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RESEARCH PAPER

Single-feed circularly polarized stacked patch antenna with small-frequency ratio for dual-band wireless applications

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A single-feed dual-band circularly polarized stacked microstrip patch antenna with a small-frequency ratio is presented. Two pair of orthogonal slits is cut on the lower circular patch for achieving circular polarization and truncated corner square patch is used as the upper parasitic element. The frequency ratio of the dual-band is 1.03. The 3 dB axial ratio bandwidth is 1.3% for the upper band and 1.1% for the lower band. Proposed structure is fabricated on the FR-4 epoxy substrate and fed by SMA connector. The measured results are in good agreement with the theoretical and simulated results. The antenna shows stable radiation characteristics in both bands of operation.

Keywords: Circular polarization, Multiband, Stacked microstrip antenna

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I. INTRODUCTION

Circularly polarized microstrip antennas have been considered as a good choice for mobile communication, global positioning system (GPS), radio frequency identification readers, wireless local area network applications due to their small size, light weight, and integrability with other millimeter, and microwave circuits [1, 2]. The major problem of concern in wireless communication is multipath interference. Circular polarization combats multipath fading by introducing polarization diversity in radio propagation environment thus providing high probability of a successful link, superior mobility, spectral efficiency, and improved system performance [3, 4]. Circular polarization can be achieved either by using single feed or dual feed [5]. A single-feed circularly polarized antenna does not require an external polarizer and are preferred for compact portable devices where miniaturization is the main designing factor. Generally, a single-feed patch radiates linearly polarized wave and to generate circularly polarized wave two orthogonal modes of equal amplitude and quadrature phase difference need to be introduced which can be achieved by perturbing the patch with respect to the feed location. A single-fed patch radiates both right-hand circularly polarized and left-hand circularly polarized wave and sense of polarization can be changed by reversing the polarity of bias field [6]. Modern smart phones are versatile devices that can be used to transfer data via Bluetooth, access data through Wi-Fi, track location through GPS along with voice-based services; for which several antennas are required for operation. By printing all these antennas onto a common patch with multiband operation the size gets miniaturized reducing production cost.

Dual-band circularly polarized antennas are considered as an ideal choice for those applications which employs two far apart operating frequencies thus acting as an alternative for two separate antennas miniaturizing operating equipment. For, many dual-band applications antenna with a small-frequency ratio is desired. A simple probe-fed antenna with two pairs of arc-shaped slots and protruding one of the arc-shaped slots with a narrow slot embedded in the circular patch has been reported [7]. The two pairs of arc-shaped slots generate two operating modes resulting dual-band operation with a frequency ratio of 1.48. A reduction in size of antenna has also been observed with the introduction of slits and slots. In literature [8], asymmetrical S-shaped slot is cut on the upper surface of the radiating patch and frequency ratio of 1.28 has been achieved. The dual frequencies can also be obtained using multilayer stacked configuration each of them radiating at different resonant frequencies. The structure can be easily fed by simple coaxial feed or by coupling feed mechanism. Over the years, several stacked structures have been reported for dual-band and multiband operation. A dual-band aperture-fed circularly polarized antenna with a minimum frequency ratio of 1.28 has been presented in [9]. In [10] single-feed aperture-coupled stacked circular patch with perturb segments for L-band applications has been reported. In the paper [11], two stacked elliptic patch antennas of different axial ratios with a small air gap in between the two patches has been reported. The bottom patch acts as a parasitic patch as the feed is provided in the upper patch. A circularly polarized antenna for triple-band

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GPS receivers has been presented in [12] which employ multi-stacked patches fed through a coaxial probe. The multiband structure has high gain, broad beamwidth, and low cross-polarization characteristics. An increase in number of layers of the stacked patch antenna leads in production of the multi-band operation. In this paper, a truncated corner-stacked square patch for dual-band operation is proposed. The simple coaxial feed is provided at the slit cut lower circular patch. The proposed antenna is theoretically analyzed on the basis of cavity model and optimization is conducted using finite-element method-based simulator Ansoft HFSS v.14 [13].

II. THEORETICAL CONSIDERATIONS

The structure of the proposed stacked antenna is shown in Fig. 1. The upper parasitic element is a square patch with truncated corners along the diagonal for circular polarization and lower driven element is a circular patch with two pair of slits cut along the boundary. The presence of parasitic patch in stacked geometry introduces two resonances associated with the two resonators. Firstly, the lower patch has been analyzed considering the effect of dielectric superstrate and neglecting the effect of upper parasitic patch. The dielectric layer above the microstrip patch causes a change in the fringing field present between the ground and microstrip patch and that effect is accounted by the effective dielectric constant calculated as [14]

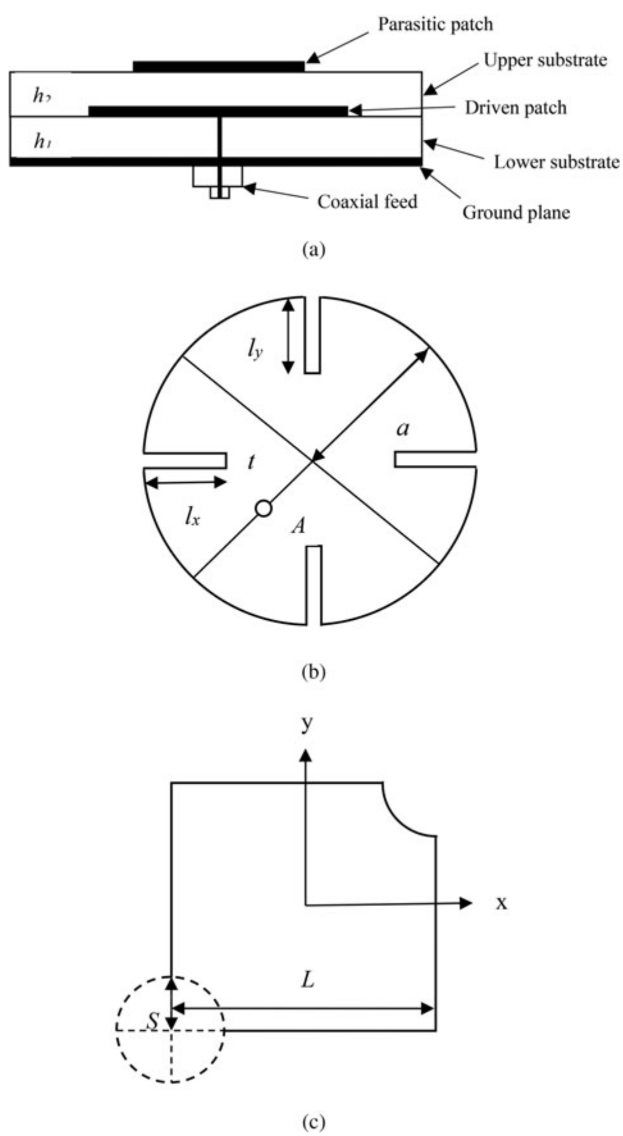

Fig. 1. Schematic representation of single-feed dual-band stacked microstrip antenna. (a) Cross-sectional view, (b) lower patch, and (c) upper patch.

$$\begin{aligned}\varepsilon_{r,eff} &= \varepsilon_{r1}p_1 + \varepsilon_{r1}(1-p_1)^2 \\ &\times [\varepsilon_{r2}^2 p_2 p_3 + \varepsilon_{r2}\{p_2 p_4 + (p_3+p_4)^2\}] \\ &\times [\varepsilon_{r2}^2 p_2 p_3 p_4 + \varepsilon_{r1}(\varepsilon_{r2}p_3 + p_4)(1-p_1-p_4)^2 \\ &+ \varepsilon_{r2}p_4\{p_2 p_4 + (p_3+p_4)^2\}]^{-1},\end{aligned} \tag{1}$$

where ε_{r1} is the relative dielectric constant of lower patch and that of superstrate is ε_{r2}.

and

$$p_1 = 1 - \frac{h_1}{2w_e}\ln\left(\frac{\pi w_e}{h_1} - 1\right) - p_4, \tag{2}$$

$$p_2 = 1 - p_1 - p_3 - 2p_4, \tag{3}$$

$$\begin{aligned}p_3 = \frac{h_1 - g}{2w_e}\ln\Bigg[\frac{\pi w_e}{h_1}\frac{\cos(\pi g/2h_1)}{\pi([1/2]+[h_2/h_1]) + [g\pi/2h_1]} \\ + \sin\left(\frac{g\pi}{2h_1}\right)\Bigg],\end{aligned} \tag{4}$$

$$p_4 = \frac{h_1}{2w_e}\ln\left(\frac{\pi}{2} - \frac{h_1}{2w_e}\right), \tag{5}$$

$$g = \frac{2h_1}{\pi}\arctan\left[\frac{(\pi h_2/h_1)}{[\pi/2](w_e/h_1) - 2}\right], \tag{6}$$

$$\begin{aligned}w_e = \sqrt{\frac{\varepsilon_r'}{\varepsilon_{r,eff}}}\Bigg[\left\{w + 0.882h_1 + 0.164h_1\left(\frac{\varepsilon_r' - 1}{\varepsilon_r'^2}\right)\right\} \\ + h_1\left(\frac{\varepsilon_r' - 1}{\pi\varepsilon_r'}\right)\left\{\ln\left(0.94 + \frac{w}{2h_1}\right) + 1.451\right\}\Bigg],\end{aligned} \tag{7}$$

$$\varepsilon_r' = \frac{2\varepsilon_{r,eff} - 1 + (1 + [10h_1/w_e])^{-0.5}}{1 + (1 + [10h_1/w_e])^{-0.5}}, \tag{8}$$

$$w = a(\pi - 2), \tag{9}$$

where h_1 and h_2 are the thickness of lower and upper substrates, respectively, and a is the radius of circular patch. The parameters w_e and ε_r' are determined by the iteration method given in [15]. The dielectric layer present above the radiating patch extends the radius of magnetic wall cavity thus changing effective radius size of the circular patch and is given as [16]

$$a_{eff} = a\left\{1 + \frac{2h}{\pi\varepsilon_{re} a}\left[\log\left(\frac{a}{2h}\right) + 1.41\varepsilon_{re} + 1.77 + \frac{h}{a}(0.268\varepsilon_{re} + 1.65)\right]\right\}^{0.5}, \quad (10)$$

and

$$\varepsilon_{re} = \frac{\varepsilon_{r1} h}{h_2 + h_1\varepsilon_{r1}}. \quad (11)$$

$$h = h_1 + h_2. \quad (12)$$

The resonant frequency of the lower patch is expressed as [17]

$$f_{r1} = \frac{\alpha_{nm} c}{P_e\sqrt{\varepsilon_{r,\,eff}}}, \quad (13)$$

where, c is the velocity of light in free space and $\alpha_{nm} = 1.84118$ for dominating the TM_{11} mode and

$$P_e = P_i\left\{1 + \frac{2h}{\pi a_{eff}\varepsilon_{re}}\left(\ln\frac{\pi a_{eff}}{2h} + 1.7726\right)\right\}^{0.5}, \quad (14)$$

where $i = 1, 2, 3$.

$$\begin{aligned} P_1 &= 2\pi a_{eff} + 4l_x, \\ P_2 &= 2\pi a_{eff} + 4l_y, \\ P_3 &= 2\pi a_{eff} - 4t, \end{aligned} \quad (15)$$

where P_1 is the effective length of the patch with slits inserted along the x-axis, P_2 is the effective length of the patch with slits inserted along the y-axis, P_3 is the effective length of the sectored geometry obtained by slitting on the lower patch, l_x is the length of the slits in the x-axis, l_y is the length of the slits along the y-axis, and t is the width of slits along the x–y-axis.

The equivalent circuit of the lower patch is a combination of resistance R_1, inductance L_1, capacitance C_1, and input impedance of the lower patch is calculated as [18]

$$Z_1 = \frac{1}{(1/R_1) + j\omega C_1 + (1/j\omega L_1)}. \quad (16)$$

Secondly, the upper patch is analyzed and the values of resistance R_2, inductance L_2, and capacitance C_2 are given as [19]

$$C_2 = \frac{\varepsilon_0\varepsilon_{r2} L^2}{2h_2}, \quad (17)$$

$$L_2 = \frac{1}{\omega_2^2 C_2}, \quad (18)$$

$$R_2 = \frac{Q_r}{\omega_2 C_2}, \quad (19)$$

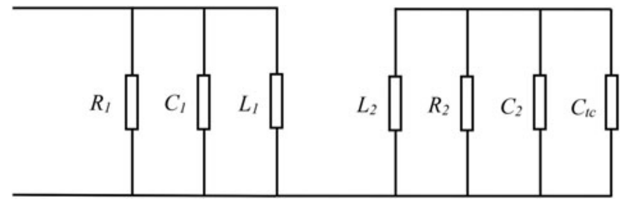

Fig. 2. Equivalent circuit of single-feed dual-band stacked microstrip antenna for circular polarization.

$$Q_r = \frac{c\sqrt{\varepsilon_r}}{4 f_2 h_2}, \quad (20)$$

where L is the length of the parasitic patch, ε_r is the effective dielectric constant of the upper substrate, and $\omega_2 = 2\pi f_2$ is

$$f_2 = \frac{c}{2(L + 2\Delta L)\sqrt{\varepsilon_r}}, \quad (21)$$

where ΔL is the fringing length of the square patch.

In the square patch truncated corner capacitive effect is calculated as [20]

$$C_{tc} = \frac{\varepsilon_0\varepsilon_{r2}\Delta S}{h_2}, \quad (22)$$

$$\Delta S = \frac{\pi S^2}{2}. \quad (23)$$

The input impedance of square microstrip antenna with truncated corner is given as

$$Z_2 = \frac{1}{(1/R_2) + j\omega_2(C_2 + C_{tc}) + [1/(j\omega_2 L_2)]}. \quad (24)$$

Now, the equivalent impedance of the stacked antenna configuration is calculated

$$Z_{in} = Z_1 + Z_2. \quad (25)$$

The equivalent circuit of the stacked antenna geometry is shown in Fig. 2 and is a combination of two antenna elements, i.e. lower circular patch and upper square patch.

Thus, the reflection coefficient and voltage standing wave ratio (VSWR) can now be calculated as for the proposed stacked configuration

$$\Gamma = \frac{Z_{in} - Z_o}{Z_{in} + Z_o}, \quad (26)$$

where Z_o is the characteristic impedance of the coaxial feed and

$$VSWR = \frac{1 + \Gamma}{1 - \Gamma}. \quad (27)$$

III. ANTENNA STRUCTURE AND DESIGN

The cross-sectional view of stacked antenna configuration is shown in Fig. 1(a). The circular patch with slits cut along the x-axis and the y-axis at the patch boundary is used as a driven lower patch and a square patch with truncated corners as upper parasitic element.

Table 1. Dimensions of the proposed structure.

Antenna parameters	Value (mm)
Thickness of lower substrate (h_1)	1.6
Radius of lower circular patch (a)	15
Length of slit along x-axis (l_x)	10
Length of slit along y-axis (l_y)	9.0
Width of slit along x-axis and y-axis (t)	1.0
Thickness of upper substrate (h_2)	1.6
Length of square patch (L)	20
Radius of truncated corner (S)	4.5

A circular patch with two pairs of slit of suitable dimensions cut at the patch boundary as perturbation elements for circularly polarized radiations is the lower layer of stacked antenna element. The lower circular patch with asymmetric slits makes possible for the excitation of two orthogonal modes of equal amplitudes and 90° phase shift for circularly polarized operation. The asymmetric length slits cut along the x-axis and the y-axis of the conventional circular patch meanders the excited patch surface current densities of the two orthogonal modes leading to a compact circularly polarized microstrip antenna configuration. Figure 1(b) shows the schematic of the lower patch element. A is the feed location, and a is the radius of the circular patch. The length of slits along the x-axis and the y-axis is denoted by l_x and l_y, respectively, and t is the width of slits.

The diagonal corners of the upper square patch of length L are truncated with a quarter part of circle of radius S mm. The upper parasitic square patch is excited by the fringing field of the lower circular patch. The schematic of the upper truncated corner square patch is shown in Fig. 1(c). The detailed design specifications of the proposed antenna structure are provided in Table 1. The antenna is fed using 50 Ω SMA connector placed along the diagonal of the patch. The sense of rotation can be changed by simply changing the position of feed along another diagonal of the stacked patch antenna. Both the patches are fabricated on 1.6 mm thick substrate of relative permittivity 4.4 and loss tangent 0.0012. Fabrication of proposed antennas is done by standard photolithography process. The electrical characteristics of the fabricated antennas are measured on Agilent Network Analyzer (PNA L-Series). The photograph of the fabricated stacked antenna prototype is depicted in Fig. 3.

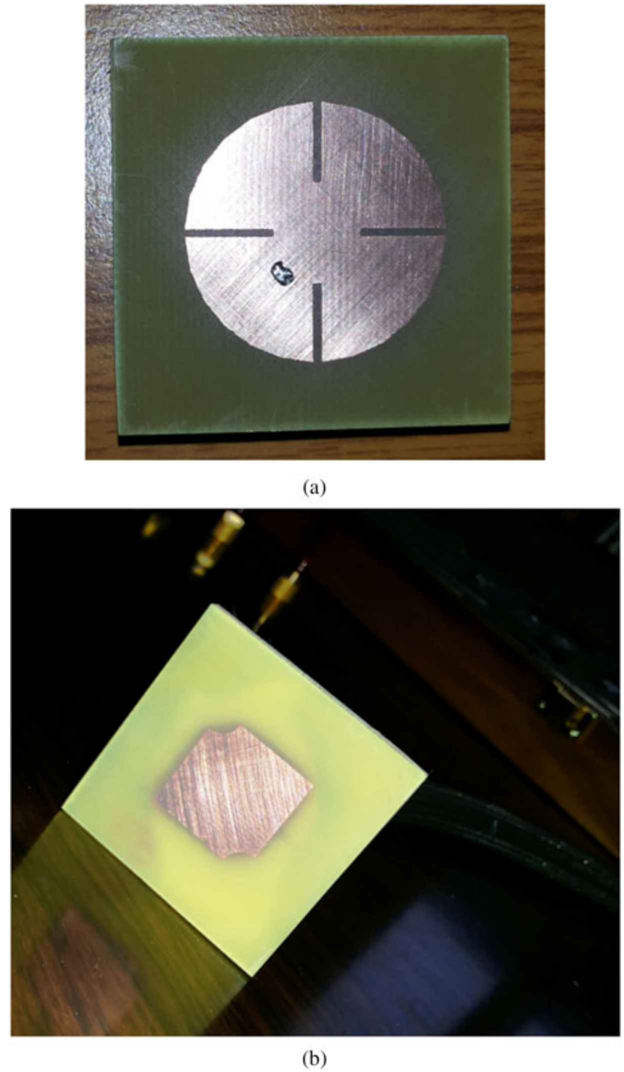

Fig. 3. Prototype of the fabricated structure (a) lower patch and (b) circularly polarized dual-band stacked microstrip antenna.

IV. RESULTS AND DISCUSSION

A dual-band characteristic is achieved by stacking the proposed patches. The resonant frequency of the circular patch decreases with increase in length of embedded slits. By embedding rectangular slits in the circular patch, path of the surface current is increased thus achieving compactness in the size of antenna. The difference in length of rectangular slits along the x-axis and the y-axis leads to excitation of two near-degenerate orthogonal modes of equal amplitudes and 90° phase difference for circularly polarized operation.

By truncating the corners of the parasitic square patch, the antenna shows circular polarization behavior. The resonant frequency of the truncated square patch decreases with increase in the radius S of truncated circular corner. While for high values of S a shift in frequency is present. For fabricating the antenna structure, the optimized values of truncated corner square patch and rectangular slits are considered.

The variation of S_{11} with the frequency of the stacked antenna is shown in Fig. 4. The first resonance occurs at 2.03 GHz and second resonance occurs at 2.10 GHz, thus a

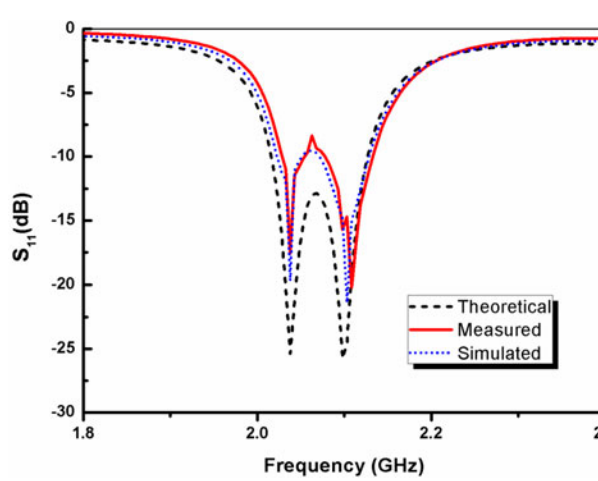

Fig. 4. Variation of S_{11} (dB) with frequency (GHz) of dual-frequency circularly polarized stacked microstrip antenna.

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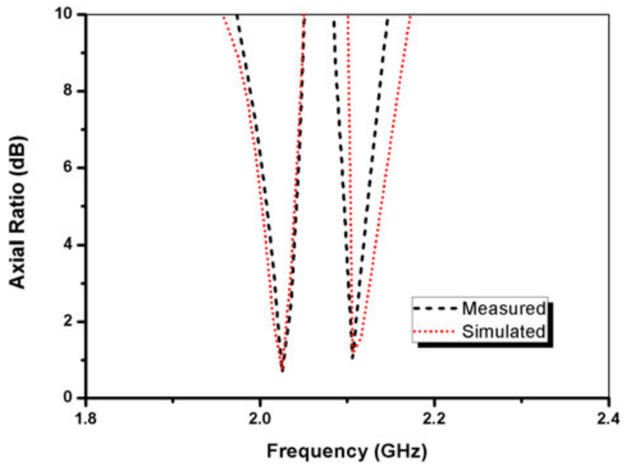

Fig. 5. Variation of axial ratio (dB) with frequency (GHz) of dual-frequency circularly polarized stacked microstrip antenna.

dual-band with a small-frequency ratio of 1.03 is achieved with circular polarization behavior at the two frequencies. The proposed stacked antenna has a good axial ratio at both bands thus producing circular polarization characteristics. The variation of axial ratio with frequency of proposed stacked antenna is shown in Fig. 5. The simulated and measured gain of the proposed antenna is shown in Fig. 6. The gain of the antenna is measured by Vector Network Analyzer using the two antenna method by designing two identical dual-band stacked antennas and measuring transmission coefficient, S_{21}. The two antennas are kept distance apart which is more than the minimum distance to receive far field. One antenna is connected to the port 1 of the network analyzer and is treated as transmitting antenna, whereas the other receiving antenna is connected to port 2 of the network analyzer. Then, using Friis transmission formula, gain of the receiving antenna is determined. The radiation characteristic is better at the first resonance. There is a slight difference between the simulated and measured results due to the use of adhesive to stick the lower patch and upper patch, the variation is affected as the adhesive will have an effect on the radiation. The usage of adhesive changes the dielectric constant as well and contributes to the variation.

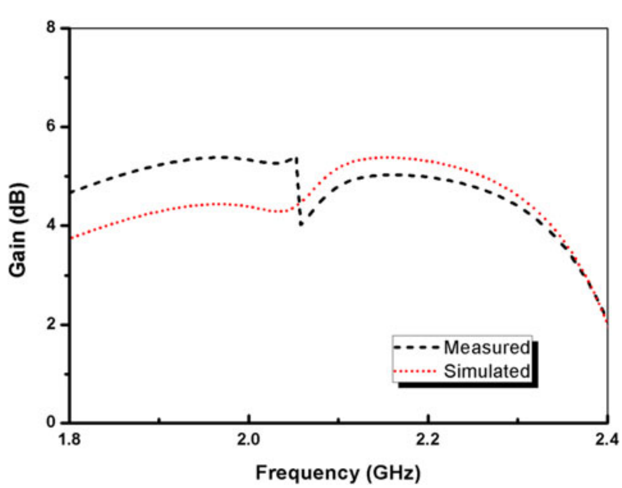

Fig. 6. Variation of gain (dB) with frequency (GHz) of dual-frequency circularly polarized stacked microstrip antenna.

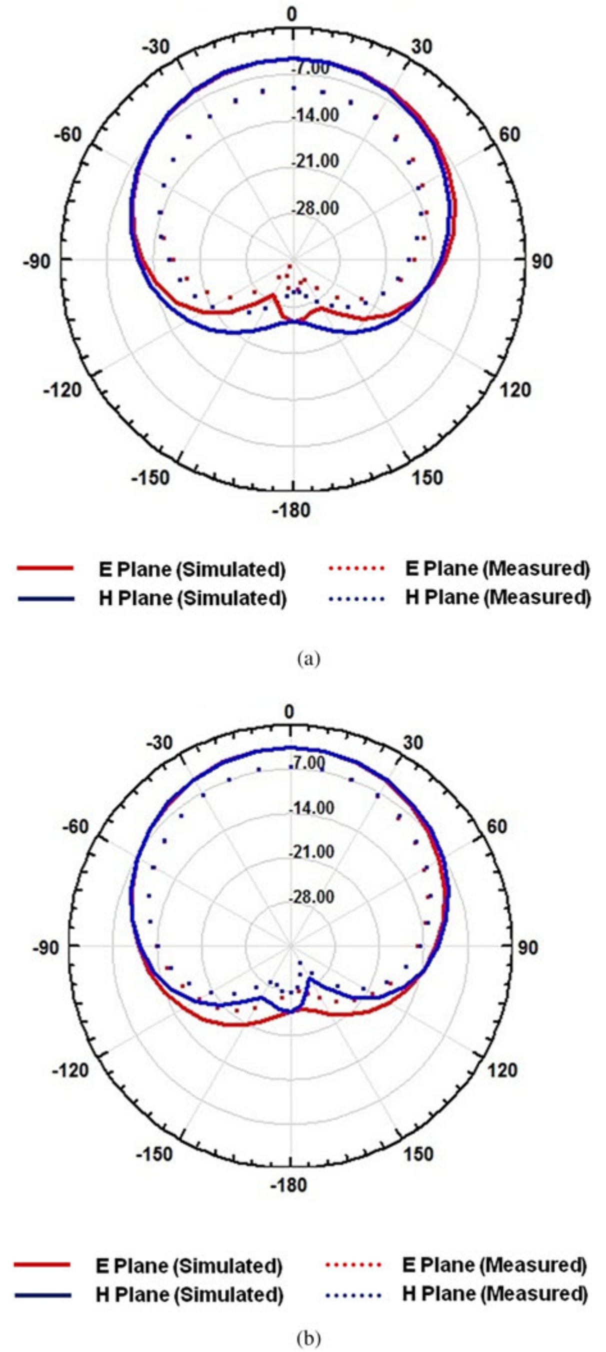

Fig. 7. Radiation pattern of the dual-band stacked microstrip antenna (a) 2.03 GHz and (b) 2.10 GHz.

Proposed antenna shows stable radiation characteristics in both the bands. The *E*-plane and *H*-plane radiation patterns at 2.03 and 2.10 GHz of the stacked antenna is shown in Fig. 7. Almost same radiation patterns are achieved for both the bands.

V. CONCLUSION

A dual-band single-feed circularly polarized stacked microstrip antenna with a small-frequency ratio of 1.03 has been presented. The proposed structure is simple to fabricate and

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shows a good quality of circular polarization at both the resonant bands. The measured results are found in good agreement with the simulated. The small difference is due to fabrication tolerance, placement of the upper patch and soldering of SMA connector. The proposed antenna may be a good choice for modern wireless communication applications where a multiband with small-frequency ratio is desired.

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