A Waveguide Antenna With Bidirectional Circular Polarizations of the Same Sense

Yang Zhao, *Student Member, IEEE*, Kunpeng Wei, *Student Member, IEEE*, Zhijun Zhang, *Senior Member, IEEE*, and Zhenghe Feng, *Fellow, IEEE*

***Abstract*—A square-aperture metallic waveguide antenna with bidirectional circularly polarized (Bi-CP) radiations of the same sense is proposed in this letter. Circular polarization was realized by two identical rectangular metal strips installed on one lateral side of the waveguide with a 45° inclination angle. The two rectangular metal strips were vertically separated by a distance of a quarter guided wavelength and horizontally intersected with an angle of 90°. They were excited with the same amplitude and phase by feeding the antenna in the middle of their diagonal line. A 90° phase difference between the two rectangular metal strips was introduced by the spatial distance of a quarter guided wavelength, and thus circular polarizations of the same sense in the two opposite radiating directions were generated. A quarter-wavelength impedance transformer was designed to help with the antenna's matching characteristic. The measured impedance bandwidth for $|S_{11}| \leq -10$ dB was 710 MHz (1.92 $\sim$ 2.63 GHz), and the measured 3-dB axial-ratio bandwidth was 200 MHz (2.34 $\sim$ 2.54 GHz). The measured bidirectional 3-dB axial-ratio beamwidth at 2.44 GHz was 62°, and the power variation was smaller than 3 dB within this angular range.**

***Index Terms*—Bidirectional, circular polarization, same sense, waveguide antenna.**

I. Introduction

ANTENNAS with bidirectional radiation patterns are required in various mobile wireless communication systems, such as a microcellular base station, a high-speed WLAN, and indoor wireless access. Circularly polarized (CP) antennas are commonly used to enhance channel stability and reliability. The mechanism of generating CP waves is to excite two orthogonal linearly polarized components with the same amplitude, but with a 90° phase difference. The methods of realizing circular polarization include single-fed, dual-fed techniques, structural rotation of linearly polarized elements, etc. CP patch antennas with single feed and perturbations, such as truncated corners and cutting slots, were analyzed and optimized in [1], but the axial-ratio bandwidth of these CP antennas was limited. A slot antenna with a stacked parasitic patch and embedded metal patches was proposed in [2] and [3], respectively, to improve the bandwidth of the traditional CP slot antennas. In addition, CP patch antennas or slot antennas with dual feed ports [4], [5] were designed to enhance the performance of the antenna's bandwidth, but an extra phase difference was needed to design for the two feeding ports, which would increase the antennas' structural complexity. An element sequential rotation method that feeds the orthogonal elements with a unique phase arrangement for circular polarization was presented in [6]. However, when designing antennas with bidirectional CP (Bi-CP) radiations, all the above-mentioned design methods will produce CP radiations of opposite senses in the two different radiating directions. That is, when right-hand circular polarization (RHCP) is radiated at one port, the sense of rotation at the opposite port would inevitably be left-hand circular polarization (LHCP). Furthermore, no signals will be received if the polarizations of the transmitter and receiver are mismatched in the opposite direction.

To realize CP radiations of the same sense in two opposite directions, a back-to-back configuration was applied in [7]–[10]. In [8], a slot-coupled patch antenna with Bi-CP radiations of the same sense was designed, where two corner-cutting CP patches were arranged back to back relative to a slot on the ground plane. A coplanar waveguide feeding structure was employed in [9] and [10] to excite the two back-to-back partially overlapped rectangular CP patches for Bi-CP radiations. However, all these proposed designs are just duplications of unidirectional CP element at the front and back sides of a common feeding scheme and have limited 3-dB axial-ratio bandwidth and insufficient 3-dB axial-ratio beamwidth.

In this letter, we propose a novel design of bidirectional waveguide antenna with circular polarizations of the same sense in the two opposite radiating directions. The generation of Bi-CP radiations with the same sense of rotation is not just a replica of unidirectional CP elements, but the inherent property of the proposed structure. Two rectangular metal strips were positioned at one lateral side of the square-aperture waveguide with a 45° inclination angle. Furthermore, they were separated by a quarter guided wavelength in the vertical direction, intersected with a 90° angle in the horizontal plane, and fed in the middle of their diagonal line for equal amplitude and phase. The 90° phase difference between the two rectangular metal strips for Bi-CP radiations was realized by the vertical separation of a quarter guided wavelength. The features of the proposed antenna include simple metallic structure, low cost, and easy fabrication. The design details are presented in the following sections.

Manuscript received March 27, 2013; accepted April 16, 2013. Date of publication April 25, 2013; date of current version May 03, 2013. This work was supported by the National Basic Research Program of China under Contract 2010CB327400, in part by the National High Technology Research and Development Program of China (863 Program) under Contract 2009AA011503, the National Natural Science Foundation of China under Contract 61271135, the Ministry of Science and Technology of China under the National Science and Technology Major Project 2010ZX03007-001-01, and Qualcomm, Inc.

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

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

Digital Object Identifier 10.1109/LAWP.2013.2259462

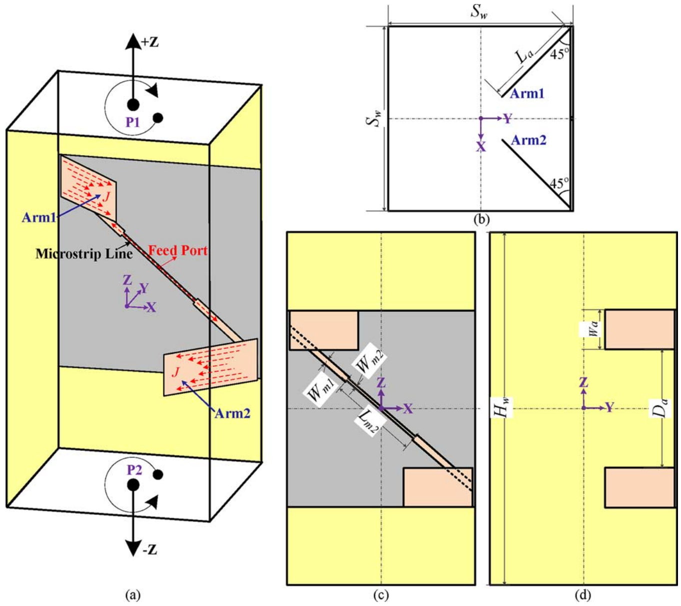

Fig. 1. Antenna geometry. (a) 3-D perspective view. Planar views: (b) xoy-plane; (c) zox-plane; and (d) zox-plane. Values of the parameters are $S_{\rm w} = 76.0$, $H_{\rm w} = 143.0$, $L_{\rm a} = 40.0$, $W_{\rm a} = 16.0$, $D_{\rm a} = 48.0$, $W_{\rm m1} = 2.7$, $W_{\rm m2} = 1.1$, $L_{\rm m2} = 36.0$ (unit: millimeter).

II. Antenna Design

A. Antenna Structure

The three-dimensional geometry of the proposed antenna with Bi-CP radiations of the same sense is shown in Fig. 1(a), where we can see that the whole antenna contains a waveguide with square aperture, two rectangular metal strips, and a stepped microstrip line. The width of the square aperture is $S_{\rm w}$, and the height of the waveguide is $H_{\rm w}$. The antenna is surrounded by four metallic lateral sides, and the upper port P1 and the lower port P2 are left open for bidirectional radiations. A 1-mm-thick dielectric substrate with a relative permittivity of 2.65 and a loss $\tan\delta$ of 0.005 is screwed on one lateral side of the waveguide. Two identical rectangular metal strips *Arm1* and *Arm2* of length $L_{\rm a}$ and width $W_{\rm a}$ are installed on the front side of the substrate with an inclination angle of 45°. These two metal arms are vertically separated by a distance of $D_{\rm a}$, which is about a quarter guided wavelength at the desired operating frequency. In addition, they are crossed with a 90° angle seen from the top plane, as indicated in Fig. 1(b). A microstrip line with the lateral sides of the metallic waveguide working as ground is constructed on the substrate to connect the diagonal line of the two rectangular metal arms. Meanwhile, a stepped microstrip line with length $L_{\rm m2}$ and width $W_{\rm m2}$ is designed so that a quarter impedance transformer is formed for impedance matching, as shown in Fig. 1(c). The waveguide antenna is fed in the middle of the microstrip line by a coaxial probe. In this way, the two arms are excited with the same phase and amplitude, and bidirectional circular polarizations of the same sense can be intrinsically radiated by the proposed antenna.

B. Operation Mechanism

The proposed antenna has the inherent characteristic of Bi-CP radiations of the same sense. The operating mechanism can be explained as follows. First, the antenna is fed in the middle of the diagonal microstrip line, and the current on the two rectangular metal arms *Arm1* and *Arm2* can be excited with the same phase and amplitude, as plotted in Fig. 1(a). A 90° phase difference between the two rectangular metal arms is introduced by the spatial distance of a quarter guided wavelength. When the antenna radiates from the upper port P1 ($+Z$ direction), the phase of *Arm2* will lag behind that of *Arm1* by 90°, and LHCP can be realized. Meanwhile, the phase of *Arm1* will lag behind that of *Arm2* by 90° when the antenna radiates from the lower port P2 ($-z$-direction), and thus LHCP is again obtained. The variation of electrical fields with a period of time at the upper and lower radiating ports is shown in Fig. 2, where we can see that the two opposite ports can exhibit CP radiations with the same type of rotation simultaneously. RHCP can be realized by rotating the two rectangular strips by 90°.

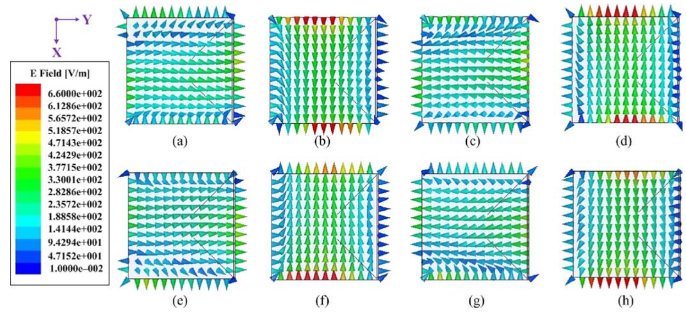

Fig. 2. Electrical field distributions of the two radiating ports at different times. Upper radiating port P1: (a) $t = 0$; (b) $t = T/4$; (c) $t = T/2$; (d) $t = 3T/4$. Lower radiating port P2: (e) $t = 0$; (f) $t = T/4$; (g) $t = T/2$; (h) $t = 3T/4$.

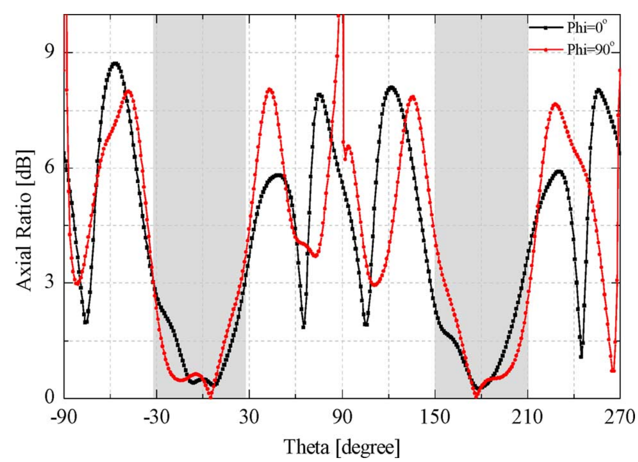

Fig. 3. Bidirectional axial-ratio beam at 2.44 GHz of the proposed antenna.

C. Simulated and Experimental Results

A prototype operating at 2.4-GHz WLAN communications was designed, fabricated, and measured to verify our proposed concept, and the values of the parameters are shown in the caption of Fig. 1. The simulation and analysis were realized by Ansoft HFSS based on the finite element method. Figs. 3 and 4 show the simulated bidirectional axial-ratio beams and the bidirectional radiation patterns in zox- and zoy-planes at 2.44 GHz, respectively, and 3-dB axial-ratio beamwidths of 58° centered at 0° (P1, $+z$) and 180° (P2, $-z$) radiating directions

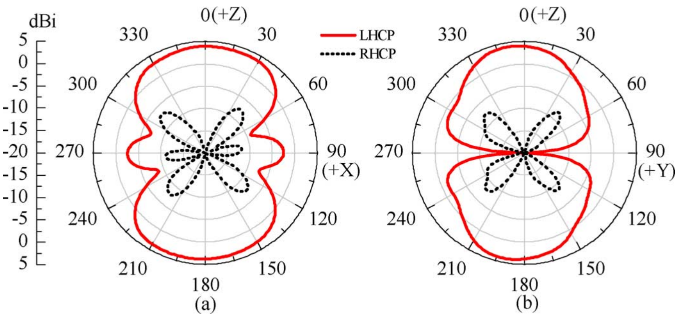

Fig. 4. Bidirectional radiated gain patterns of the proposed antenna at 2.44 GHz: (a) zox-plane; (b) zoy-plane.

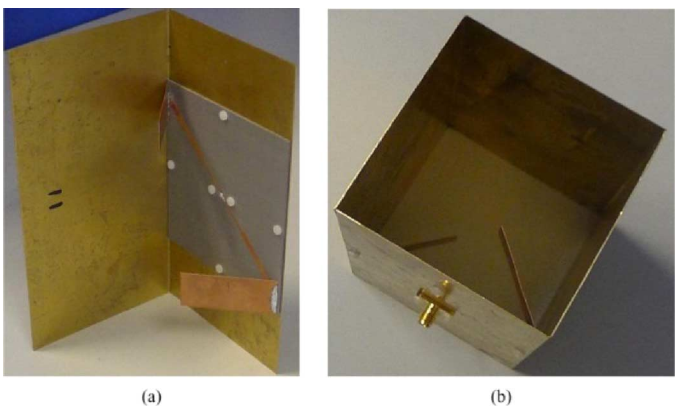

Fig. 5. Photograph of the fabricated antenna prototype: (a) installation of the microstrip line and the two inclining rectangular metal arms; (b) whole composite waveguide antenna.

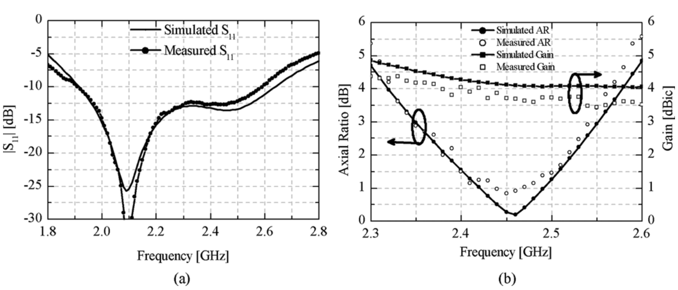

Fig. 6. Simulated and measured (a) reflection coefficients and (b) axial ratios of the proposed antenna.

were realized in the two principal planes, respectively. Meanwhile, an identical maximum realized gain of about 4.1 dBic was realized in the two opposite directions. The gain variation was smaller than 3 dB within the angular range of the 3-dB axial-ratio beamwidth. The photograph of the manufactured prototype is shown in Fig. 5. Fig. 6 compares the measured and the simulated reflection coefficient, axial ratio, and gain in $+z$-direction. The comparison of axial ratio and gain in $-z$-direction shows almost the same characteristics. The simulated and measured impedance bandwidths for $|S_{11}| \leq -10$ dB were 710 MHz (31.2%, 1.92–2.63 GHz) and 680 MHz (30.2%, 1.91–2.59 GHz), respectively. The simulated and measured 3-dB axial-ratio bandwidth in the two opposite radiation directions were 200 MHz (8.2%, 2.35–2.55 GHz) and 190 MHz (7.8%, 2.35–2.54 GHz), respectively. The measured maximum gain was 3.8 dBic at 2.44 GHz in the two ports, and a variation

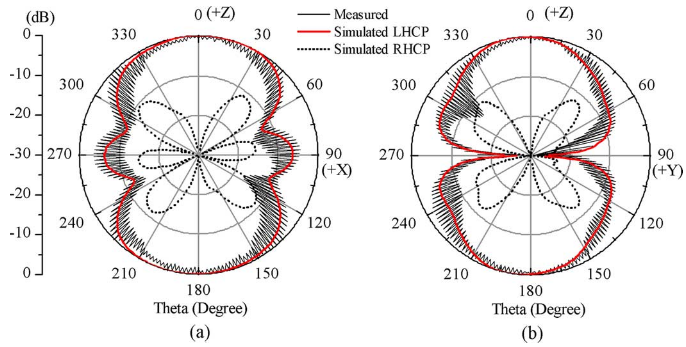

Fig. 7. Normalized CP radiation pattern at 2.44 GHz of the proposed antenna: (a) zox-plane; (b) zoy-plane.

of about 0.8 dB was observed within the bandwidth of 3-dB axial ratio. Fig. 7 shows the measured normalized CP radiation patterns at 2.44 GHz with a spinning transmitting horn, which agree well with the simulated ones. The zigzag of the measured CP patterns represents the maximum and minimum values of the corresponding axial ratio. The radiation patterns in the two opposite directions were symmetric, indicating that the power was equally divided and radiated. The radiation pattern in the whole operating band remained stable. Overall, the measured and the simulated results showed good agreement, and the little discrepancies can be attributed to manufacturing deviation and measurement system setup.

III. Parameter Study

The proposed waveguide antenna has a natural characteristic of Bi-CP radiations of the same sense. The procedure to design the proposed antenna working at a desired frequency f_0 can be summarized as follows. Based on the following equation:

$$f_{\mathrm{c}} = \frac{c_0}{\lambda_{\mathrm{c}}} = \frac{c_0}{(2 \times S_w)} \tag{1}$$

where c_0 represents the light velocity, we first decided the aperture size S_{w} of the waveguide whose cutoff frequency f_{c} should be lower than that of the desired operating frequency f_0. Then, using the following equation:

$$D_{\mathrm{a}} = \frac{\lambda_{\mathrm{g}}}{4} = \frac{\lambda_0}{4 \times \sqrt{1 - \left(\frac{\lambda_0}{\lambda_{\mathrm{c}}}\right)^2}} = \frac{\frac{c_0}{f_0}}{4 \times \sqrt{1 - \left(\frac{f_{\mathrm{c}}}{f_0}\right)^2}} \tag{2}$$

we calculated the vertical distance D_{a} of the two rectangular metal arms to make them separated by a quarter guided wavelength ($\lambda_{\mathrm{g}}/4$). Next, we adjusted the width W_{a} and length L_{a} of the two metal arms to obtain a minimum axial ratio at the operating frequency. Finally, we employed a stepped microstrip line with width W_{m2} and length L_{m2} to match the antenna for $|S_{11}| \leq -10$ dB over the operating band.

To further understand the working principle of the proposed antenna, we investigated some important parameters that significantly influence the antenna's performance. The reflecting coefficients and axial ratios were considered when adjusting one of the parameters while keeping all the others listed in the caption of Fig. 1 unchanged. The waveguide height H_{w} almost had no impact on the impedance matching, but it played a major role in the power division between the two opposite radiating

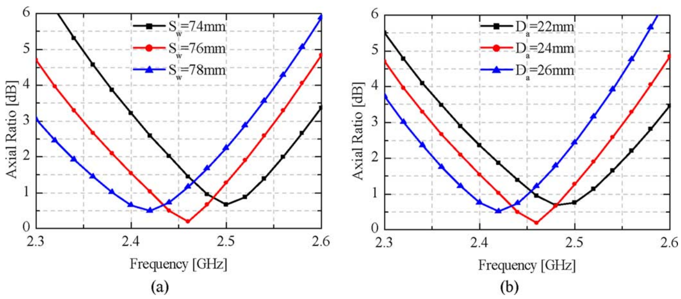

Fig. 8. Axial ratio of the proposed waveguide antenna with different dimension of (a) aperture size S_w; and (b) vertical distance of the two metal arms D_a.

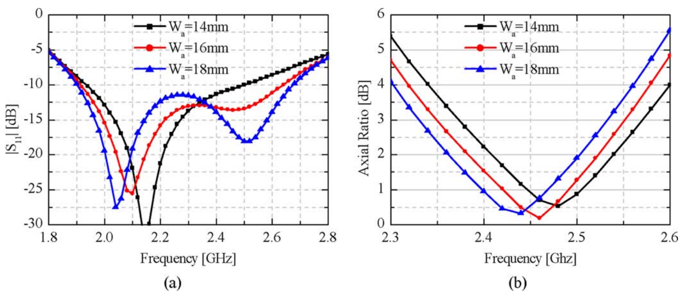

Fig. 9. Reflection coefficient (a) and axial ratio (b) of the proposed waveguide antenna with different width W_a of the two identical rectangular metal arms.

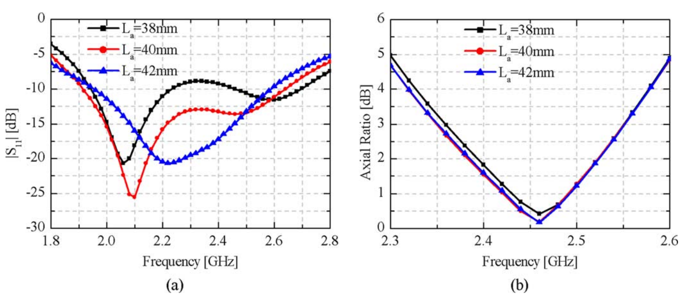

Fig. 10. Reflection coefficient (a) and axial ratio (b) of the proposed waveguide antenna with different length L_a of the two identical rectangular metal arms.

ports and the purity of circular polarization. By optimizing the waveguide height $H_{\rm w}$ and the position of the inserted rectangular metal arms, the proposed antenna could radiate equally in the two directions. The parameters that influence the axial ratio of the proposed antenna include the size of the waveguide aperture $S_{\rm w}$, the spatial separation $D_{\rm a}$, and the width $W_{\rm a}$ of the two rectangular arms. Fig. 8 shows the simulated axial ratio with varying aperture size $S_{\rm w}$ and vertical separation $D_{\rm a}$, where we can observe that these two parameters have a great influence on the axial ratio because they both determine the phase difference at the desired operating frequency. The frequency with a minimum axial ratio becomes lower with the increase in $S_{\rm w}$ and $D_{\rm a}$. The influence of the width $W_{\rm a}$ and length $L_{\rm a}$ of the two arms on the reflecting coefficient and axial ratio is shown in Figs. 9 and 10, respectively. The change in the width $W_{\rm a}$ shifts both the reflecting coefficient and axial ratio, and the length $L_{\rm a}$ has almost no impact on the axial ratio, but has a great influence on impedance matching. In addition, the variation in reflecting coefficient with different width $W_{\rm m2}$ and length $L_{\rm m2}$ of the stepped microstrip line is shown in Fig. 11, where we can observe that the quarter wavelength impedance transformer can

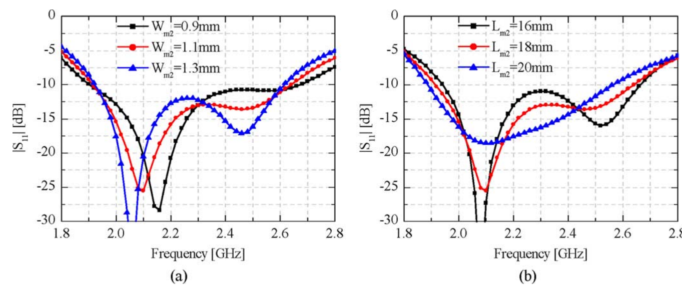

Fig. 11. Reflection coefficient of the proposed waveguide antenna with different dimensions of the microstrip line (a) width W_{m2}; and (b) length L_{m2}.

make the whole antenna matched for $|S_{11}| \leq -10$ dB over a wide band.

IV. Conclusion

A waveguide antenna with inherent circular polarizations of the same sense in two opposite radiating directions has been proposed in this letter. Two rectangular metal arms, vertically separated by a quarter guided wavelength, were inserted on one lateral side of the waveguide with a 45° inclination angle. These two arms were intersected with a 90° angle in the azimuth plane. A quarter-wavelength impedance transformer was employed for antenna matching. The proposed design could naturally generate Bi-CP radiations of the same sense, which is not a copy of unidirectional CP element in the two opposite directions. The proposed antenna is simple in geometry and easy to fabricate, which is advantageous in many mobile wireless communications. A prototype for 2.4-GHz WLAN applications was manufactured and experimentally tested to verify our design. The measured and the simulated results agree well with each other. The size of the proposed antenna can be made suitable for small mobile terminals by loading of the waveguide with dielectric materials.

References

[1] P. C. Sharma and K. C. Gupta, "Analysis and optimized design of single feed circularly polarized microstrip antennas," *IEEE Trans. Antennas Propag.*, vol. AP-31, no. 6, pp. 949–955, Nov. 1983.

[2] Y.-T. Chen, S.-W. Wu, and J.-S. Row, "Broadband circularly-polarized slot antenna array," *Electron. Lett.*, vol. 43, no. 24, pp. 1323–1324, 2007.

[3] S.-P. Pan, J.-Y. Sze, and P.-J. Tu, "Circularly polarized square slot antenna with a largely enhanced axial-ratio bandwidth," *IEEE Antennas Wireless Propag. Lett.*, vol. 11, pp. 969–972, 2012.

[4] A. Adrian and D. H. Schaubert, "Dual aperture-coupled microstrip antenna for dual or circular polarization," *Electron. Lett.*, vol. 23, no. 23, pp. 1226–1228, 1987.

[5] Y.-F. Lin, H.-M. Chen, F.-H. Chu, and S.-C. Pan, "Bidirectional radiated circularly polarized square-ring antenna for portable RFID reader," *Electron. Lett.*, vol. 44, no. 24, pp. 1383–1384, 2008.

[6] J. Huang, "A technique for an array to generate circular polarization with linearly polarized elements," *IEEE Trans. Antennas Propag.*, vol. AP-34, no. 9, pp. 1113–1124, Sep. 1986.

[7] H. lwasaki, "A back-to-back rectangular-patch antenna fed by a CPW," *IEEE Trans. Antennas Propag.*, vol. 46, no. 10, pp. 1527–1530, Oct. 1998.

[8] H. lwasaki, "Slot-coupled back-to-back microstrip antenna with an omni- or a bi-directional radiation pattern," *Inst. Elect. Eng. Proc. Microw. Antennas Propag.*, vol. 146, no. 3, pp. 219–223, 1999.

[9] Q.-Y. Zhang, G.-M. Wang, and D.-Y. Xia, "Bidirectional circularly polarized microstrip antenna fed by coplanar waveguide," in *Proc. IEEE ISAPE*, 2006, pp. 1–3.

[10] A. Z. Narbudowicz, X. L. Bao, and M. J. Ammann, "Bidirectional circularly polarized microstrip antenna for GPS applications," in *Proc. LAPC*, 2010, pp. 205–208.