measured gain is 7.7 dB. This maximum gain occurs at 3.46 GHz which is located inside the 3 dB axial-ratio frequency band.

## VI. CONCLUSION

A circularly polarized cylindrical dielectric resonator antenna excited by an external tape helix has been presented. The helix is fed by a coaxial line through a hole on a finite size ground plane. The configuration offers a compact and easy to fabricate feeding network providing a 3 dB axial-ratio bandwidth of 6.4%, while having a single point feed. The concept was experimentally verified by comparing simulation and measured results of the return loss, radiation pattern, and axial ratio. Design guidelines were given in the communication on how to choose suitable dimensions for the DRA and helix exciter.

## REFERENCES

[1] R. K. Mongia and P. Bhartia, "Dielectric resonator antennas-a review and general design relations for resonant frequency and bandwidth," *Int. J. Microw. Millimeter-Wave Comput.-Aided Engrg*, vol. 4, no. 3, pp. 230–247, May 1994.

[2] A. Petosa, *Dielectric Resonator Antenna Handbook*. Boston, MA, USA: Artech House, 2007.

[3] E. Lim, K. Leung, and X. Fang, "The compact circularly-polarized hollow rectangular dielectric resonator antenna with an underlaid quadrature coupler," *IEEE Trans. Antennas Propag.*, vol. 59, no. 1, pp. 288–293, Jan. 2011.

[4] L. Hady, A. Kishk, and D. Kajfez, "Dual-band compact DRA with circular and monopole-like linear polarizations as a concept for GPS and WLAN applications," *IEEE Trans. Antennas Propag.*, vol. 57, no. 9, pp. 2591–2598, Sep. 2009.

[5] A. A. Kishk, "An elliptic dielectric resonator antenna designed for circular polarization with single feed," *Microw. Opt. Technol. Lett.*, vol. 37, no. 6, pp. 454–456, 2003.

[6] L. Zou and C. Fumeaux, "A cross-shaped dielectric resonator antenna for multifunction and polarization diversity applications," *IEEE Antennas Wireless Propag. Lett.*, vol. 10, pp. 742–745, 2011.

[7] B. Li, C.-X. Hao, and X.-Q. Sheng, "A dual-mode quadrature-fed wideband circularly polarized dielectric resonator antenna," *IEEE Antennas Wireless Propag. Lett.*, vol. 8, pp. 1036–1038, 2009.

[8] K. Leung, "Circularly polarized dielectric resonator antenna excited by a shorted annular slot with a backing cavity," *IEEE Trans. Antennas Propag.*, vol. 52, no. 10, pp. 2765–2770, Oct. 2004.

[9] K. W. Leung and H. K. Ng, "Theory and experiment of circularly polarized dielectric resonator antenna with a parasitic patch," *IEEE Trans. Antennas Propag.*, vol. 51, no. 3, pp. 405–412, Mar. 2003.

[10] M. Simeoni, R. Cicchetti, A. Yarovoy, and D. Caratelli, "Plastic-based supershaped dielectric resonator antennas for wide-band applications," *IEEE Trans. Antennas Propag.*, vol. 59, no. 12, pp. 4820–4825, Dec. 2011.

[11] K.-W. Khoo, Y.-X. Guo, and L. C. Ong, "Wideband circularly polarized dielectric resonator antenna," *IEEE Trans. Antennas Propag.*, vol. 55, no. 7, pp. 1929–1932, Jul. 2007.

[12] S. Malekabadi, M. Neshati, J. Rashed, and A. Attari, "Circular polarized cylindrical dielectric resonator antenna using a single probe feed," in *Proc. Int. Conf. on Microwave and Millimeter Wave Technology*, Apr. 2008, vol. 3, pp. 1098–1101.

[13] B. Li, K. So, and K. Leung, "A circularly polarized dielectric resonator antenna excited by an asymmetrical u-slot with a backing cavity," *IEEE Antennas Wireless Propag. Lett.*, vol. 2, no. 1, pp. 133–135, 2003.

[14] Y. Pan and K. W. Leung, "Wideband circularly polarized trapezoidal dielectric resonator antenna," *IEEE Antennas Wireless Propag. Lett.*, vol. 9, pp. 588–591, 2010.

[15] C.-Y. Huang, J.-Y. Wu, and K.-L. Wong, "Cross-slot-coupled microstrip antenna and dielectric resonator antenna for circular polarization," *IEEE Trans. Antennas Propag.*, vol. 47, no. 4, pp. 605–609, Apr. 1999.

[16] C.-Y. Huang and C.-W. Ling, "Frequency-adjustable circularly polarised dielectric resonator antenna with slotted ground plane," *Electron. Lett.*, vol. 39, no. 14, pp. 1030–1031, Jul. 2003.

[17] H. Nakano, S. Kirita, N. Mizobe, and J. Yamauchi, "External-excitation curl antenna," *IEEE Trans. Antennas Propag.*, vol. 59, no. 11, pp. 3969–3977, Nov. 2011.

[18] T. A. Latef and S. K. Khamas, "Measurements and analysis of a helical antenna printed on a layered dielectric hemisphere," *IEEE Trans. Antennas Propag.*, vol. 59, no. 12, pp. 4831–4835, Dec. 2011.

[19] J. Volakis, *Antenna Engineering Handbook*, 4th ed. New York, NY, USA: McGraw-Hill, 2007.

[20] J. D. Kraus, *Antennas*, 2nd ed. New York, NY, USA: McGraw-Hill, 1988.

[21] T.-S. Chu and N. Kilcoyne, "The excitation of a dielectric-rod antenna by a helix," *IRE Trans. Antennas Propag.*, vol. 9, no. 4, pp. 416–417, Jul. 1961.

[22] R. E. Collin, *Field Theory of Guided Waves*, 2nd ed. New York, NY, USA: Wiley-Interscience, 1991.

[23] D. A. Watkins, *Topics in Electromagnetic Theory*. New York, NY, USA: Wiley, 1958.

[24] D. G. Kiely, *Dielectric Aerials*. New York, NY, USA: Wiley, 1952.

[25] D. Kajfez and P. Guillon, *Dielectric Resonators*, 2nd ed. New York, NY, USA: Nobel Publishing, 1998.

[26] C. A. Balanis, *Antenna Theory: Analysis and Design*, 3rd ed. Hoboken, NJ, USA: Wiley-Interscience, 2005.

[27] W. Hansen and J. Woodyard, "A new principle in directional antenna design," *Proc. Inst. Radio Eng.*, vol. 26, no. 3, pp. 333–345, Mar. 1938.

---

# A Sequential-Phase Feed Using a Circularly Polarized Shorted Loop Structure

Yue Li, Zhijun Zhang, and Zhenghe Feng

***Abstract*—This communication presents a new 4-port feeding structure with sequential phase (SP) of 0°, 90°, 180° and 270° using a circularly polarized (CP) shorted loop. A $2 \times 2$ single-fed circularly polarized corner-truncated patch array is connected to the loop's four shorting strips, which serve as 4 feeding ports with stable phase difference. By using the proposed SP feed, the axial ratio (AR) bandwidth of the array is increased to more than 7%, wider than the previous design. A prototype of the proposed antenna is built to validate the design experimentally, and a global bandwidth of 4.86–5.12 GHz is achieved ($\mathrm{S_{11}} < -10$ dB, $\mathrm{AR} < 3$ dB, and gain variation within 3 dB).**

***Index Terms*—Antenna array feeds, circular polarization, loop antennas.**

## I. INTRODUCTION

With the rapid progress of modern wireless technology, circularly polarized (CP) antenna arrays have been widely adopted in the applications of satellite and mobile communication. Polarization alignment is not necessary between the transmitting and the receiving antennas. However, the axial ratio (AR) bandwidth is one of the most significant issues for CP antenna arrays.

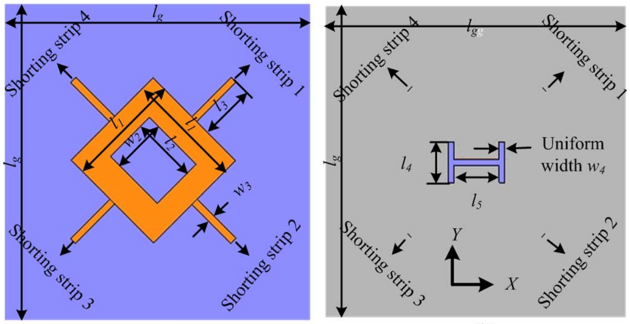
The feeding topology of a CP antenna array is an effective solution to improve the AR bandwidth. One type is the series feed. For example, the two slots in the coplanar waveguide (CPW) structure are utilized to feed the patch array [1]. In [2], the corner-chamfered patches were

Manuscript received March 28, 2012; revised May 31, 2012; accepted October 15, 2012. Date of publication November 16, 2012; date of current version February 27, 2013. This work was supported in part by the National Basic Research Program of China under Contract 2009CB320205, the National High Technology Research and Development Program of China (863 Program) under Contract 2011AA010202, the National Natural Science Foundation of China under Contract 61271135, the National Science and Technology Major Project of the Ministry of Science and Technology of China 2010ZX03007-001-01, and in part by Qualcomm Inc.

The authors are with the State Key Laboratory on Microwave and Digital Communications, Tsinghua National Laboratory for Information Science and Technology, Department of Electronic Engineering, Tsinghua University, Beijing 100084, China (e-mail: zjzh@tsinghua.edu.cn).

Color versions of one or more of the figures in this communication are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/TAP.2012.2227103



(a) (b)

Fig. 1. Geometry and dimensions of the proposed feeding structure (a) front view; (b) back view.

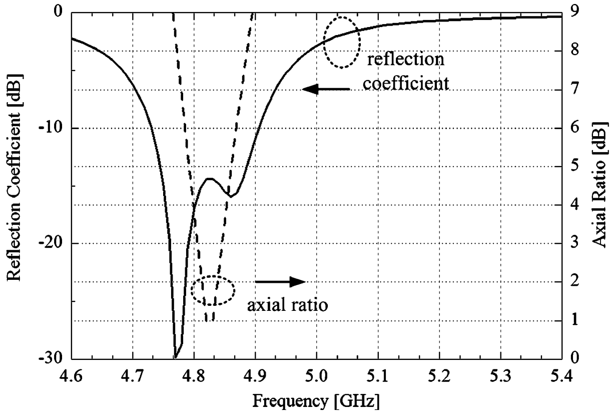


Fig. 2. Simulated reflection coefficient and AR of the loop.

connected directly and operated as a traveling wave array to achieve circularly polarization. Traveling wave structure is also adopted in the feed line to excite the slot-coupled patch array [3]. Another type is the parallel feed, such as the sequential-phase (SP) feed. The benefit in axial ratio (AR) bandwidth by using SP feed has been theoretically analyzed in [4] and [5]. Typically, the microstrip lines with different electric lengths are utilized to achieve the phases of 0°, 90°, 180°, and 270° at four ports. A series of designs [6]–[12] by using the SP method are simulated and measured to validate the AR bandwidth enhancement. Based on this idea, several new structures are presented. An SP feed microstrip line with uniform width is proposed in [13] with compact size and simple impedance matching. A series-parallel strip with curve structure is also proved to feed a 2 × 2 array in [14] and [15]. In the study of Baik *et al.* [16], another novel SP feeding structure is achieved by using two crossed dipoles with 90°-phase delay line. Another wideband feeding network using a hybrid ring is studied in [17], and compared with the traditional series and parallel structures.

However, for single-fed corner-truncated patch array, the AR bandwidth improvement is limited. For example, the AR bandwidth of 2 × 2 patch array is less than 4% using traditional SP microstrip line [5]. For newly proposed SP feed structure, approximately 4.8% is achieved in [13] and 5.4% in [14]. In this communication, we propose a new and feasible SP feed to achieve wider AR bandwidth. The proposed SP feed is a CP loop antenna with four shorting strips. For similar 2 × 2 patch array application in [5], [13], [14], more than 7% AR bandwidth is achieved. The aim of this communication is to present a new array feed solution to achieve stable phase difference using a loop antenna, which is able to generate CP radiation itself. The center-symmetrical structure of the proposed SP feed also makes it flexible to position the element with suitable distance in the array design. Experiment has been taken to validate the design strategy, including the results of reflection coefficient, AR bandwidth, radiation patterns, and gain.

## II. SEQUENTIAL-PHASE FEEDING STRUCTURE

Fig. 1 shows the geometry of the proposed SP feed, which consists of a loop with four shorting strips (1 to 4). The loop is formed by cutting an $l_2 \times w_2$ rectangle from an $l_1 \times l_1$ square, and supported by a 3-mm thick Teflon substrate with $\varepsilon_r = 2.4$, tan$\delta = 0.002$ at 5 GHz. Four strips are connected to each side of the loop at one end and shorted to the ground at the other end. The four short ends are with the equal distance from the center of the loop. The ground is on the back side of the board with the dimensions of $l_g \times l_g$. An H-shaped slot is cut from the ground as the feed of the loop, as shown in Fig. 1(b).

The microstrip loop with four shorting strips is a CP antenna. Due to the unequal values of $l_2$ and $w_2$, two orthogonal fundamental one-wavelength modes are excited along the loop to generate a left-hand circularly polarized (LHCP) mode. The operating frequency is determined by the dimensions of the loop $(l_1)$ and the shorting strip $(l_3)$. The shorting strip can be treated as an extension of the loop to tune the operating frequency. The distance between two short ends is also dictated by the value of $l_3$. The values of $l_2$ and $w_2$ will affect the operating frequencies of dual modes on the loop, which generate the circularly polarization. The impedance of the loop antenna can be matched by tuning the dimensions ($l_4$ and $l_5$) of the feeding slot. The values of each parameter are optimized by using the Ansoft High-Frequency Structure Simulator (HFSS) software. The detailed values are listed in Table I. In this design, the overall dimension of this SP feed is only $23 \times 23$ mm$^2$ ($0.5\lambda_g \times 0.5\lambda_g$ at 5 GHz). Fig. 2 shows the simulated reflection coefficient and the AR bandwidth of the loop antenna. The bandwidths of the 10-dB reflection coefficient and the 3-dB AR are 4.73–4.91 GHz and 4.805–4.845 GHz.

TABLE I
DETAILED DIMENSIONS (UNIT: m)

| $l_g$ | $l_1$ | $l_2$ | $w_2$ | $l_3$ | $w_3$ | $l_4$ | $w_4$ | $l_5$ |
|---|---|---|---|---|---|---|---|---|
| 100 | 16.8 | 9.5 | 8 | 8 | 1 | 6.4 | 1 | 7.8 |

The current distribution on the loop antenna operating at 4.83 GHz is shown in Fig. 3. At the phases of 0°, 90°, 180°, and 270°, the current appears periodically along the loop at the one-wavelength mode and flows in a circular direction, which generates circular polarization. Due to the structure symmetry, the currents on four shorting strips also appear periodically with stable phase difference. Sequential phases of 0°, 90°, 180°, and 270° appear at the four shorting strips, which can serve as four feeding ports.

## III. APPLICATION IN 2 × 2 CP PATCH ARRAY

The proposed SP feed is utilized to feed a 2 × 2 single-fed CP corner-truncated patch array. As shown in Fig. 4(a), four patch elements are connected to four shorting strips with shorting vias ($\Phi = 0.6$ mm) to the ground. On the back side of the board, as shown in Fig. 4(b), the H-shaped slot is fed through a capacitive-coupled feeding patch. The cross-sectional view of AA$'$ plane is shown in Fig. 4(c). Between the H-shaped slot and the copper patch, there is a 0.5-mm-thick FR4 board with $\varepsilon_r = 4.4$. Therefore, the overall height of the antenna array is 3.5 mm. A 50-$\Omega$ coaxial cable is used to feed the antenna array. The inner conductor is connected to the feeding patch and the outer conductor to the ground, as illustrated in Fig. 4(b).

Three key issues are analyzed to achieve good AR and impedance bandwidths for array design. The first one is the use of four shorting vias on the feeding strips between the proposed SP feed and the patch elements. Stable phase difference is provided by the CP loop in the

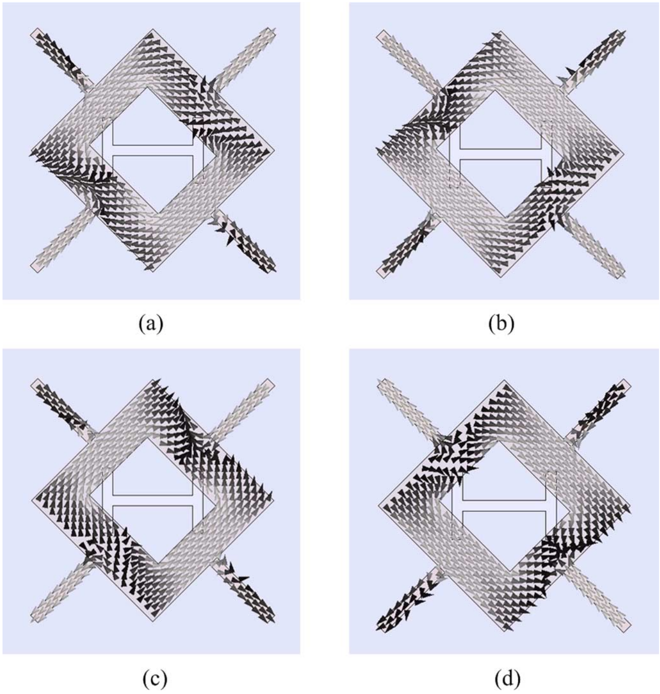
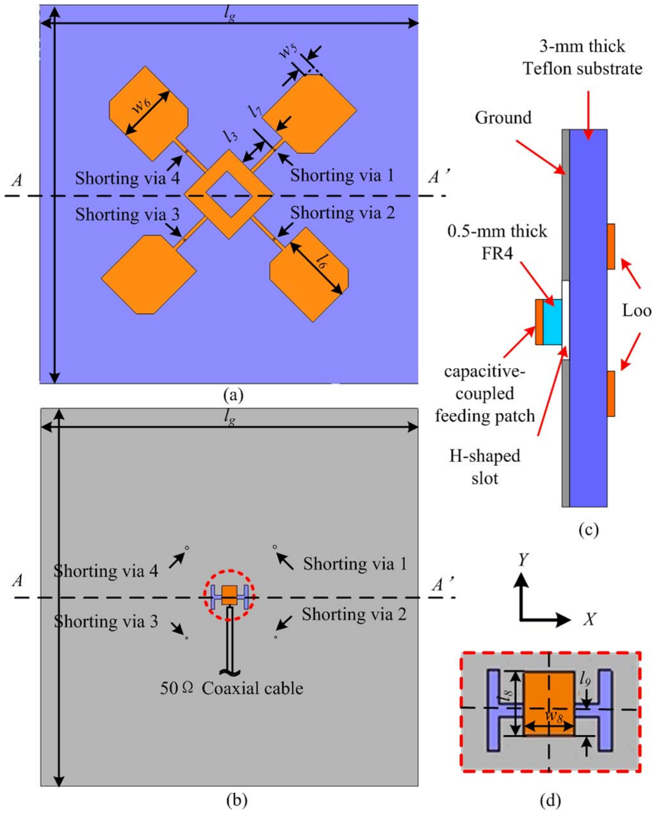

(a) (b) (c) (d)

Fig. 3. Current distribution on the loop at 4.83 GHz with different phase: (a) 0°, (b) 90°, (c) 180°, (d) 270°.



(a) (b) (c) (d)

Fig. 4. Geometry and dimensions of the $2 \times 2$ array using the proposed feeding structure (a) front view; (b) back view; (c) cross-sectional view of A-A′ plane; (d) detailed view of capacitive-coupled in red circle of (b).

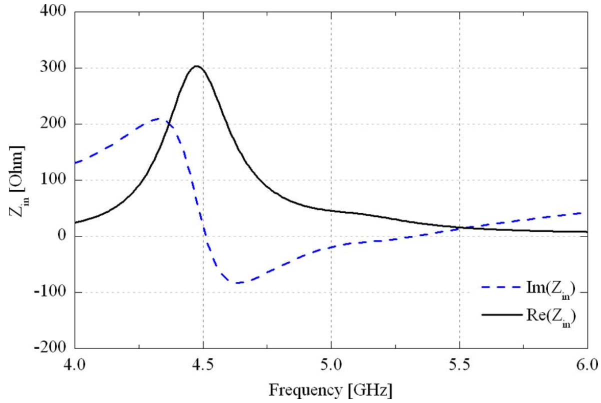


Fig. 5. Input impedance of single edge-fed patch.

center. If the patch element is connected directly to the center loop without the shorting point, the CP performance of the loop will be destroyed and the phase difference between each port is also changed. The shorting vias operates as a shunt inductance to control the energy couple to the patch element. When the feeding strip is shorted to the ground, weak coupling is achieved between the element and the strip and the phase difference is maintained.

The second one is the impedance matching between the patch element and the shorting vias. The impedance at the shorting point is a small value. A microstrip line with the length of $l_7$ is used for impedance matching from the shorting point to the patch element. However, the input impedance of the edge-fed patch used is a large value near the resonant frequency (4.5 GHz), as shown in Fig. 5. In our design, we have matched the patch element at the band higher than the resonant frequency for wider impedance bandwidth.

The third one is the impedance matching of the overall antenna array. We used a capacitive-coupled patch above the H-shaped slot on the back side. The impedance curve using the capacitive-coupled patch is shown on the Smith chart in Fig. 6. If we feed the antenna array directly using the inner conductor of the coaxial cable, as shown in the red dash-dot curve, the impedance curve is far away the circle of $\mathrm{VSWR} = 2:1$. The capacitive-coupled patch serves as a series capacitance. By tuning the values of $l_8$ and $w_8$, the overall antenna array can be well matched, as shown in the black solid curve in Fig. 6. The optimized values of each parameter are listed in Table II. The distance between two patch elements is 42.2 mm ($0.707\lambda_0$ at 5 GHz, $\lambda_0$ is the wavelength in the free space). The dimension of antenna array is $100 \times 100 \times 3$ mm$^3$, and the capacitive-coupled feed part is $5 \times 4 \times 0.5$ mm$^3$.

The simulated results of the $2 \times 2$ SP-fed CP patch array are shown in Figs. 7 and 8. Fig. 7 compares the AR bandwidths between the CP array and a single CP patch. For single elements, the AR bandwidth is only 5.03–5.12 GHz (2% at 5 GHz). In the band lower than 5.03 GHz, the advanced phase of $+\mathrm{y}$-component over $+\mathrm{x}$-component is less than 90°. However, for the proposed SP feed in this band, this value is more than 90°. Therefore, the phase difference between two orthogonal components has been complemented. When the four patch elements are fed by the proposed SP feeding structure, the AR bandwidth is enhanced by 4.8–5.15 GHz (7% at 5 GHz). In the band lower than 4.9 GHz, the patch elements operate with linear polarization but the proposed SP feed operates with circularly polarization.

The simulated radiation patterns at 5 GHz are illustrated in Fig. 8. The cross-polarization (RHCP) at the broadside (+Z direction) is more than 20 dB lower than the co-polarization (LHCP). The front-back ratio is also better than 30 dB in both $xz$- and $yz$-planes.

## IV. EXPERIMENTAL RESULTS

The proposed $2 \times 2$-element patch array has been fabricated as shown in Fig. 9. The feeding cable soldered on the edge can be treated

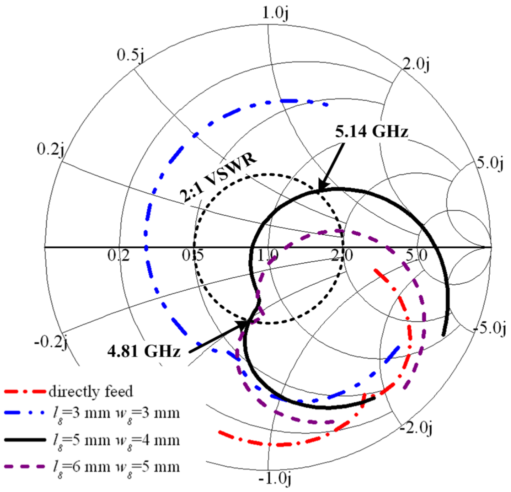


Fig. 6. Smith chart of impedance matching using capacitive-coupled patch. (The simulated frequency band is 4.5–5.5 GHz).

TABLE II
DETAILED DIMENSIONS (UNIT: mm)

| $w_5$ | $l_6$ | $w_6$ | $l_7$ | $l_8$ | $w_8$ | $l_9$ |
|---|---|---|---|---|---|---|
| 3.2 | 19.2 | 16.5 | 4 | 5 | 4 | 1.5 |

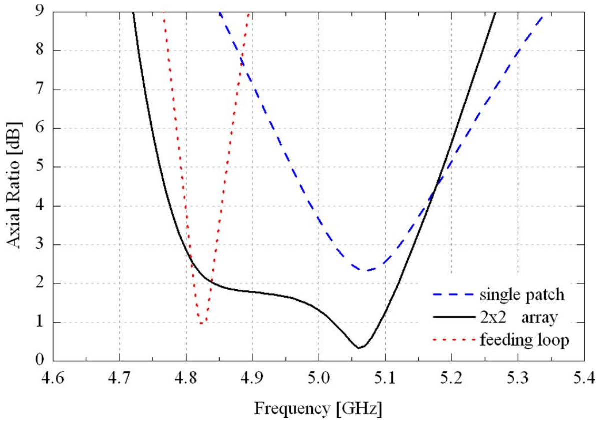
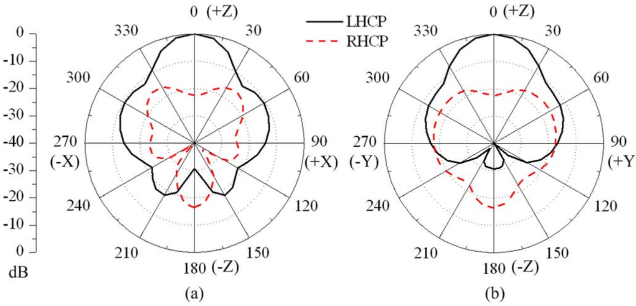


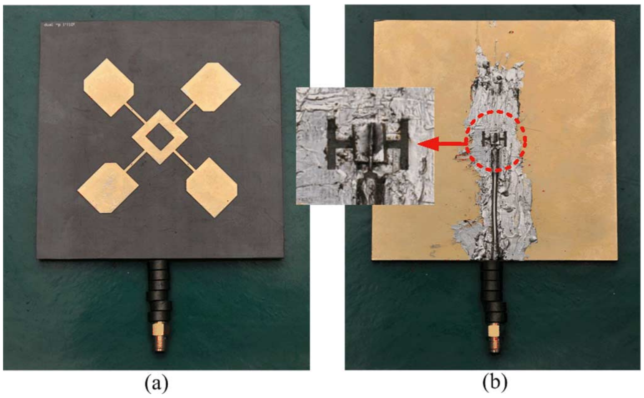
Fig. 7. Simulated AR of the 2 × 2 array, single patch and feeding loop.



(a) (b)

Fig. 8. Simulated normalized radiation pattern of the 2 × 2 array at 5 GHz in (a) $xz$-plane and (b) $yz$-plane.

as an extension of the ground. As we know, the size of the ground is sensitive to the CP performance. To maintain the ground size, a series of magnetic beads are used to prevent surface current on the feeding cable.



(a) (b)

Fig. 9. Photograph of the 2 × 2 array with the proposed feeding structure (a) front view, (b) back view.

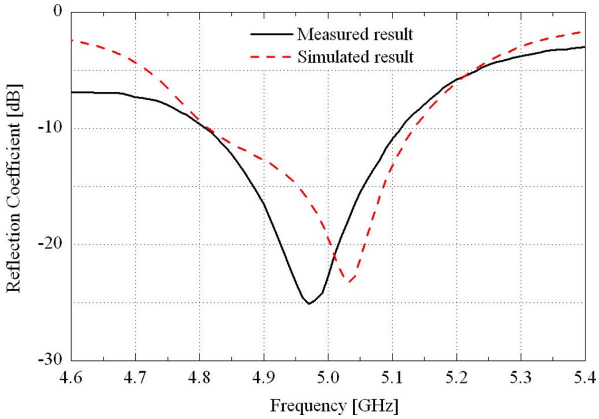


Fig. 10. Simulated and measured reflection coefficient of the 2 × 2 array.

Fig. 10 shows the measured reflection coefficient of the proposed antenna array, which agreed well with the simulated results. The 10-dB reflection coefficient bandwidth is from 4.82 GHz to 5.12 GHz. The measured and the simulated AR bandwidths are illustrated in Fig. 11. The 3-dB AR bandwidth is from 4.84 GHz to 5.13 GHz. The difference between simulation and measurement is mainly comes from the fabrication error, also with uncertain permittivity of the substrate and surface roughness. Approximately 1-dB error of AR appears in the measurement. The experimental results have validated the design strategy of the proposed SP feed. The measured radiation patterns in xz- and yz-planes at 5 GHz are shown in Fig. 12. The front-back ratio is better than 16 dB in both two planes. Good AR is achieved at the broadside.

The measured gain at the broadside is shown in Fig. 13 and compared with the simulated results. In the band higher than 4.94 GHz, the gain is greater than 9 dBic, and the peak gain is 10.5 dBic. However, for the band lower than 4.94 GHz, the gain decreases and is similar to a single CP patch element. In this band, the CP performance is mainly contributed from the radiation of the SP feeding structure itself. As a result, the 2 × 2-element patch array is with little contribution to the gain of LHCP in the band of 4.8–4.94 GHz. As shown in Fig. 13, the bandwidth with gain variation less than 3 dB is from 4.86 GHz to a frequency higher than 5.2 GHz. Considering the measured 10-dB reflection coefficient bandwidth, 3-dB AR bandwidth and 3-dB gain variation bandwidth, the global bandwidth of the proposed antenna is

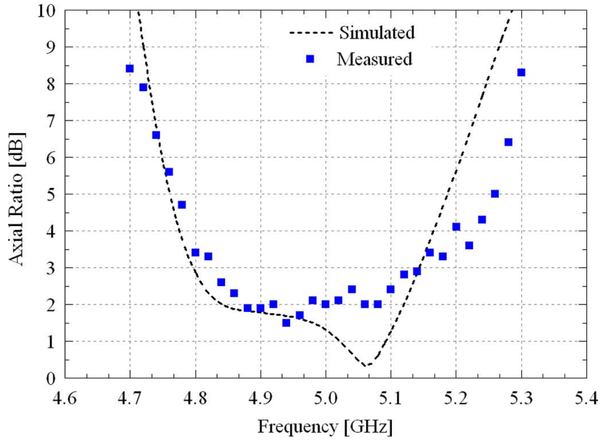


Fig. 11. Simulated and measured axial ratio of the 2 × 2 array.

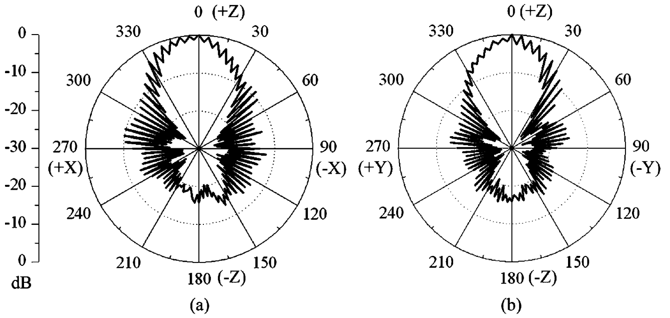


Fig. 12. Measured normalized radiation patterns of the 2 × 2 array at 5 GHz. (a) $xz$-plane; (b) $yz$-plane.

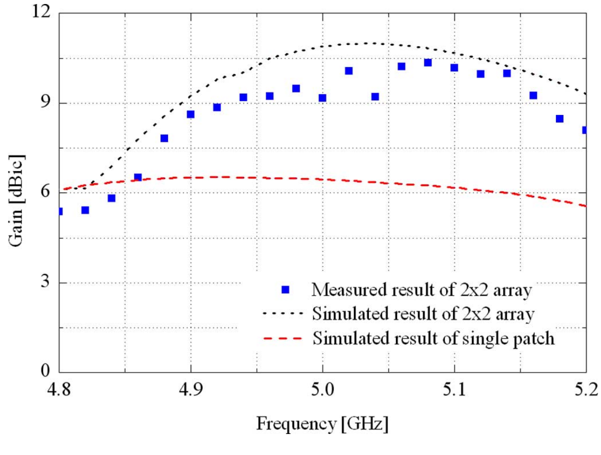


Fig. 13. Simulated and measured gains of the 2 × 2 array.

4.86–5.12 GHz. The measured results have proved that the proposed SP feed is an acceptable candidate for the CP array feeding.

## V. CONCLUSION

This communication gives a feasible solution of SP feed using a CP shorted loop. To the authors' knowledge, it is the first time to adopt CP antenna to provide stable phase difference among each feeding port. The proposed SP feed has the merits of simple structure, compact dimensions and easy impedance matching. By adopting the proposed feeding structure with a 2 × 2 single-fed corner-truncated patch array, the AR bandwidth has been improved from 2% of single CP patch to 7% of the CP array, wider than the previous designs. A measured global bandwidth (S11 $< -10$ dB, AR $< 3$ dB and gain variation within 3 dB) of 4.86–5.12 GHz has achieved. The proposed SP feed also has the advantages of center-symmetry and compact dimension, which are flexible for the element arrangement in the array design.

## REFERENCES

[1] I. Chen, C. Huang, and P. Hsu, "Circularly polarized patch antenna array fed by coplanar waveguide," *IEEE Trans. Antennas Propag.*, vol. 52, no. 6, pp. 1607–1609, 2004.

[2] P. Hallbjörner, I. Skarin, K. From, and A. Rydberg, "Circularly polarized traveling-wave array antenna with novel microstrip patch element," *IEEE Antennas Wireless Propag. Lett.*, vol. 6, pp. 1825–1828, 2007.

[3] C. Min and C. Free, "Dual-ring circularly-polarized microstrip patch array using hybrid feed," *IEEE Trans. Antennas Propag.*, vol. 57, no. 6, pp. 1825–1829, 2009.

[4] A. Smolders and U. Johannsen, "Axial ratio enhancement for circularly-polarized millimeter-wave phased-arrays using a sequential rotation technique," *IEEE Trans. Antennas Propag.*, vol. 59, no. 9, pp. 3465–3469, 2011.

[5] P. S. Hall, "Application of sequential feeding to wide bandwidth, circularly polarized microstrip patch arrays," in *Proc. Inst. Elect. Eng.*, May 1989, vol. 136, pp. 390–398, pt. H.

[6] S. Fu, S. Fang, Z. Wang, and X. Li, "Broadband circularly polarized slot antenna array fed by asymmetric CPW for L-band applications," *IEEE Antennas Wireless Propag. Lett.*, vol. 8, pp. 1014–1016, 2009.

[7] A. R. Weily and Y. J. Guo, "Circularly polarized ellipse-loaded circular slot array for millimeter-wave WPAN applications," *IEEE Trans. Antennas Propag.*, vol. 57, no. 10, pp. 3680–3684, 2009.

[8] J. Huang, "A Ka-band circularly polarized high-gain microstrip array antenna," *IEEE Trans. Antennas Propag.*, vol. 43, no. 1, pp. 113–116, 1995.

[9] R. Caso, A. Buffi, M. R. Pino, P. Nepa, and G. Manara, "A novel dual-feed slot-coupling feeding technique for circularly polarized patch arrays," *IEEE Antennas Wireless Propag. Lett.*, vol. 9, pp. 183–186, 2010.

[10] U. R. Kraft, "An experimental study on 2□$box$2 sequential-rotation arrays with circularly polarized microstrip radiators," *IEEE Trans. Antennas Propag.*, vol. 45, no. 10, pp. 1459–1466, 1997.

[11] R. Ramirez, F. Flaviis, and N. Alexopoulos, "Single-feed circularly polarized microstrip ring antenna and arrays," *IEEE Trans. Antennas Propag.*, vol. 48, no. 7, pp. 1040–1047, 2000.

[12] K. H. Lu and T.-N. Chang, "Circularly polarized array antenna with corporate-feed network and series-feed elements," *IEEE Trans. Antennas Propag.*, vol. 53, no. 10, pp. 3288–3292, 2005.

[13] S. Lin and Y. Lin, "A compact sequential-phase feed using uniform transmission lines for circularly polarized sequential-rotation arrays," *IEEE Trans. Antennas Propag.*, vol. 59, no. 7, pp. 2721–2724, 2011.

[14] A. Chen, Y. Zhang, Z. Chen, and S. Cao, "A Ka-band high-gain circularly polarized microstrip antenna array," *IEEE Antennas Wireless Propag. Lett.*, vol. 9, pp. 1115–1118, 2010.

[15] Y. Qin, S. Gao, and A. Sambell, "Broadband high-efficiency circularly polarized active antenna and array for RF front-end application," *IEEE Trans. Microw. Theory Tech.*, vol. 54, no. 7, pp. 2910–2916, 2006.

[16] J. Baik, T. Lee, S. Pyo, S. Han, J. Jeong, and Y. Kim, "Broadband circularly polarized crossed dipole with parasitic loop resonators and its arrays," *IEEE Trans. Antennas Propag.*, vol. 59, no. 1, pp. 80–88, 2011.

[17] S. S. Yang, R. Chair, A. A. Kishk, K. F. Lee, and K. M. Luk, "Study on sequential feeding networks for subarrays of circularly polarized elliptical dielectric resonator antenna," *IEEE Trans. Antennas Propag.*, vol. 55, no. 2, pp. 321–333, 2007.