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Multi-Band Circularly Polarized Slot Antenna for GPS, Bluetooth and WiMAX Bands

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Abstract—This paper describes the concept, design, and measurement of a multi-band circularly polarized printed slot antenna with a single microstrip feed line. The antenna design for circular polarization (CP) at 1.5 GHz for GPS, 2.4 GHz for Bluetooth, and 3.75 GHz for WiMAX application is given. The proposed antenna also provides a fourth linear polarized band over 5.2 to 6 GHz covering the WLAN band. The design is such that all three CP bands can be tuned for any other desired frequencies. Three configurations of the proposed antenna with different design parameters for different circularly polarized bands are reported in the paper. A prototype of the proposed antenna is fabricated, and measured results are compared with those of the simulations.

1. INTRODUCTION

The increase in development of wireless communication systems has triggered the need for multifunctional and multiband antennas. Requirements of modern communication systems have also led to an increased demand for more compact and low cost designs. Therefore, multifunctional compact antennas are highly desirable in wireless communications. For the purpose of a flexible reciprocal orientation between the transmitting and receiving antennas and reducing multipath effects, circular polarization (CP) is also becoming more and more popular. In view of these perspectives, compact circular polarized antennas with multi-band operations will be more useful in the future wireless systems.

CP antennas have been designed by using single- [1] and double-feed [2] structures. In [3] the authors use double-feed structure for stacked patch antennas to cover all three GPS bands. Although double-feed structures usually have wider CP bandwidth, they usually require a wider space to be implemented. Furthermore, due to the need of phase-delay circuits, double-feed structures provide lower gain.

In the single-feed design, there are generally two approaches towards multi-band CP radiation: stacked patch design [4–6] and single-layer design [7–9]. In [4], to obtain tri-band CP operation stacked patches with a coaxial feed is used. Such structures, having at least two substrate layers, are costly and are also difficult to manufacture especially when mass production is required.

For a single-layer design, patch [7, 8] and slot [9–11] configurations have been used to excite two orthogonal resonant modes with 90° phase difference between them. Since slot antennas radiate bidirectionally, it is a good candidate for applications in some wireless systems and spatial power combining.

In [10], a dual-band dual-sense circularly polarized slot antenna is obtained by loading the original antenna structure by stub-like slots. In [11], four asymmetrical unequal circular-shaped slots are used on the diagonal of a square patch in order to get dual RFID bands. It is shown that by changing the radiu of each circular slot, the resonant frequency of the antenna can be tuned to the desired frequency. However, these single layer antennas can only provide dual circularly polarized bands, and multi-band CP operation is not reported much in open literature. Moreover, most of the reported dual-band CP antennas have large size.

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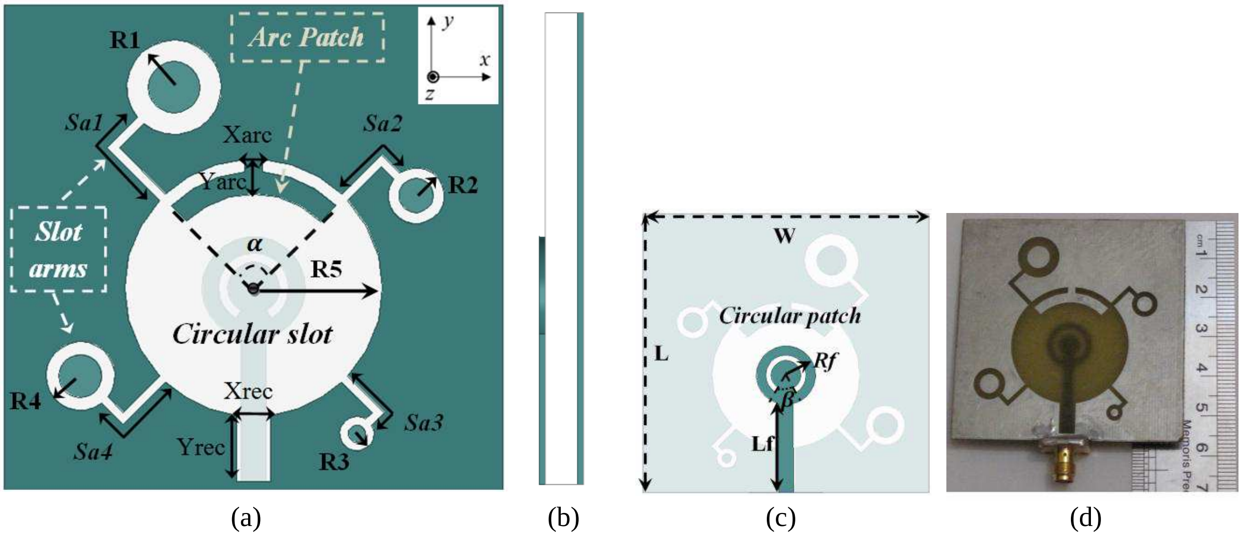

Figure 1. Configuration of the Multi-band circularly polarized printed slot antenna. (a) Slot layer, (b) side view, (c) feed and patch layer, and (d) the fabricated prototype.

In this paper, a single-layer compact multi-band circularly polarized printed slot antenna is presented. This antenna is composed of a wide circular slot with four similar L-shaped arms attached to it. This structure is used to create a dual-band single-layer CP antenna. The center frequency of each of the bands can be tuned by adjusting the overall length of the appropriate slot arms. To generate a third CP band, an arc is incorporated in the upper part of the circular-slot antenna. The circular-slot antenna is fed by a simple microstrip line fed circular patch. The proposed antenna structure is simulated via HFSS software package. A prototype of the antenna is fabricated, and measured results are compared with those of simulation and discussed.

2. ANTENNA STRUCTURE AND DESIGN

It is well known that to obtain circular polarization from an antenna, two equal amplitude modes with 90-degree phase difference between them is required. A circular slot with 4 unequal slot arms quarterly attached to it can, under certain conditions, provide dual orthogonal modes over two different frequency bands [10]. This basic idea is improved to provide a reduced size slot antenna with multiple circularly polarized bands and a linear polarized (LP) band.

The geometry of the proposed antenna is shown in Figure 1. The antenna has a wide circular slot in the ground plane to which four L-shaped slot arms are attached, each loaded with smaller ring slots. It is shown that no difference in CP performance is noticed when the L-shaped arms with small ring slots are attached to the wide circular slot as compared to the straight arms reported in [10]. As shown in Figure 1, to reduce the overall size of the antenna, the four arms are bent, thus, forming the L-shaped arms. This circular-slot antenna is fed through a microstrip-fed circular patch placed on the other side of the substrate.

It is seen that a wide circular slot fed by a microstrip line has resonances at frequencies proportional to the perimeter of the circular slot. By attaching each slot arm to the wide circular slot, a new resonant mode is created.

In the design of the proposed antenna, at first the largest and smallest L-shaped slot arms (slot arm 1 and 3) are placed at 135° and 315°, and their perimeters are adjusted to provide two different frequency bands operating in a single mode. By adding two other L-shaped slot arms at 45° and 225° (slot arms 2 and 4) with almost equal perimeters around the circular slots, one can convert the single mode of operation of the initial structure into two orthogonal modes. In the proposed antenna, the perimeters of the L-shaped slot arms 1 and 3 are adjusted to create two linear resonances at 1.5 and 2.4 GHz frequencies, and the perimeters of L-shaped slot arms 2 and 4 are adjusted to add two other orthogonal modes at each of these bands. Therefore, dual-band circularly polarized antenna is obtained by these four L-shaped slot arms.

In order to create the third CP band, an arc-shaped patch is attached to the ground plane of the antenna. Because this arc patch can offer a new electric current path, a new resonant frequency can be created. Similar to the T-shaped strip in [12], used for creation of dual circularly polarized bands, this arc-shaped patch in conjunction with the L-shaped slots arms 3 and 4 will result in a new circularly polarized resonance.

It is observed that the axial ratio bandwidth of this third band is narrow. Since the electric current on an arc shaped patch is x-directed, by attaching a y-directed stub slot at the bottom of the main circular slot, another CP resonance can take place near the third resonance, resulting in a broader CP bandwidth (covering almost the WiMAX band). By changing the angle of this arc-shaped patch (α) and radius of the main circular-shaped slot (R_5), the center frequency of the third circularly polarized band can be finely tuned.

The antenna structure is fed by a $50\,\Omega$ microstrip transmission line with a circular patch attached to its end. This circular patch is used in order to improve the impedance matching between the slot antenna and the $50\,\Omega$ microstrip feed line. It should be mentioned that this circular patch has its own resonant frequency that can be determined approximately by the following formula [13]:

$$f_{TM_{11}} = \frac{c}{2\pi R_f \sqrt{\varepsilon_r}} \times 1.8412 \tag{1}$$

in which R_f is the radius of patch and c the speed of light.

Here, the value chosen for R_f is 5.5 mm, resulting in a resonant frequency of 7.6 GHz, as calculated by (1). To reduce this resonant frequency a 300 degree arc slot is etched on the circular patch. By adding this arc slot, a linear broad-band frequency over 5.2 to 6.5 GHz is generated covering the wireless local-area network (WLAN, IEE802.11.a) band. It should be pointed out that since there is a wide slot antenna at the ground plane, the circular patch acts as a monopole antenna with linearly-polarized omnidirectional pattern.

The final circularly polarized antenna operates effectively at three frequency bands of 1.5 GHz, 2.4 GHz and 3.75 GHz, while it shows a linear polarized (LP) wave over 5.2 to 6 GHz. The antenna is fabricated on an FR4 substrate, which has a relative permittivity of 4.4. The overall dimensions of the antennas are $58 \times 58 \times 1.6\,\text{mm}^3$. Other design parameters of the proposed antenna structure are as follow: $Sa_1 = 13.6\,\text{mm}$, $Sa_2 = 9.5\,\text{mm}$, $Sa_3 = 8\,\text{mm}$, $Sa_4 = 10.5\,\text{mm}$, $R_1 = 5.5\,\text{mm}$, $R_2 = 3.25\,\text{mm}$, $R_3 = 2\,\text{mm}$, $R_4 = 4\,\text{mm}$, $R_5 = 15\,\text{mm}$, $L_f = 18\,\text{mm}$, $R_f = 5.5$ mm, $X_{rec} = 4\,\text{mm}$, $Y_{rec} = 7.5\,\text{mm}$, $X_{arc} = 2\,\text{mm}$, $Y_{arc} = 4.5\,\text{mm}$, $\alpha = 90°$ deg, $\beta = 60°$ deg. The radii of the circular patches located in the L-shaped slot arms are 3 mm, 2 mm, 1 mm and 2.5 mm for the L-shaped slot arms 1, 2, 3 and 4, respectively, and the slot widths of all the L-shaped slot arms are set at 1 mm.

3. NUMERICAL ANALYSIS AND MEASUREMENTS RESULTS

To get a clear picture of how circular polarization is created, one can study the behavior of the current distribution on the proposed antenna. Figure 2 shows the current distribution of the proposed antenna at three frequencies of 1.5 GHz, 2.4 GHz and 3.7 GHz for both 0° and 90° phases. It should be mentioned that only the distributions of the aforementioned phases are plotted since those of 180° and 270° are equal in magnitude and opposite in phase to those of 0° and 90°. From Figure 2(a) it can be seen that at phase = 0°, due to currents around the slot arms 1 and 4, a mode is produced which is horizontally polarized while at phase = 90° an orthogonal mode, vertically polarized, is created around the slot arms 1 and 2. According to the rotation of the resultant vector, it is seen that this antenna produces left-hand circular polarization (LHCP) at 1.5 GHz frequency.

Similarly, from the current distributions shown in Figure 2(b), one can see that a right-hand circular polarization (RHCP) wave is produced at 2.4 GHz band. Thus, the proposed antenna structure has a dual-sense feature at these two bands.

Figure 2(c) shows the current distribution at 3.7 GHz frequency for both 0° and 90° phases. It can be seen that this circularly polarized band is created by the L-shaped arms 2 and 3, the arc-shaped patch attached to the ground and the rectangular slot above the feed line.

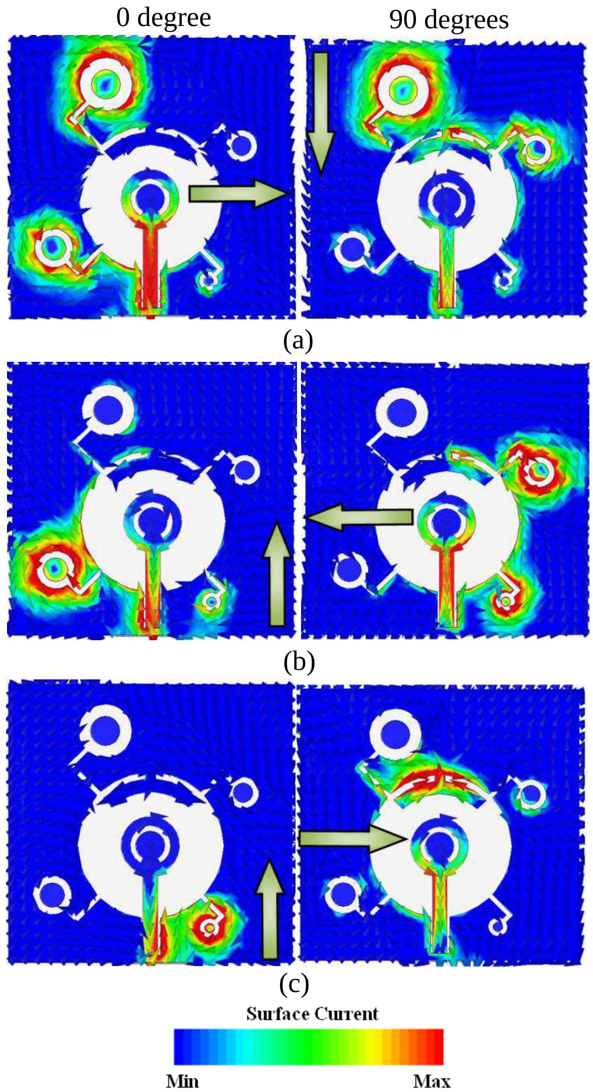

Figure 2. Simulated current distribution of the proposed antenna for 0 and 90 degree phases at: (a) 1.5 GHz, (b) 2.4 GHz, (c) 3.7 GHz.

The simulated and measured results of reflection coefficient and axial ratio of the proposed antenna are shown in Figures 3 and 4, respectively. As can be seen, the measured results are in a reasonable agreement with those of the simulations.

From the measured reflection coefficient result, the impedance bandwidths are 14% (1380–1590 MHz) for the first CP band, 22% (2050–2550 MHz) for the second band, 12% (3450–3900 MHz) for the third band and 27% (4950–6500 MHz) for the fourth LP band. Thus, the proposed antenna can cover the whole GPS, Bluetooth, WiMAX, and WLAN bands.

From the measured axial ratio results, it can be seen that the antenna has CP performance at the first three bands with 3-dB axial ratio bandwidth of 9% (1450–1590 MHz), 7% (2350–2525 MHz) and 11% (3475–3875 MHz). These bandwidths are obtained by curve fitting between the measured axial ratio results in Figure 4.

Each resonant frequency of the proposed antenna can be tuned over a wide range of frequencies through its relative parameters, without affecting the antenna performance much. To investigate this characteristic of the proposed antenna, two other configurations of the compact printed slot antenna are simulated and compared with the original antenna (Antenna I) as shown in Table 1.

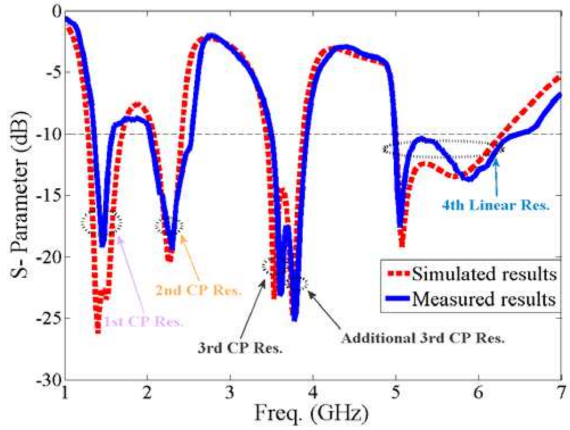

Figure 3. Simulated and measured reflection coefficient of the proposed antenna.

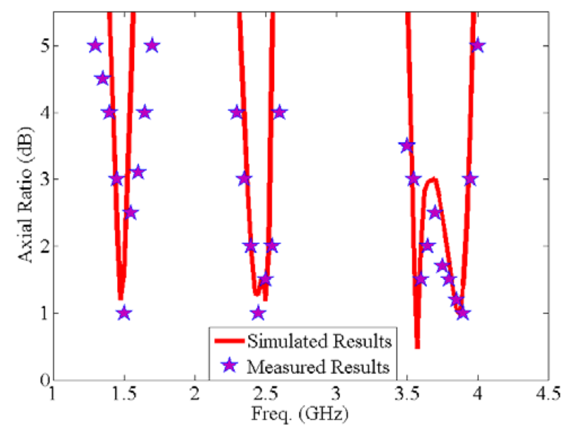

Figure 4. Simulated and measured axial ratio of the proposed antenna.

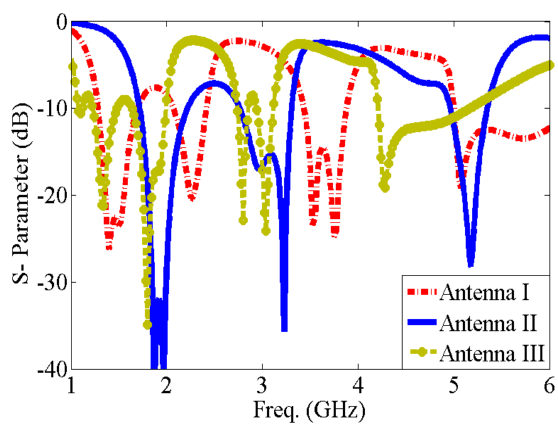

Figure 5. Simulated reflection coefficient of Antenna I (the original antenna), Antenna II (the smaller configuarion of the original antenna) and Antenna III (the bigger configuarion of the original antenna).

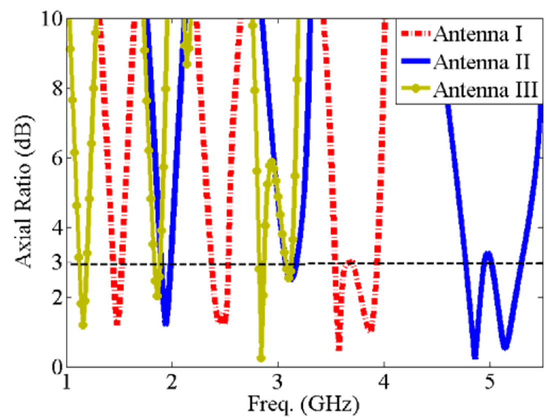

Figure 6. Simualted axial ratio of Antennas I, II and III.

Table 1. Dimensions of the proposed circular-polarized slot Antennas I, II and III.

	Sa_1	Sa_2	Sa_3	Sa_4	R_1	R_2	R_3	R_4	R_5	R_f	X_{rec}	Y_{rec}	L_f	α^o	**Dimensions**
Antenna I	13.6	9.5	8	10.5	5.5	3.25	2	4	15	5.5	4	7.5	18	90	$58 \times 58\,\mathrm{mm}^2$
Antenna II	10.1	8.5	5.2	7.6	4.4	2.6	1.6	3.1	12	4.5	3.5	4.2	14	60	$46 \times 46\,\mathrm{mm}^2$
Antenna III	12.5	7	8.5	9.5	5.5	3.25	2	4	9	6.6	4.8	9.6	25.5	114	$72 \times 72\,\mathrm{mm}^2$

Note: The units of all dimensions are in mm.

As can be seen, Antenna II is a smaller version of the original antenna, and Antenna III is a larger one. The parameters associated with each of these antennas are listed in Table 1. The parameters that are not mentioned in the table have negligible effect on the antenna performance.

The reflection coefficient and axial ratio of these antennas are simulated and compared in Figures 5 and 6, respectively. From these figures, it can be seen that Antenna II has circularly polarized bands around 1.9 GHz, 3.1 GHz and 5 GHz while Antenna III has circularly polarized bands around 1.1 GHz, 1.8 GHz and 3 GHz. From this figure, it is clear that the frequency ratio of each antenna is different from the other. For instance, the frequency ratio of third/first band for the Antenna I is 2.5 while this is 2.6 and 2.7 for Antennas II and III, respectively. This means that the proposed antenna can be tuned for desired frequencies which are close or apart from each other.

To further evaluate the performance of the proposed antenna, a parametric study on some of the important parameters of the antenna is performed.

Figures 7 and 8 show the effect of the radius of slot arm 1 (R_1) on the reflection coefficient and the axial ratio of the proposed antenna, respectively. As described before, slot arm 1 is responsible for creation of the first resonance of the antenna. Therefore, changing R_1 results in changing the performance of the first resonance of the antenna. From these figures, it can be seen that R_1 has much more effect on the axial ratio of the first band than the reflection coefficient. It is clear that decreasing R_1 results in adverse effect on the axial ratio of the first resonance frequency.

Figure 9 shows the effect of the radius of slot arm 3 on the reflection coefficient of the proposed antenna. According to the fact that slot arm 3 is mainly responsible for the second and third resonance frequencies of the proposed antenna, any variation in its value will lead to shifting the resonance frequency of these bands.

The effect of arc patch angle α on the frequency response of the antenna is shown in Figure 10. From this figure, it can be seen that by changing the value of α, part of the third resonance (additional 3rd CP resonance in Figure 3) of the antenna is varied, over a wide range of frequencies.

Figure 11 shows the measured RHCP and LHCP gains of the proposed antenna at the CP bands of

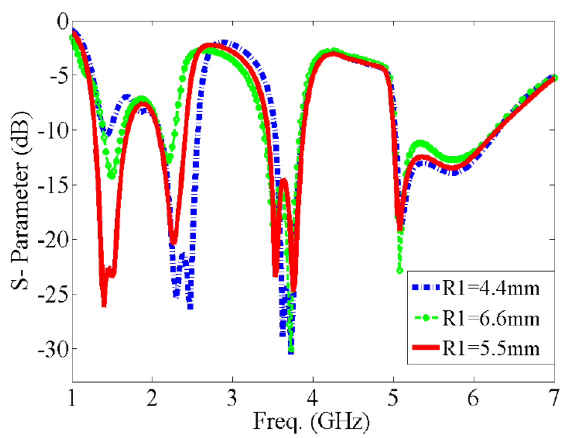

Figure 7. Simulated reflection coefficient of the proposed antenna with different R_1 radius.

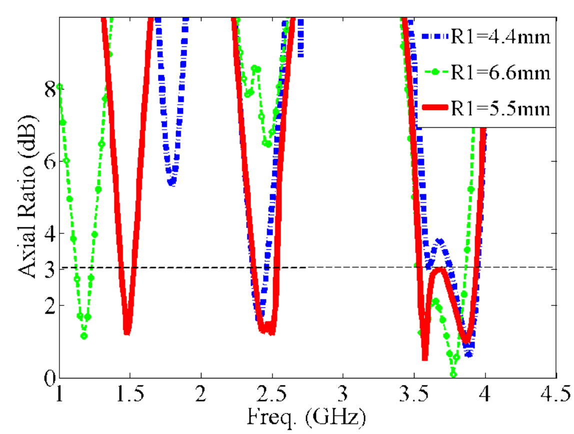

Figure 8. Simulated axial ratio of the proposed antenna with different R_1 radius.

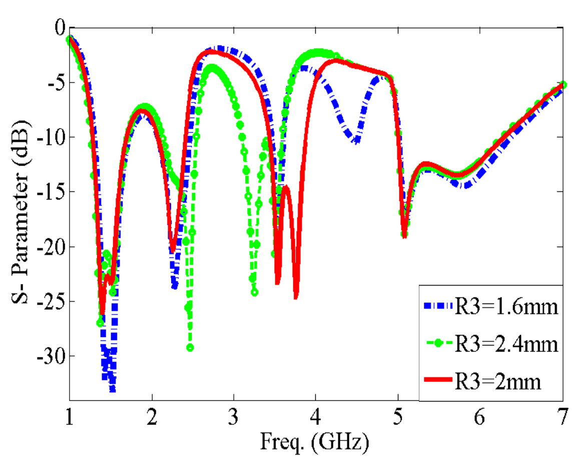

Figure 9. Simulated reflection coefficient of the proposed antenna with different R_3 radius.

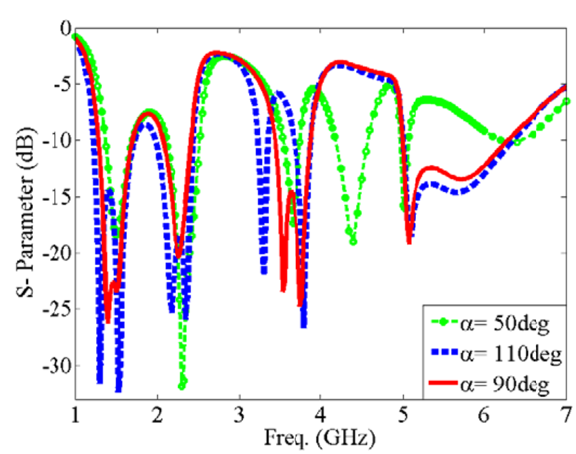

Figure 10. Simulated reflection coefficient of the proposed antenna with different α angle.

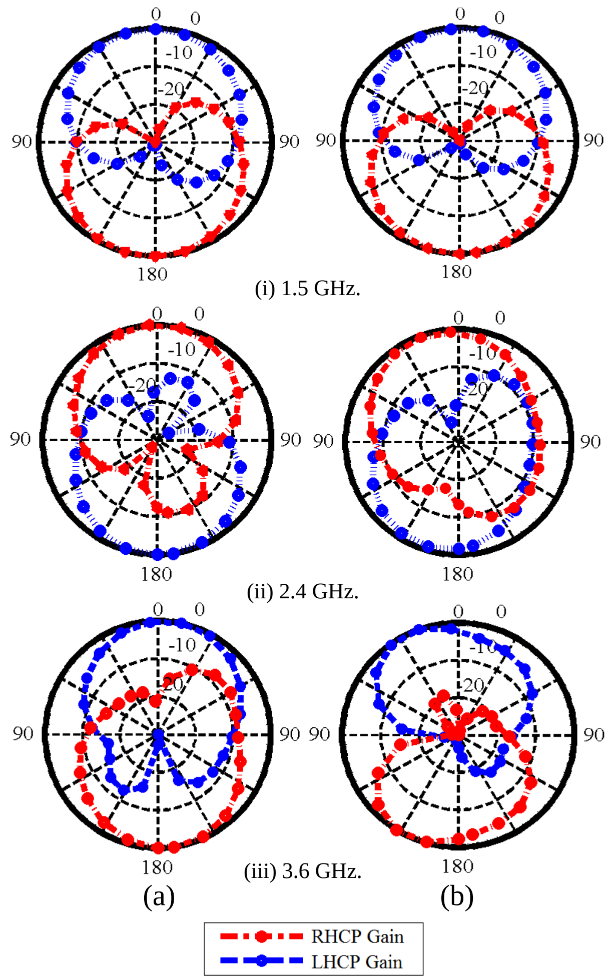

Figure 11. Measured RHCP and LHCP gains of the proposed antenna. (a) H-plane. (b) E-plane.

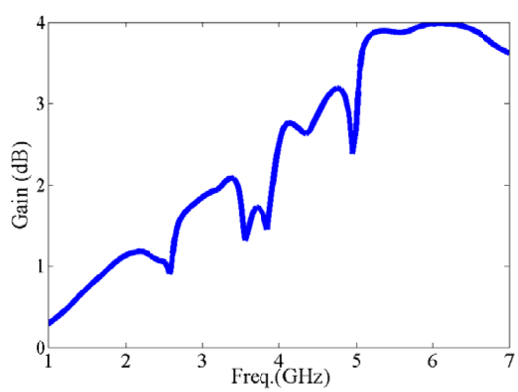

Figure 12. Measured gain versus frequency.

1.5 GHz, 2.4 GHz and 3.7 GHz in the H- and E-planes. Since the proposed slot antenna is a bidirectional radiator, the radiation patterns in both sides are almost the same. It is also clear that in the boresight direction, the antenna has cross polarization well below 15 dB in all CP bands. The antenna has LHCP radiation in 1.5 and 3.7 GHz bands while the radiation of 2.4 GHz band is RHCP.

The measured gain of the proposed antenna is shown in Figure 12.

4. CONCLUSION

The design of a multi-band circularly polarized printed slot antenna with a single microstrip feed line has been presented in this paper. The proposed antenna has circularly polarized radiation at 1.5 GHz for GPS, 2.4 GHz for Bluetooth, and 3.75 GHz for WiMAX application with 14%, 22%, 12% impedance bandwidth and 9%, 7%, 11% axial ratio bandwidth, respectively. The measured results of the fabricated antenna show stable radiation patterns with triple sense over these bands. The proposed antenna also provides a fourth linear polarized band over 5.2 to 6 GHz covering the WLAN band. The proposed antenna has the advantage of being tunable in its resonance frequencies; as such two different configurations of the reported antenna with different resonant frequencies have been simulated and compared with the original one. All results show that the proposed antenna is a good candidate for multifunctional and multiband applications.

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