig. 5(a), parameter di is the separated distance between the elements. A small di introduces strong mutual coupling among the elements, which results in the deterioration of the radiation performance, whereas a big di increases antenna size. In the present study, di is optimized as $0.71\lambda_0 = 22.6$ mm at 9.3 GHz (λ_0 is the wavelength in free space) for optimal gain and AR characteristic. Parameter s is the distance from the SIW shorted end to feed location, which is denoted as $s = 6.6$ mm. d is the length of delay line with electrical length 90 deg for compensating the phase caused by sequential rotation. The value of d is important for the AR bandwidth. After optimization, the final value for d is 3.1 mm. The coax feeding probe is located in the centre of the SIW power divider. Here the SIW power divider has a simple structure, low loss with SIW transmission line, and wideband impedance matching characteristic. The above advantages will certainly improve the radiation efficiency and array gain.

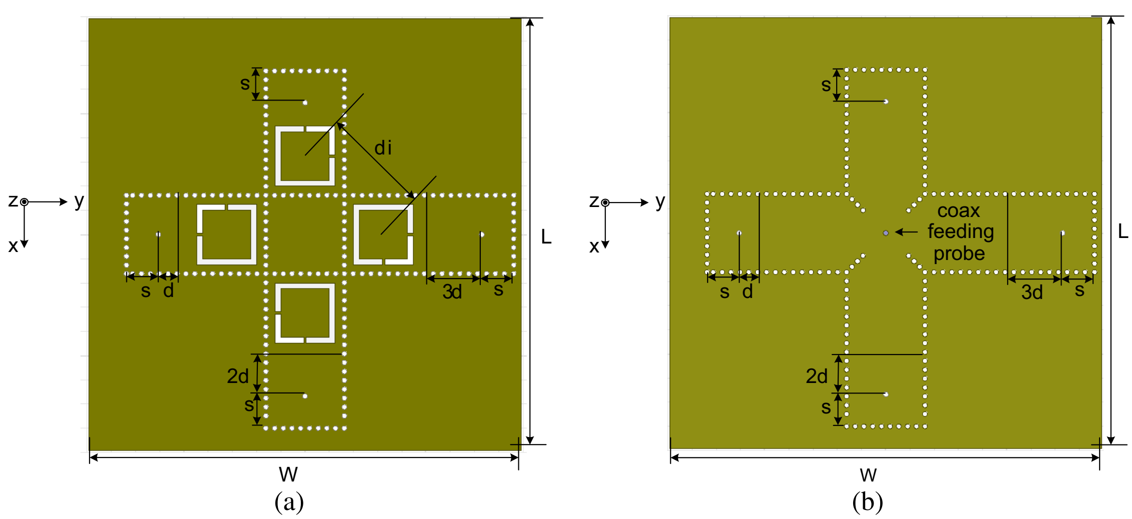
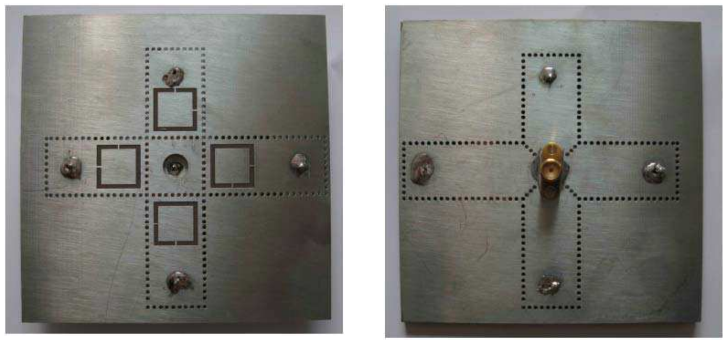


Figure 5. Layout for the antenna array. (a) Radiating antennas on the top layer, (b) power divider on the bottom layer.

3. EXPERIMENTAL RESULTS

The fabricated SIW antenna array according to the above design parameters is shown in Fig. 6. Its overall size is $W \times L = 89.2\,\text{mm} \times 89.2\,\text{mm}$ with height of 3.04 mm. The four coax probes for every element in top and bottom substrates are connected together to guarantee that the energy from the input port is transmitted to the radiating layer as shown in Fig. 6. A circle in the center, with diameter 5.5 mm, is cut from the top substrate to allow convenient soldering of the SMA connector. This process does not influence the impedance and radiation performance of the antenna. The measured VSWR is shown in Fig. 7 with the help of the vector network analyzer E8363B from Agilent Technologies. It can be seen that the impedance bandwidth is 8.5% (8.96 GHz to 9.76 GHz), and the measured impedance bandwidth is larger than simulated one. This difference may be caused by the fabrication error.



(a) (b)

Figure 6. Fabricated antenna array. (a) Top layer, (b) bottom layer.

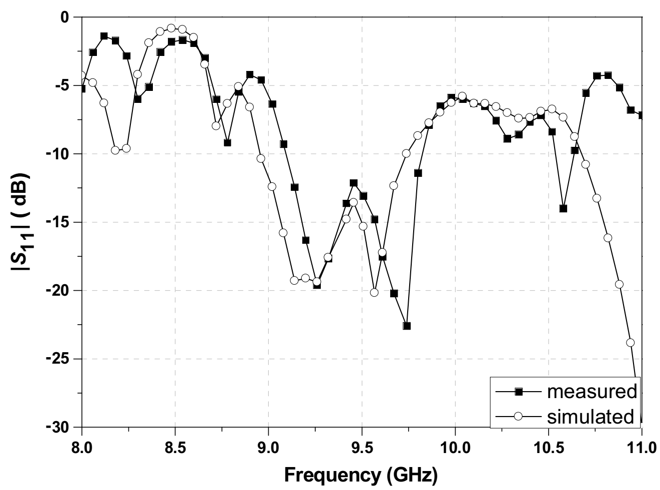
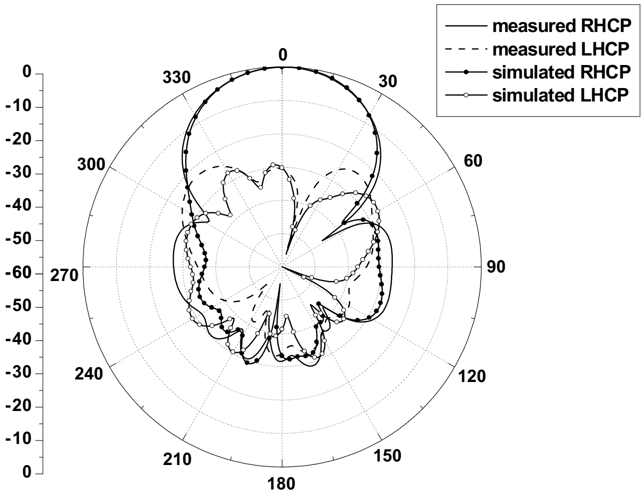


Figure 7. Simulated and measured VSWR against frequency.

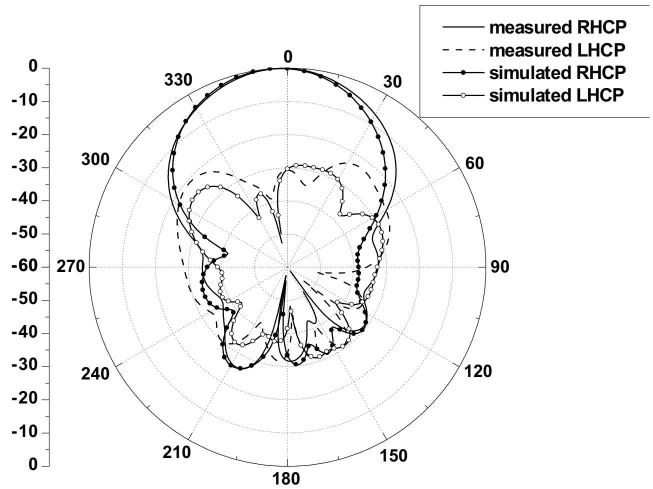
The measured and simulated RHCP and LHCP radiation patterns in *xoz* and *yoz* planes at 9.3 GHz of the SIW antenna array are plotted in Figs. 8(a) and (b), respectively. It can be seen that the proposed antenna satisfies the RHCP generation with a lower cross-polarization more than 20 dB in the boresight direction, which verifies the effectiveness of the sequential rotation technique.

The measured AR and gain versus frequency are depicted in Fig. 9. The measured AR bandwidth below 3 dB is 6.1% (8.88 GHz to 9.44 GHz) which is much larger than the AR bandwidth of the element. It has certified the effectiveness with the sequential rotation method, and the measured maximum gain in the boresight direction is 13.1 dBi at 9.3 GHz. From 9.15 GHz to 9.5 GHz, the antenna array has a stable gain more than 12 dBi.

Radiation efficiency has been measured by using the D/G method [19], as shown in Fig. 10. The efficiency is found to be more than 79% from 8.9 GHz to 9.4 GHz. It can be seen that the SIW array has lower loss and higher radiation efficiency than microstrip line antenna array [17].



(a)



(b)

Figure 8. Measured radiation pattern at 9.3 GHz. (a) *xoz* plane and (b) *yoz* plane.

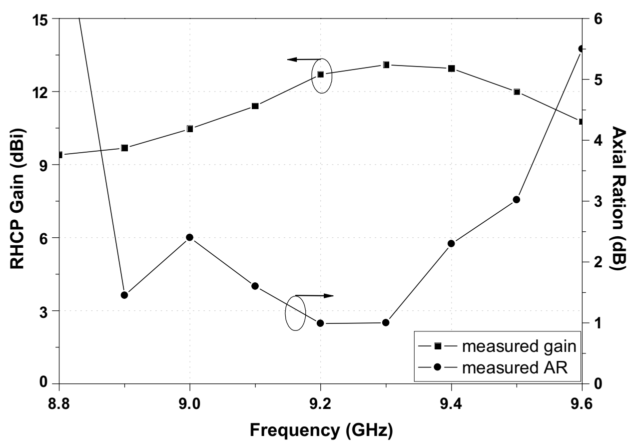


Figure 9. Measured gain and AR versus frequency.

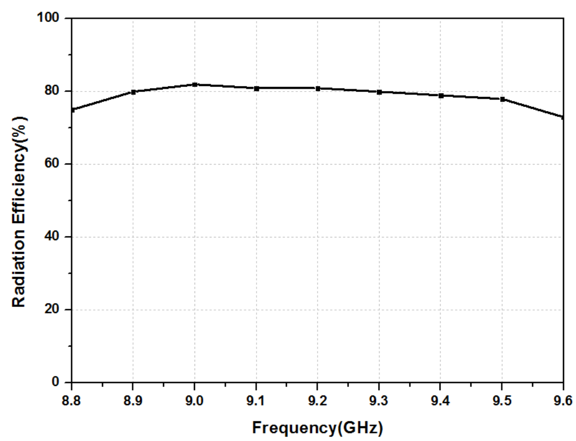


Figure 10. Measured radiation efficiency versus frequency.

4. CONCLUSION

In short, a RHCP antenna array with high gain and large AR bandwidth is presented in this study. Large AR bandwidth is obtained by employing the sequential rotation feeding method. This design method is simple and easy for fabrication. The SIW antenna array achieves 8.5% impedance and 6.1% AR bandwidths, respectively. The realized gain is 13.1 dBi in the boresight direction with a low cross polarization at 9.3 GHz. The array can be applied in satellite communication system with excellent CP characteristic and high gain.

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REFERENCES

1. Xu, F. and K. Wu, "Guided-wave and leakage characteristic of substrate integrated waveguide," *IEEE Transactions on Microwave Theory and Technology*, Vol. 53, No. 1, 66–73, 2005.
2. Chen, P., W. Hong, Z. Q. Kuai, et al., "A substrate integrated waveguide circular polarized slot radiator and its linear array," *IEEE Antennas and Wireless Propagation Letters*, Vol. 59, 120–123, 2009.
3. Luo, G. Q., Z. F. Hu, Y. P. Liang, et al., "Development of low profile cavity backed crossed slot antennas for planar integration," *IEEE Transactions on Antennas and Propagation*, Vol. 57, No. 10, 2972–2979, 2009.
4. Kim, D., J. W. Lee, C. S. Cho, et al., "X-band circular ring-slot antenna embedded in single-layered SIW for circular polarization," *Electronics Letters*, Vol. 45, 668–669, 2009.
5. Kim, D., J. W. Lee, T. K. Lee, et al., "Design of SIW cavity-backed circular-polarized antennas using two different feeding transitions," *IEEE Transactions on Antennas and Propagation*, Vol. 59, No. 4, 13980–1403, 2011.
6. Lacik, J., "Circularly polarized SIW square ring-slot antenna for X-band applications," *Microwave and Optical Technology Letters*, Vol. 54, 2590–2593, 2012.
7. Li, Y., N. C. Zhi, X. M. Qing, et al., "Axial ratio bandwidth enhancement of 60-GHz substrate integrated waveguide-fed circularly polarized LTCC antenna array," *IEEE Transactions on Antennas and Propagation*, Vol. 60, No. 10, 4619–4626, 2012.
8. Masa-Campos, J. L. and P. Rodriguez-Fernandez, "Monopulse circularly polarized SIW slot array antenna in millimetre band," *Journal of Electromagnetic Waves and Applications*, Vol. 25, Nos. 5–6, 857–868, 2011.
9. Peng, J. Z., S.-Q. Xiao, X.-J. Tang, and J. C. Lu, "A novel Ka-band wideband slot antenna for system-on-package application," *Journal of Electromagnetic Waves and Applications*, Vol. 22, Nos. 11–12, 1705–1712, 2008
10. Luo, G. Q., X. H. Zhang, L. X. Dong, W. J. Li, and L. L. Sun, "A gain enhanced cavity backed slot antenna using high order cavity resonance," *Journal of Electromagnetic Waves and Applications*, Vol. 25, Nos. 8–9, 1273–1279, 2011.
11. Teshirogi, T., M. Tanaka, and W. Chujo, "Wideband circularly polarized array antenna with sequential rotations and phase shifts of elements," *Proceeding International Symposium on Antennas Prop. ISAP*, 117–120, Tokyo, Japan, 1985.
12. Hall, P. S., "Application of sequential feeding to wide bandwidth circularly polarized microstrip patch arrays," *IEE Proceedings H Microwave, Antenna and Propagation*, Vol. 136, No. 5, 390–398, 1989.
13. Wu, J.-W. and J.-H. Lu, "2×2 circularly polarized patch antenna arrays with broadband operation," *Microwave and Optical Technology Letters*, Vol. 39, 360–363, 2003.
14. Lu, Y., D. G. Fang, and H. Wang, "A wideband circular polarized 2×2 sequentially rotated patch antenna array," *Microwave and Optical Technology Letters*, Vol. 49, 1405–1407, 2007.
15. Evans, H. and A. Sambell, "Wideband 2×2 sequentially rotated patch antenna array with a series feed," *Microwave and Optical Technology Letters*, Vol. 40, 292–294, 2004.
16. Chen, A. X., Y. J. Zhang, Z. Z. Chen, et al., "Development of Ka-band wideband circularly polarized 64-element microstrip antenna array with double application of the sequential rotation feeding technique," *IEEE Antennas and Wireless Propagation Letters*, Vol. 10, 1270–1273, 2011.
17. Soliman, E. A., S. Brebels, E. Beyne, et al., "Sequential-rotation arrays of circularly polarized aperture antennas in the MCM-D technology," *Microwave and Optical Technology Letters*, Vol. 44, 581–585, 2005.
18. Fan, F. F., Z. H. Yan, P. Xu, et al., "Sequential rotation feeds microstrip array," *Microwave & RF*, Vol. 52, 55–58, 2013
19. Lai, Q., G. Almpanis, C. Fumeaux, H. Benedickter, and R. Vahldieck, "Comparison of the radiation efficiency for the dielectric resonator antenna and the microstrip antenna at Ka band," *IEEE Transactions on Antennas and Propagation*, Vol. 56, No. 11, 3589–3592, Nov. 2008.