Bidirectional Radiated Circularly Polarized Annular-Ring Slot Antenna for Portable RFID Reader

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Abstract— A novel single-layer, microstrip-to-slotline transition technique for coupling a circularly polarized annular-ring slot antenna in the UHF band is presented. In the proposed design, circular polarization is generated using a proper asymmetry within the annular-ring slot structure and feeding the annular-ring slot using a slotline feed at 135° from the asymmetry. The direct slotline feed is used which is coupled to a 50-Ω microstrip line on the opposite side of the substrate. The asymmetry in the proposed design is a meandered-slot section and the proposed CP design is achieved by the two orthogonal linear modes of the annular-ring slot. Simulated and measured results indicate that the proposed structure can achieve good CP radiation performances, and an impedance bandwidth and a 3-dB axial-ratio bandwidth obtained for the design are about 17.6% and 3.72%, respectively.

Index Terms— Annular-ring slot antenna, circular polarization (CP), microstrip–to-slotline transition, RFID reader.

I. INTRODUCTION

Radio frequency identification (RFID) system in the ultra-high frequency (UHF) band has gained much interest in several service industries, purchasing and distribution logistics, manufacturing companies and goods flow system [1]. The RFID system generally consists of the reader and the tag, and the UHF RFID system operates at the bands of North America (902-928 MHz), Taiwan (920-928 MHz) and Europe (865-867 MHz). The reader can be a read device that uses an antenna which sends a radio frequency signal to a tag. The RFID reader antenna is one of the important components in RFID system and has been designed with CP operation. Circularly polarized antennas can reduce the loss caused by the multi-path effects between the reader and the tag antenna. A CP antenna with a low profile, small size, and light weight is required in portable RFID reader.

A typical technique for generating circular polarization radiation is to excite two orthogonal degenerate resonant modes with a 90^0 phase difference. Single-fed circularly polarized annular-ring, square and circular patch antennas with symmetrical or asymmetrical perturbation elements are reported [2-5]. Using perturbation cuts or strips to suitably differentiate the two orthogonal modes at resonant frequency, the antenna can easily radiate CP wave. However, these antennas provide small impedance bandwidth and narrow axial ratio (AR) bandwidth. To enhance an AR bandwidth, a single-fed slot-coupled microstrip antenna for circular polarization operation is preferred [6-8]. The CP antenna is achieved by using an inclined nonlinear coupling slot or unequal arm of cross-slot. However, a common slot coupling patch antenna in its basic structure consists of two substrates separated by a ground plane. Two substrates increase the volume of the antenna and the complexity of fabrication. Another drawback is that a multi-layered substrate with the coupling slot on the ground plane can result in coupled surface-wave modes, which will lead to distorted radiation patterns.

To improve the operating bandwidth and not increase the antenna size, using the printed slot antenna is a possible method. Since the printed slot antenna is a dual of the microstrip antenna, it is also possible that by introducing some perturbations to the slot antenna, CP radiation of slot antenna can be achieved. However, the single-layer slot antenna with circular polarization has a few studied up to now. The CP radiation can be obtained by the introducing of some symmetrical or asymmetrical perturbation elements into a single-feed slot antenna, and the bandwidth is greater than that of a conventional circularly polarized microstrip antenna operated in the fundamental mode [9-12].

In this paper, a novel and single-layer annular-ring slot antenna has been proposed to obtain circularly polarized radiation. The proposed antenna has a simple narrow annular-ring slot with asymmetry and is fed from the microstrip line coupling to the slotline, as shown in Fig. 1. The proposed asymmetry has a simple structure of a meandered slot section. Additionally, the antenna operates at its fundamental orthogonal modes for the UHF band, and the two near-degenerated resonant modes for circularly polarization of an annular-ring slot antenna are generated by etching diagonal asymmetrical meandered-slot to the annular-ring slot. Details of the antenna design and the obtained experimental results of the antenna performance are presented and discussed.

II. ANTENNA CONFIGURATION

The configuration of the proposed antenna is shown in Fig. 1, in which an annular-ring slot antenna with a meandered slot section is etched on the ground plane (100 × 100 mm^2) of FR4 substrate with thickness h = 1.6 mm and relative permittivity 4.4. The outer and inner radii of the annular-ring slot radiator are R_1 and R_2, respectively, and the slot width W is R_1-R_2. The meandered slot section is a U-shaped slot, which is placed at the annular-ring slot edge with an angle

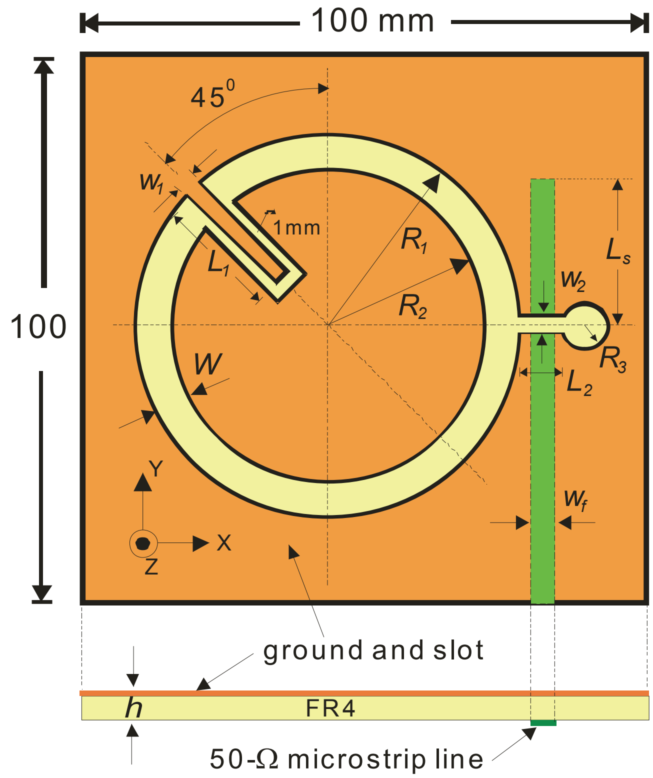


Fig. 1. Geometry of the single-layer circularly polarized annular-ring slot antenna.

of 45° from the y-axis. The U-shaped slot has a side length of L_1, a gap distance of W_1 and a fixed uniform width of 1 mm. In addition, the annular-ring slot is fed by a simple slotline on the same side of the substrate, which energy is coupled from the 50-Ω microstrip feed line. The simple slotline consists of a narrow rectangular slot with dimensions $L_2 \times W_2$ and a circular slot of radius R_3 for open stub. A 50-Ω microstrip feed line with a width W_f = 3.0 mm is printed on the opposite side of the FR4 substrate. The microstrip line is extended beyond the center of the slotline by a length L_s = 0.16λ_g (25 mm) for the tuning stub, where λ_g is the feed line wavelength at 915 MHz. The tuning stub has improved the impedance matching of the proposed antenna. The field in the annular-ring slot antenna is excited from the feed line through the slotline. Therefore, radiation from the annular-ring slot can be enabled.

In order to reduce experimental cut-and-try design cycles, the simulation software HFSS is used to guide fabrication. For conventional annular-ring slot antennas, the fundamental resonant mode (TE_{11} mode) occurs at a frequency whose wavelength in the ring-slot approximately corresponds to the mean circumference of the ring-slot [13]. That is,

$$f = \frac{c}{\pi (R_1 + R_2)\sqrt{\varepsilon_{eff}}} \quad (1)$$

$$\varepsilon_{eff} = 1 + q(\varepsilon_r \text{-} 1) \quad (2)$$

where c is the speed of light in free space, f is the fundamental frequency of the conventional annular-ring slot antenna, $\pi(R_1 + R_2)$ is the mean circumference of the annular-ring slot, ε_{eff} is the effective dielectric constant and q is the correction factor considering the presence of the different dielectric material on the two sides of the annular-ring slot. In this study, slot width of $W = R_1 - R_2$ and dielectric constant of substrate $\varepsilon_r = 4.4$ were used in all measurements and the value of q is obtained from many simulations for the narrow slot width. It can be found that the effective dielectric constant decreases when the slot width W is increased. In this study, it has to be noted that the q factor of 0.082 in equation (2) is an average value for the narrow annular-ring slot with a width of 2 mm to 6 mm, and then the calculated resonance frequency of the fundamental TE_{11} mode is approximately 1207 MHz for slot width of 4 mm.

With the introduced meandered slot section (U-shaped slot), the symmetry of the annular-ring slot antenna is perturbed and the fundamental resonant mode can be split into two orthogonal degenerate resonant modes with equal amplitudes and a 90^0 phase difference required for the generation of circular polarization. One of the resonant lengths of the degenerate modes is left perimeter of annular-ring slot from the diagonal line and the other resonant length is right perimeter, which operates at its fundamental mode and corresponds to about half guided wavelength of the center frequency.

III. PARAMETRIC STUDY

To achieve optimum performance, a parametric study by using commercial EM software HFSS 10.0 is carried out to investigate the characteristics of the proposed annular-ring slot antenna. The antenna's initial values, unless otherwise stated, are fixed at R_1 = 37 mm, R_2 = 33 mm, W_f = 3 mm, L_s = 25 mm, L_1 = 21 mm, W_1 = 3 mm, L_2 = 4.8 mm, W_2 = 1 mm and R_3 = 3 mm.

A. Operational Mechanism of CP Radiation

In Fig. 1, a U-shaped slot with an angle 45^0 from the y-axis is etched on the edge of the annular-ring slot, and a horizontal slotline segment terminated by a small circular slot, as a tuning stub, is centrally fed by a microstrip line for coupling the electromagnetic energy to the annular-ring slot. In this antenna configuration, it was shown that by introducing the U-shaped slot in the annular-ring slot located at 45^0 with respect to the y-axis circular polarization can be excited. In order to check this operating mechanism, Fig. 2 shows the simulated electric current flow and distribution on the annular-ring slot antenna. It can be observed that the null currents are located at the diagonal line with azimuth angle ϕ of 45^0 and 225^0, respectively; that is, one of the resonant current lengths of the degenerate modes is the perimeter of annular-ring slot from A-C-B line and the other resonant length is the perimeter of A-D-B line, which operates at its fundamental mode and corresponds to about half guided wavelength of the center frequency. That is,

$$f_a \approx \frac{c}{2[\pi(R_1 + R_2)/2 + 2(L_1 - W/2)\text{-}W_1 + 1]\sqrt{\varepsilon_{eff}}} \quad (3)$$

$$f_b \approx \frac{c}{2[\pi(R_1 + R_2)/2 + 2L_2 + 2\pi R_3 - 2W_2]\sqrt{\varepsilon_{eff}}} \quad (4)$$

$$\varepsilon_{eff} = 1 + 0.082(\varepsilon_r \text{-} 1)$$

the q factor of effective dielectric constant can be approximately expressed as 0.082 in equation (2). The total resonant length, from point A through point C, then to point B, is about 149.9 mm ($\pi(R_1+R_2)/2+2(L_1\text{-}W/2)\text{-}W_1+1$) which is about $0.5\lambda_s$ at f_a = 884 MHz. The other current flow from points A and D to point B can also generate a half wavelength mode at f_b = 930 MHz, which resonant length is about 142.6 mm ($\pi(R_1+R_2)/2+2L_2+2\pi R_3\text{-}2W_2$). Note that the right-handed circularly polarized (RHCP) wave is obtained because the higher frequency f_b leads the lower frequency f_a by phase difference 90^0.

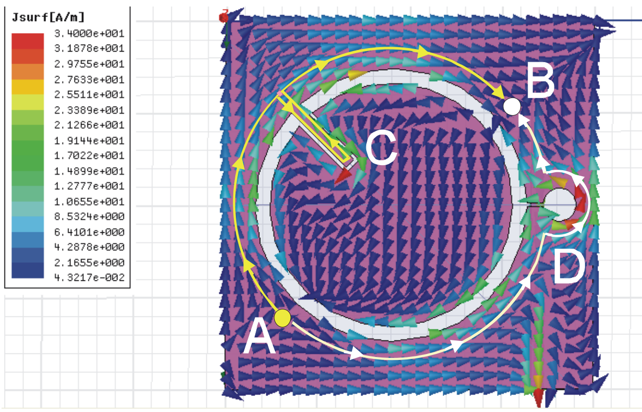


Fig. 2. Simulated current flow and distribution of the proposed antenna at 915 MHz.

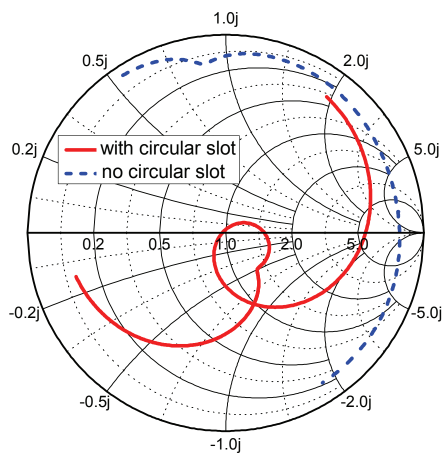


Fig. 3. Simulated Smith Chart for different circular slot radii (R_3).

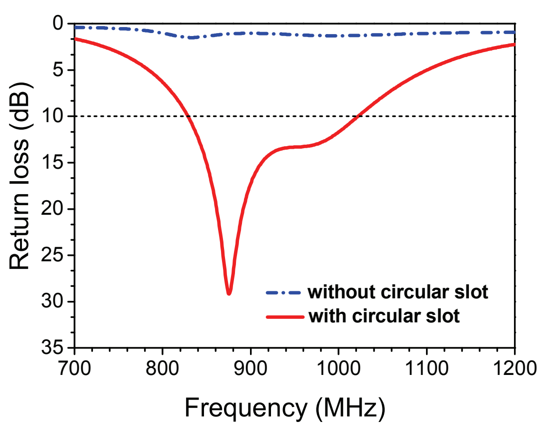


Fig. 4. Simulated return loss for different circular slot radii (R_3).

B. Effects of Circular Slot Radius

The radius (R_3) of the circular slot on the end of the slotline is a major design parameter for the antenna, and it determines the phase difference of the two degenerate modes of the proposed antenna and the impedance matching. Figs. 3 and 4 show the simulated input impedance on the Smith Chart and the simulated return loss for various radii (R_3). It is first noted that a small loop can be obtained in the impedance loci for the CP operation and it can be tuned to obtain an optimum axial ratio after the impedance matching is achieved. For R_3 = 0 mm (no circular slot), there are no loop in the impedance loci and it has larger inductive impedance, i.e. without the circular slot did not excite the CP radiation. Observing the results in Fig. 4, no CP radiation is occurred without the presence of circular slot. A good CP performance in terms of the loop and good impedance matching is achieved when R_3 = 4.0 mm.

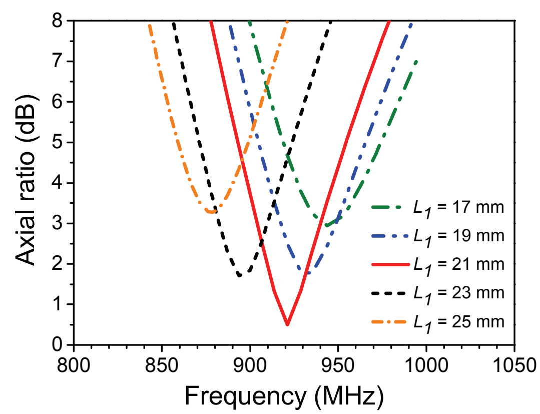


Fig. 5. Simulated axial ratio for different lengths of meandered slot section (L_1).

C. Effects of Meandered Slot Section

For the annular-ring slot antenna, the proposed CP design procedure can be applied to different size of meandered slot section. Figure 5 shows the simulated axial ratio with different length L_1. As expected, the CP center frequency decreases when the length L_1 is increased. Fig. 6 shows the simulation return loss for the different width W_1 with a fixed length of L_1 = 21 mm. Also as expected in equation (3), there are no significantly effects for the various width of W_1.

D. Effects of Inner Radius of Annular-Ring Slot

Fig. 7 shows the simulated axial ratio versus frequency for different inner radius R_2. It can be find that a good axial ratio for different R_2 is obtained. Additionally, the CP center frequency decreases when the radius R_2 is increased. As expected in equation (1), the CP center frequency decreases with increasing the mean circumference of the annular-ring slot ($\pi(R_1+R_2)$).

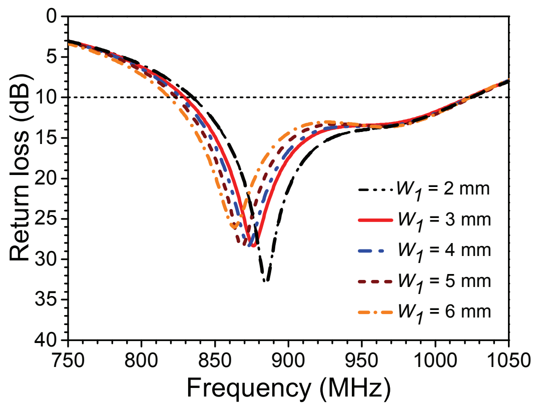


Fig. 6. Simulated return loss for different widths of meandered slot section (W_1).

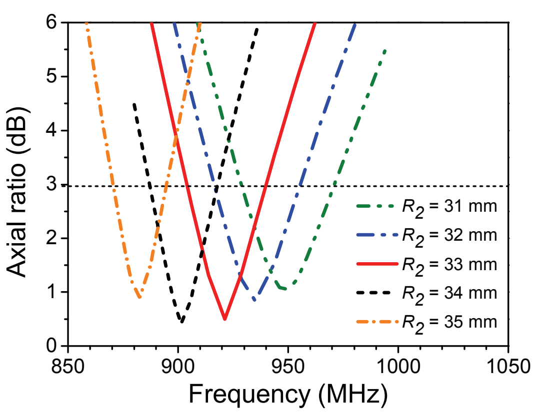


Fig. 7. Simulated axial ratio versus frequency for different inner radii (R_2).

IV. EXPERIMENTAL RESULTS

The proposed CP antenna is designed to operate at the center frequency of about 915 MHz in the UHF band for RFID reader. The return loss is measured using an Agilent N5230A vector network analyzer, and axial ratio and radiation patterns are evaluated in anechoic chamber with an NSI-800F10 antenna measurement system. Fig. 8 shows the simulated and measured return loss of the proposed antenna. The measured impedance bandwidth for 10 dB return loss is 17.6%, ranging from 830 to 990 MHz, and agrees well with the HFSS simulated results (829-1021 MHz). Fig. 9 shows the simulated phase diagram for the proposed antenna. It can be found that the operational principle of this circularly polarized antenna is based on the fact that the generated mode can be separated into two orthogonal modes (f_a = 884 MHz and f_b = 930 MHz) of equal amplitude and about 89^0 phase difference and resulted in a good RHCP radiation. In addition, the measured axial ratio in the broadside direction versus frequency is also presented in Fig. 10. The 3-dB axial-ratio CP bandwidth is about 34 MHz or 3.71% around the center frequency at 915 MHz. Note that the minimum axial-ratio value is about 0.52 dB at the frequency (920 MHz), indicating that the circular polarization is pure.

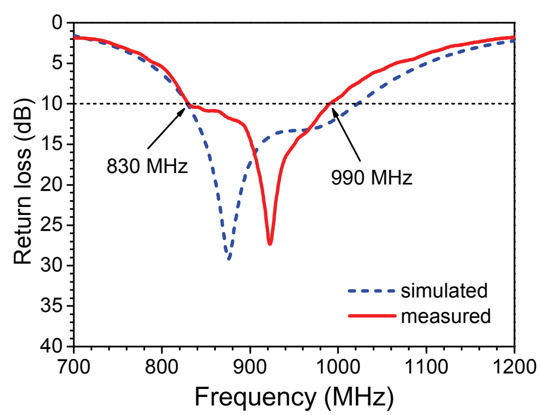


Fig. 8. Measured and simulated return loss of the proposed antenna.

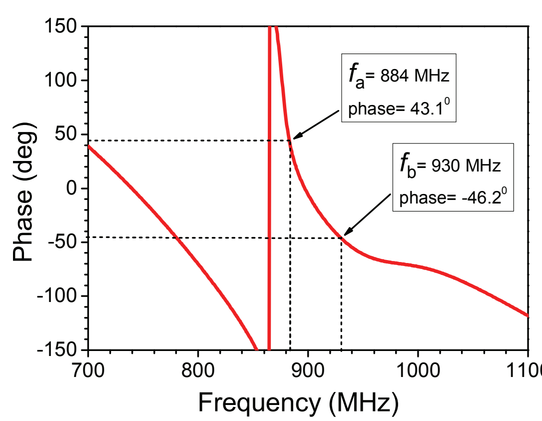


Fig. 9. Simulated phase diagram versus frequency for the proposed antenna.

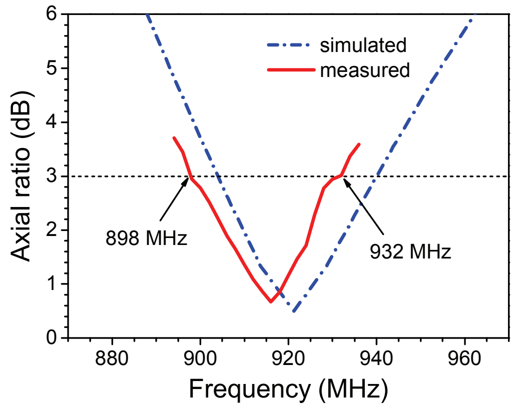
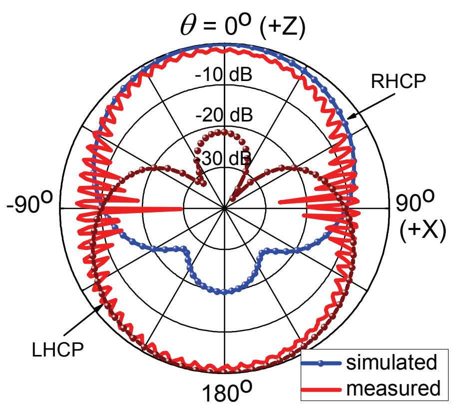
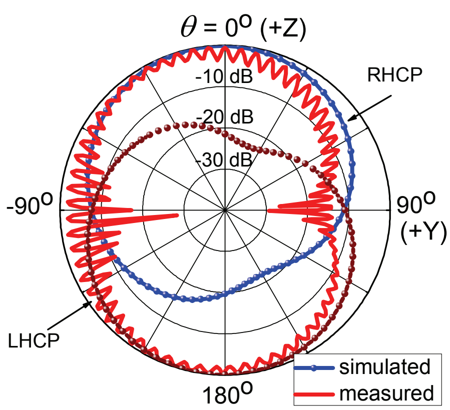


Fig. 10. Measured and simulated axial ratios of the proposed antenna.



(a)



(b)

Fig. 11. Measured and simulated normalized RHCP/LHCP radiation patterns of the proposed antenna at 915 MHz. (a) x-z; (b) y-z plane.

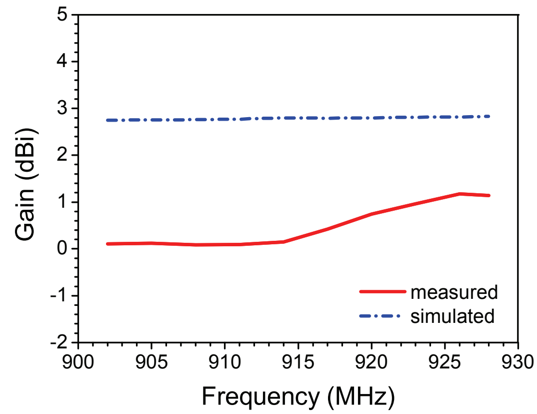


Fig. 12. Measured and simulated antenna gains versus frequency for the proposed antenna.

The measured and simulated RHCP/LHCP radiation pattern at 915 MHz is plotted in Fig. 11, and good symmetry of bidirectional radiation has been observed. Note that a CP slot antenna without a reflector radiates a bidirectional wave, and the radiation patterns in both sides of the slot antenna are about the same with contrary circular polarization; that is, the front-side radiates RHCP while back-side radiates LHCP. Also, it can be observed from the pattern that the 3-dB beam widths are about 96^0 ($-50^0 \sim 46^0$) with symmetry in the x-z plane and 98^0 ($-55^0 \sim 43^0$) beam widths with a tilt to left in the y-z plane. The measured gain was obtained using the gain transfer method where standard gain horn antenna was used as a reference. The obtained peak antenna gain is from 0 dBi to 1.5 dBi in the UHF band (902-928 MHz) owing to the small size of the antenna.

V. CONCLUSIONS

A microstrip-to-slotline feed mechanism of circularly polarized annular-ring slot antenna with an asymmetrically meandered slot section for RFID reader is designed and measured. The asymmetrically meandered slot section is used to excite two orthogonal linear polarized modes. Experimental results show that the proposed antenna can have a 3-dB CP bandwidth of about 3.71% and an impedance bandwidth of about 17.6%. In addition, the proposed antenna is compact, bidirectional radiated and easily to find application as transmitting antenna in portable

RFID reader.

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