A Design of Dual-Frequency Dual-Sense Circularly-Polarized Slot Antenna

Yu Shao and Zhangyou Chen

***Abstract*—A single-feed dual-frequency dual-sense circularly-polarized (CP) printed slot antenna etched on a single substrate is proposed. This antenna is composed of an annular slot and a cross slot, which produce two different frequency bands. The lower band and the upper band are controlled by the annular slot and the cross slot respectively. By introducing asymmetry on both annular slot and cross slot, CP radiation at the two frequencies can be obtained. The method of impedance matching has been discussed in detail. The key parameters of the design are investigated to show how to obtain dual-frequency and dual circular polarization. Two antenna prototypes are fabricated and measured, experimental results show that good CP radiation performances are obtained at both frequencies.**

***Index Terms*—Annular slot, cross slot, dual-frequency, dual-sense circular polarization.**

I. Introduction

PRINTED slot antennas have attractive features of light weight and low profile. Compared to patch antennas, slot antenna has wider bandwidth, less conductor loss and less sensitivity to manufacturing tolerances. Moreover, by specially designing, they can produce two different operating frequency bands and circularly-polarized (CP) radiation.

Several dual-frequency designs for slot antenna have been proposed [1]–[4], all these designs are linear polarization. Several technologies have been proposed to produce circular polarization [5]–[7], all these designs only realize CP radiation at a single frequency. In [8], a dual-frequency annular slot antenna with identical circular polarization is discussed. However, relatively few designs of dual-frequency slot antenna with dual orthogonal circular polarization have been reported. In [9], a dual-frequency microstrip antenna with dual circular polarization is proposed, however, the structure has three dielectric layers, which introduces the complexity and difficulty in manufacture process. In [10], a dual-frequency dual CP slot antenna is achieved by using a single-layer substrate. This antenna consists of an annular slot and four additional linear slots. In [11], a zonal slot and an annular slot are used to realize dual-band and dual CP radiation, both of the slots are cut on a conducting cavity. In [12], a spiral slot is used to obtain dual-frequency and dual CP radiation, but the range of the frequency ratio is limited.

In this paper, a dual-frequency dual-sense circularly-polarized printed slot antenna which utilizes annular slot and cross slot is proposed. The antenna is single-feed and is etched on single dielectric layer. Compared with the previous design, the proposed antenna is easy to fabricate and has the flexibility to obtain arbitrary polarization at each frequency. Section II shows the structure of this antenna and discusses the mechanism of this antenna. To obtain 50 Ω input impedance, the design of feed line is discussed in Section III. The effects of varying some key parameters are studied with the aid of CST Microwave Studio in Section IV. In Section V, some antenna prototypes are implemented and experimental results are presented and discussed.

II. Antenna Structure

The configuration of the proposed dual-frequency dual CP slot antenna is shown in Fig. 1. The antenna is printed on a substrate of thickness h and relative permittivity ε_r. The antenna consists of an annular-ring slot and a centered cross slot. The annular-ring slot has a mean radius R and a width $S1$. To realize CP radiation, we use a pair of notches placed at 45° and 225° from the feed point, the notch has a width W_p and a depth d_p. The centered cross slot consists of two orthogonal rectangular slots whose lengths are $L1$ and $L2$, and width is $S2$. To realize CP radiation, we should adjust $L1$ and $L2$ to be different, the difference is $\triangle L = L1 - L2$. The microstrip feed line is composed of a 50 Ω transmission line, which has a stub length L_s and a width W_f and an impedance transformer with the dimensions of L_t and W_t [13], [14], which transforms the slot impedance, seen at the edge of the ring slot, to the required input impedance of 50 Ω at the feed point.

For conventional annular-ring slot, at the frequency of the fundamental resonant mode, the wavelength in the ring slot approximately equals to the mean circumference of the ring. By introducing a pair of notches, the symmetry of the ring slot will be perturbed. This perturbation will split the fundamental resonant mode into two orthogonal degenerate modes for CP radiation. For conventional rectangular slot, the fundamental resonant mode occurs at the frequency whose half wavelength in the slot approximately corresponds to the length of the slot. The difference between the lengths of the two orthogonal rectangular slots will excite two orthogonal resonant modes with 90° phase difference and CP performance will be achieved. The frequency decided by annular-ring slot is lower than the frequency decided by cross slot, so the CP radiation at the lower frequency is controlled by R, W_p and d_p the CP radiation at the upper frequency

Manuscript received December 06, 2011; revised March 20, 2012; accepted June 25, 2012. Date of publication August 13, 2012; date of current version October 26, 2012.

Y. Shao is with the Electronic Information School, Wuhan University, Wuhan 430072, China, and also with Auburn University, Auburn, AL 36830 USA (e-mail: shaoyu200531200259@163.com; YZS0016@tigermail.auburn.edu).

Z. Chen is with the Electronic Information School, Wuhan University, Wuhan 430072, China (e-mail: chzhyou@whu.edu.cn).

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

Digital Object Identifier 10.1109/TAP.2012.2208444

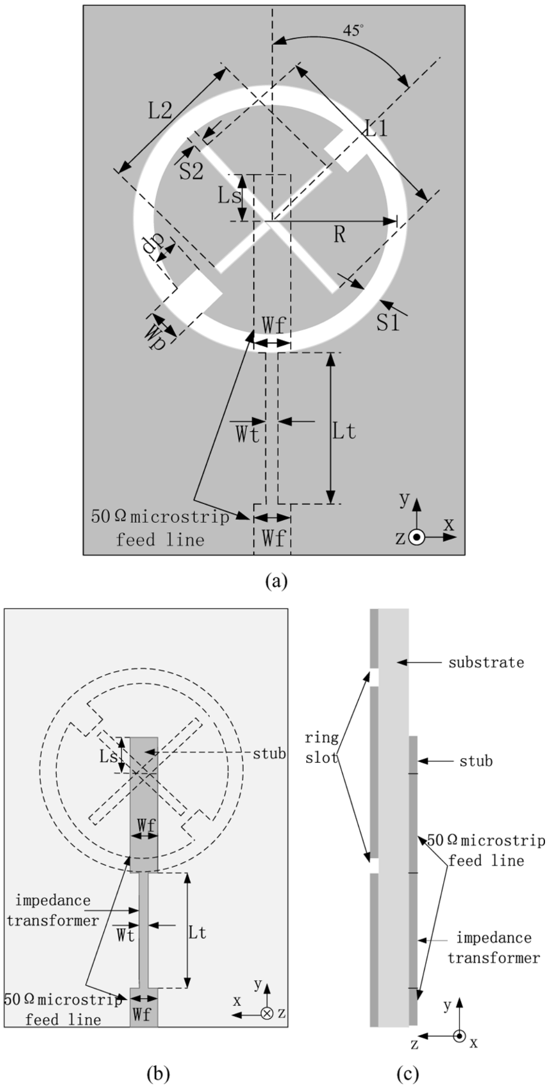


Fig. 1. Geometry of proposed dual-frequency dual CP printed slot antenna. (a) Top view. (b) Back view. (c) Side view.

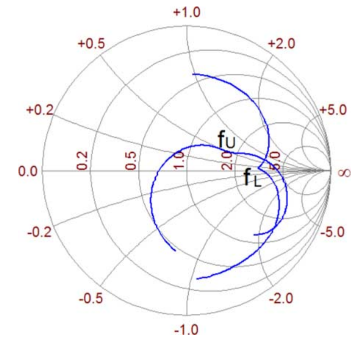


Fig. 2. Impedance seen at the edge of the ring slot of the antenna (without impedance transformer); $L_s = 1$ mm, $W_t = 2.8$ mm; $f_L = 2.4$ GHz, $f_U = 5.8$ GHz.

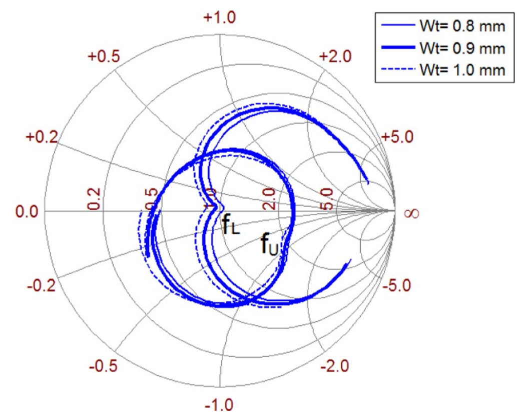


Fig. 3. Effect of various W_t on the input impedance of the antenna; $L_t = 18$ mm, $L_s = 1$ mm; $f_L = 2.4$ GHz, and $f_U = 5.8$ GHz.

is controlled by $L1$ and $L2$. Furthermore, it is found that, by adjusting the stub length L_s and the dimensions of the impedance transformer L_t and W_t, two frequencies with dual circular polarization can be excited with good impedance matching.

III. Impedance Matching

Due to the fact that the proposed antenna is dual-frequency, in order to obtain good impedance matching at both frequencies, we have to adjust the feed line dimensions carefully. With the aid of CST Microwave Studio software, an example is selected to show the process of impedance matching.

In this example, the relative permittivity of the substrate is $\varepsilon_r = 4.2$, the thickness of the substrate is $h = 1.45$ mm, $R = 14$ mm, $S1 = 1$ mm, $W_p = 3$ mm, $d_p = 4$ mm, $L1 = 16$ mm, $L2 = 14.5$ mm, $S2 = 1$ mm, the width of 50 Ω microstrip feed line on this substrate is $W_f = 2.8$ mm. We will study the effect of various L_s, L_t and W_t on the input impedance, only one parameter is varied at a time.

Fig. 2 shows the impedance seen at the edge of ring slot of the antenna with no impedance transformer, in other words, the width of transformer W_t is the same as the width of 50 Ω microstrip feed line W_f which is $W_t = W_f = 2.8$ mm. Two dip points can be found in the impedance loci. Around the dip points, axial ratio is less than 3 dB and CP radiation can be obtained. So it is assumed that the dip point's frequency is close to the center frequency of CP, so we only need to analyze the impedance around the dip points. In Fig. 2, the two CP frequencies ($f_L = 2.4$ GHz, $f_U = 5.8$ GHz) don't achieve good impedance matching. It is found that the dimension of feed line has little effect on axial ratio and resonant frequency. This property is useful for us to adjust impedance without affecting other characteristics. Furthermore, the stub length L_s has little effect on the lower frequency, whereas the impedance of upper frequency changes greatly with L_s, so we can use impedance transformer to realize impedance matching at the lower frequency, then by adjusting L_s impedance matching at upper frequency can be achieved.

A. Effects of W_t

Fig. 3 shows the input impedance in the case of $W_t = 0.8$, 0.9, and 1.0 mm, when L_t and L_s are fixed to be 18 and 1 mm. When W_t varies, the two CP frequencies f_L and f_U are constant ($f_L = 2.4$ GHz, $f_U = 5.8$ GHz). From the result, it is found that the impedance of upper frequency is slightly changed for various W_t, it is clearly seen that the impedance of lower frequency changes from 53 to 43 Ω when W_t is increased from 0.8

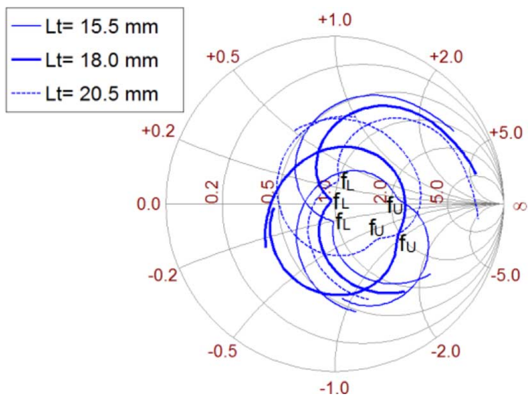


Fig. 4. Effect of various L_t on the input impedance of the antenna; $W_t = 0.9$ mm, $L_s = 1$ mm; $f_L = 2.4$ GHz, and $f_U = 5.8$ GHz.

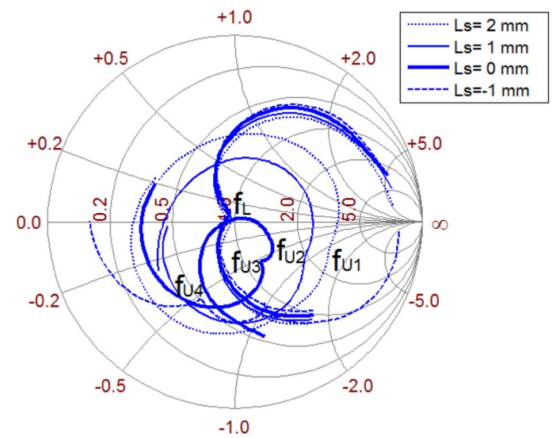


Fig. 5. Effect of various L_s on the input impedance of the antenna; $W_t = 0.9$ mm, $L_t = 18$ mm; $f_L = 2.4$ GHz, $f_{U1} = 5.7$ GHz, $f_{U2} = 5.8$ GHz, $f_{U3} = 5.8$ GHz, and $f_{U4} = 5.9$ GHz.

to 1 mm. To obtain good impedance matching, we should set W_t to be 0.9 mm.

B. Effects of L_t

Fig. 4 shows the input impedance in the case of $L_t = 15.5$, 18, and 20.5 mm, when W_t and L_s are fixed to be 0.9 and 1 mm. When L_t varies, the two CP frequencies f_L and f_U are constant ($f_L = 2.4$ GHz, $f_U = 5.8$ GHz). From the figure, it is found that L_t affects impedance of both frequencies, it seems that it is hard to obtain good impedance matching at both frequencies at the same time, so here we only concern about the lower frequency, for the upper one can be matched by adjusting L_s which will be discussed in Section III-C. In Fig. 4 we can see that the impedance of lower frequency is real when L_t is 18 mm, which is one quarter of the guided wavelength referred to this frequency (2.4 GHz). When L_t is 15.5 and 20.5 mm, the input impedance of lower frequency is respectively capacitive and inductive.

C. Effects of L_s

Fig. 5 shows the input impedance in the case of $L_s = 2$, 1, 0, -1 mm, when W_t and L_t are fixed to be 0.9 and 18 mm. It is found that when L_s varies, the lower frequency is constant ($f_L = 2.4$ GHz), and its impedance remains around 50 Ω. The upper frequency has an addition of 3.5% (from 5.7 to 5.9 GHz) when L_s decreases from 2 to -1 mm. L_s also greatly affects impedance of the upper frequency, from the result showed in Fig. 5, to obtain impedance matching, we should set L_s to be 0 mm, then both frequencies are matched well.

From the above example, we can summarize the process of impedance matching as follows. 1) A quarter-wave impedance transformer is used to transform the impedance of the lower frequency, which is about 160 Ω seen at the edge of the ring slot in this example, to 50 Ω seen at the feed point. 2) The open circuited stub L_s has little effect on the lower frequency, whereas the impedance of the upper frequency changes greatly with it, so we can tune L_s to achieve impedance matching at the upper frequency without affecting the lower one.

IV. Parameter Study

So many variables in the antenna structure introduce complexity in the design process. The outside ring slot and the inside cross slot are coupling together, all critical physical parameters, such as R, W_p, d_p, $L1$ and $\triangle L$ ($L2$ is then determined by $L1 - \triangle L$), should be adjusted carefully in order to achieve a dual circular polarization design with good performance. In this section, we will examine the effects of these parameters on reflection coefficient and axial ratio when only one parameter is varied at a time. The feed line dimension is set to be $W_t = 0.9$ mm, $L_t = 18$ mm, $L_s = 1$ mm, which are optimal values we obtained in Section III. The width of the slots are fixed to be $S1 = S2 = 1$ mm.

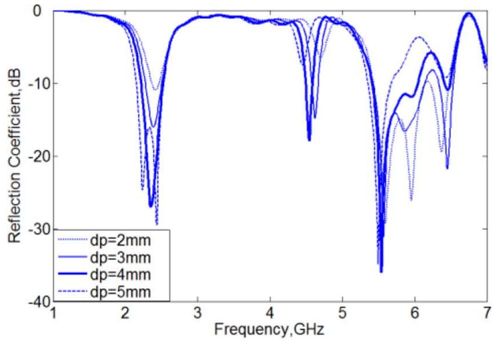
We have mentioned that the lower frequency is decided by ring slot and the upper frequency is decided by cross slot, so it is obvious that the radius of ring slot (R) can affect the lower frequency while the length of cross slot (L1) can influence the upper one.

A. Effects of d_p

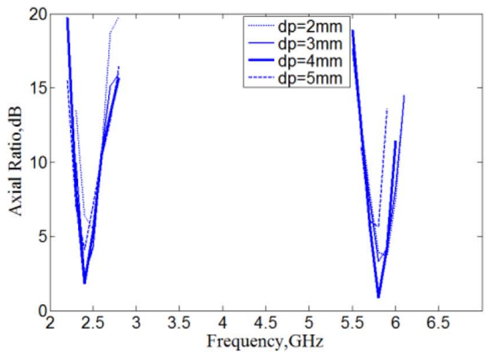
The effect of altering the depth of notches is shown in Fig. 6. This is a critical parameter which decides the axial ratio of lower frequency. If the value of d_p is too small ($d_p = 2$ mm) or too large ($d_p = 5$ mm), the CP performance will be deteriorated. It is noted that d_p can also affect the axial ratio of upper frequency, it indicates the coupling of the ring slot and cross slot.

B. Effects of W_p

In Fig. 7, the width of notches is varied. Just like the parameter of d_p, W_p controls the axial ratio of lower frequency. It is interesting to note the similarity of the variation of lower frequency between Figs. 6 and 7. It indicates that W_p and d_p have similar effect on lower frequency. Compared with d_p, W_p has little effect on upper frequency, so it is useful to optimize

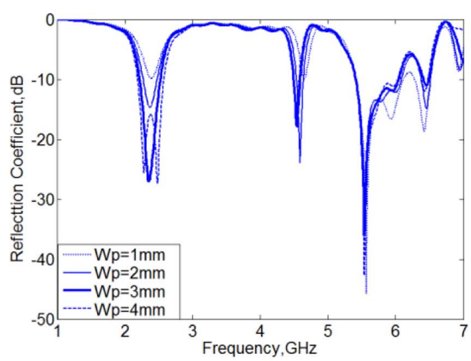


(a)

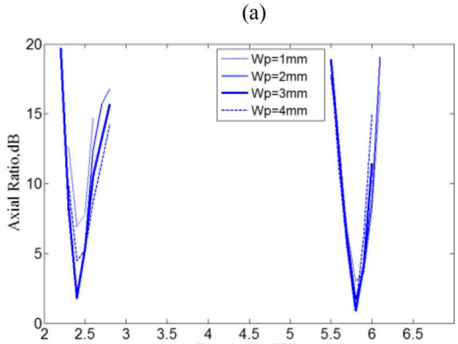


(b)

Fig. 6. Simulated (a) reflection coefficient and (b) axial ratio against frequency for various d_p. $R = 14\ \mathrm{mm}$, $W_p = 3\ \mathrm{mm}$, $L1 = 8\ \mathrm{mm}$, and $\triangle L = 1.5\ \mathrm{mm}$.



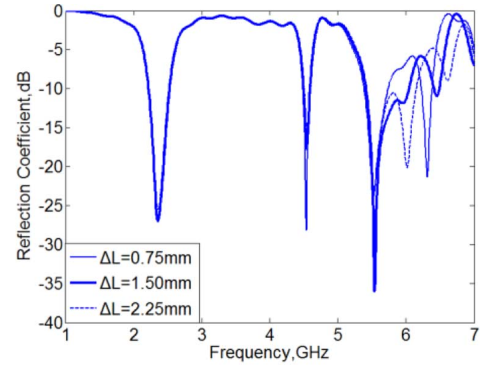
(a)



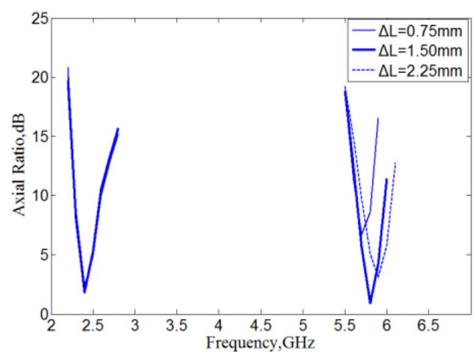
(b)

Fig. 7. Simulated (a) reflection coefficient and (b) axial ratio against frequency for various W_p. $R = 14\ \mathrm{mm}$, $d_p = 4\ \mathrm{mm}$, $L1 = 8\ \mathrm{mm}$, and $\triangle L = 1.5\ \mathrm{mm}$.

the performance of lower frequency without affecting the upper one.



(a)



(b)

Fig. 8. Simulated (a) reflection coefficient and (b) axial ratio against frequency for various $\triangle L$. $R = 14\ \mathrm{mm}$, $d_p = 4\ \mathrm{mm}$, $W_p = 3\ \mathrm{mm}$, and $L1 = 8\ \mathrm{mm}$.

C. *Effects of* $\triangle L$

Fig. 8 shows the effects of $\triangle L$, which is the difference of the two orthogonal slots. As expected, $\triangle L$ has a great effect on axial ratio of the upper frequency but almost does not affect the lower frequency. To realize CP radiation at upper frequency, $\triangle L$ must be optimized. If the value of $\triangle L$ is too small $(\triangle L = 0.75\ \mathrm{mm})$ or too large $\triangle L = 2.25\ \mathrm{mm})$, the CP performance will be deteriorated.

From the above discussion, we can sum up the design process as follows: 1) set the radius of ring slot according to the lower frequency, then adjust d_p and W_p to obtain CP radiation at lower frequency; 2) set the length of cross slot according to the upper frequency, then adjust $\triangle L$ to obtain CP radiation at upper frequency; 3) adjust the dimensions of feed line to achieve impedance matching at both frequencies, specifically we can use impedance transformer to match the lower frequency and adjust stub length to change the impedance of the upper frequency.

V. Experimental Results and Discussion

Based on the guide of Sections III and IV, a prototype of the proposed antenna was designed, fabricated and measured. The antenna was etched on a substrate of thickness $h = 1.45\ \mathrm{mm}$ and relative permittivity $\varepsilon_r = 4.2$. Fig. 9 shows the measured reflection coefficient and axial ratio of this antenna, the dimensions of the antenna were also showed in Fig. 9. From the measured results, it is clearly seen that, the prototype has two operating frequencies: the lower frequency f_L is 2.5 GHz, and the polarization sense is found to be right-hand CP at this frequency, the measured bandwidth, referred to 3-dB axial ratio, is 5.92%

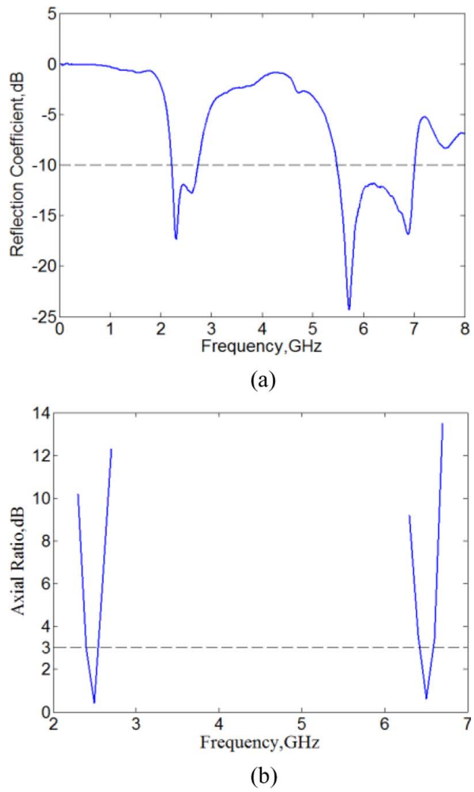


Fig. 9. Measured (a) reflection coefficient and (b) axial ratio for antenna prototype with $\varepsilon_r = 4.2, h = 1.45$ mm; $R = 14$ mm, $d_p = 4$ mm, $W_p = 4$ mm, $L1 = 8$ mm, $\triangle L = 2$ mm, $S1 = S2 = 1$ mm; $W_t = 0.96$ mm, $L_t = 18$ mm, and $L_s = 0$ mm.

(148 MHz); the upper frequency f_H is 6.5 GHz, and the polarization sense is found to be left-hand CP at this frequency, the measured bandwidth, referred to 3 dB axial ratio, is 2.46% (160 MHz). Impedance matching, determined by -10 dB reflection coefficient, is also achieved within the two CP operating bands.

The simulated radiation patterns in two orthogonal planes at these two CP frequencies are plotted in Fig. 10. The radiation patterns are bidirectional, the peak gain is 3.8 dBi at the lower frequency and 5.5 dBi at the upper frequency.

The ratio of the two CP frequencies of the antenna in Fig. 9 is 2.6, to obtain a lower frequency ratio, and also to apply the design to a different substrate, another prototype etched on substrate of $\varepsilon_r = 2.2, h = 3$ mm was constructed and measured. The dimensions and results are shown in Fig. 11.

In this antenna, the lower CP frequency f_L is 2.4 GHz, and the polarization sense is found to be right-hand CP at this frequency, the measured bandwidth is 5.54% (134 MHz); the upper frequency f_H is 4.9 GHz, and the polarization sense is found to be left-hand CP at this frequency, the measured bandwidth is 4.29% (210 MHz). Impedance matches at the two CP operating bands. The radiation patterns of this antenna are similar with Fig. 10, the peak gain is 4.1 dBi at the lower frequency and 5.8 dBi at the upper frequency. Here, the frequency ratio is 2.04.

To obtain a small frequency ratio, we can increase the length of cross slot and decrease the radius of ring slot, so that the upper frequency can be decreased and the lower frequency can be increased. However, with the increasing of cross slot and decreasing of ring slot, the two slots will be closer and closer, and eventually intersect. Consequently, the proposed antenna has a minimum limitation in the frequency ratio, which is about 1.64. In above prototypes, the lower frequency is right-hand CP and the upper frequency is left-hand CP. When the notches are put along the other diagonal direction, left-hand CP radiation can be obtained at the lower frequency. Respectively, by setting

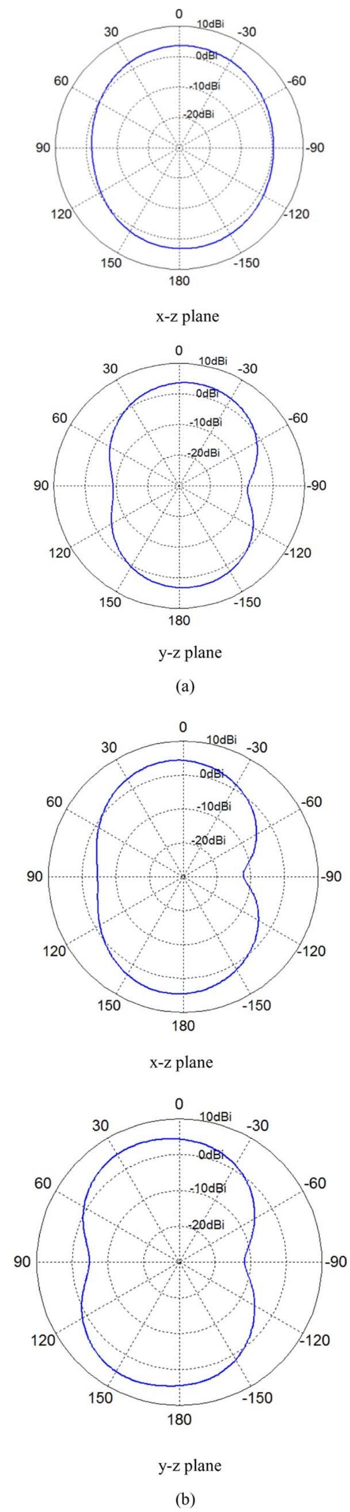
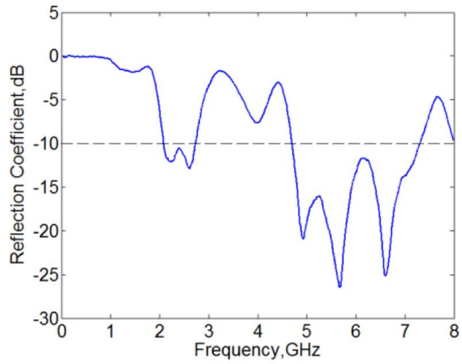
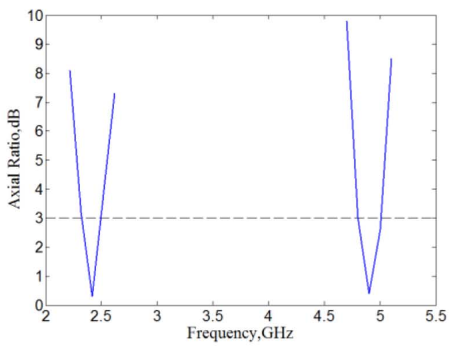


Fig. 10. Simulated radiation patterns for antenna in Fig. 9. (a) $f = 2.5$ GHz. (b) $f = 6.5$ GHz.



(a)



(b)

Fig. 11. Measured (a) reflection coefficient and (b) axial ratio for antenna prototype with $\varepsilon_r = 2.2, h = 3\ \mathrm{mm}$; $R = 16\ \mathrm{mm}, d_p = 5\ \mathrm{mm}, W_p = 5\ \mathrm{mm}, L1 = 11\ \mathrm{mm}, \triangle L = 2.5\ \mathrm{mm}, S1 = S2 = 1.3\ \mathrm{mm}$; $W_t = 3.8\ \mathrm{mm}, L_t = 22\ \mathrm{mm}$, and $L_s = -2\ \mathrm{mm}$.

$L2$ to be longer than $L1$, we can change the upper frequency to right-hand CP.

VI. Conclusion

In this paper, a dual-frequency dual circularly-polarized printed slot antenna that utilizes a ring slot and a cross slot has been proposed. This antenna is single-feed and only one dielectric layer is required, therefore the structure is simple. Impedance matching can be realized by an impedance transformer and a tuning stub, dimensions of feed line have been discussed. The effects of several key parameters are studied in detail. These results provide a good design guide for this antenna. Prototypes of the antenna have been constructed and measured, two orthogonal polarizations at two frequencies have been achieved, and the bandwidth, the gain and frequency ratio are presented.

Acknowledgment

The author thanks Dr. S. Wang for valuable discussion.

References

[1] J.-S. Chen, "Dual-frequency annular-ring slot antennas fed by CPW feed and microstrip line feed," *IEEE Trans. Antennas Propag.*, vol. 53, no. 1, pp. 569–571, Jan. 2005.

[2] F. LeBolzer and A. Louzir, "Multi-band annular slot antenna for WLAN applications," in *Proc. Inst. Elect. Eng. 11th Int. Conf. Antennas Propag.*, Apr. 2001, pp. 529–532.

[3] H. Tehrani and K. Chang, "A multi-frequency microstrip-fed annular slot antenna," in *IEEE AP-S Int. Symp. Dig.*, 2000, pp. 632–635.

[4] C. M. Su, H. T. Chen, F. S. Chang, and K. L. Wong, "Dual-band slot antenna for 2.4/5.2 GHz WLAN operation," *Microw. Opt. Technol. Lett.*, vol. 35, no. 4, pp. 306–308, Nov. 2002.

[5] T. Vlasits, E. Korolkiewicz, A. Sambell, and B. Robinson, "Performance of a cross-aperture coupled single feed circular polarized patch antenna," *Electron Lett.*, vol. 32, no. 7, pp. 612–613, Mar. 1996.

[6] K. Hirose and H. Nakano, "Dual-loop slot antenna with simple feed," *Electron. Lett.*, vol. 25, no. 18, pp. 1218–1219, Aug. 1989.

[7] K. L. Wong, C. C. Huang, and W. S. Chen, "Printed ring slot antenna for circular polarization," *IEEE Trans. Antennas Propag.*, vol. 50, no. 1, pp. 75–77, Jan. 2002.

[8] W. Ren, J. Y. Deng, S. H. Hong, and K. S. Chen, "Design of dual-band circularly polarized annular slot antenna for wireless local area network applications," (in Chinese) *J. Zheiiang Univ. (Eng. Sci.)*, vol. 42, no. 8, pp. 1306–1309, Aug. 2008.

[9] C. H. Cai, J. S. Row, and K. L. Wong, "Dual-frequency microstrip antenna with dual circular polarization," *Electron Lett.*, vol. 42, no. 22, pp. 1261–1262, Oct. 2006.

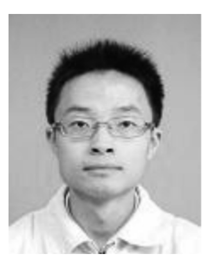
[10] X. Bao and M. J. Ammann, "Dual-Frequency dual-sense circularly-polarized slot antenna fed by microstrip line," *IEEE Trans. Antennas Propag.*, vol. 56, no. 3, pp. 645–649, Mar. 2008.

[11] Y. Ding and K. W. Leung, "Dual-band circularly polarized dual-slot antenna with a dielectric cover," *IEEE Trans. Antennas Propag.*, vol. 57, no. 12, pp. 3757–3764, Dec. 2009.

[12] X. L. Bao and M. J. Ammann, "Monofilar spiral slot antenna for dual-frequency dual-sense circular polarization," *IEEE Trans. Antennas Propag.*, vol. 59, no. 8, pp. 3061–3065, Aug. 2011.

[13] J.-S. Row, "Design of aperture-coupled annular-ring microstrip antennas for circular polarization," *IEEE Trans. Antennas Propag.*, vol. 53, no. 5, pp. 1779–1784, May 2005.

[14] S. D. Targonski, R. B. Waterhouse, and D. M. Pozar, "Design of wideband aperture-stacked patch microstrip antennas," *IEEE Trans. Antennas Propag.*, vol. 46, no. 9, pp. 1245–1251, Sep. 1998.



Yu Shao was born in Kunming, Yunnan Province, China, on January 12, 1987. He received the B.Eng. degree in electrical engineering and M.Eng. degree in electromagnetic fields and microwave technology from Wuhan University, Wuhan, China, in 2009 and 2011, respectively. He is currently working toward the Ph.D. degree at Auburn University, Auburn, AL.

His research interests include computational electromagnetics, antennas, coils in MRI, and RF circuits.

Zhangyou Chen received the B.S. and M.S. degrees in radio physics from Wuhan University, Wuhan, China, in 1992 and 1995, respectively, and the Ph.D. degree in electrical science from Shizuoka University, Hamamatsu, Japan, in 2002.

Since 2002, he has been with the School of Electronic Information, Wuhan University, as an Associate Professor. He has authored approximately 20 publications. His research interests include antennas, electromagnetic engineering, and RF circuits.