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RESEARCH PAPER

Gain enhancement over a wideband in CPW-fed compact circular patch antenna

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The present paper reports the gain enhancement over a wideband (12–15 GHz) in a coplanar waveguide (CPW)-fed circular patch antenna with circular defected ground structure (DGS). Two compact coplanar circular antennas have been designed and fabricated with and without DGS of same volume 18 × 20 × 1.6 mm^3, built over FR4-epoxy substrate ($\varepsilon_r = 4.4$). Gain enhancement has been achieved by optimizing the current distribution with suitable DGS. For this purpose, structural designs have been optimized by parametric simulations in HFSS and CST MWS. Both the antennas can perform well in variety of wireless communication including WLAN IEEE 802.11 g/a (5.15–5.35 GHz and 5.725–5.825 GHz) and X-band applications including short range, tracking, missile guidance, and radar communication that ranges roughly from 8.29 to 11.4 GHz. The measured experimental results show that impedance bandwidth ($S_{11} < -10$ dB) of antenna with DGS is 100%. The antenna with DGS offers gain improvement by 2.7 dB for 13 GHz and 7 dB for 14 GHz. The performance of antenna with DGS is compared to conventional CPW-fed circular patch antenna (without DGS) in terms of reflection coefficient, radiation characteristics, and gain.

Keywords: Antenna design, Modeling and measurements, Antennas and propagation for wireless systems

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I. INTRODUCTION

The role of compact antennas is increasing day by day due to rapid growth of wireless communications and microwave applications, which is supported by small-sized devices. For this purpose, antennas with broadband characteristics are in strong demand. In order to have good antenna performance, antennas having thick dielectric substrate with a low dielectric constant are preferred as they provide good efficiency, larger bandwidth, and better radiation characteristics. However, there exists a trade-off among the antenna performance, antenna size, and cost. Various methods are used in past to enhance the bandwidth, and improve the radiation characteristics of antennas and some of the techniques include increase of the substrate thickness [1, 2], the use of a low dielectric substrate, use of various impedance matching and feeding techniques, multiple resonators, and the use of slot antenna geometry [3–5]. Also researchers have taken care to protect the microstrip patch antennas from adverse effects of dielectric and surface wave losses. One of the methods to mitigate such kinds of losses is to use defected ground structures (DGS). Recently, many patch antennas with DGS are suggested in various applications [6, 7]. DGS is realized by etching a defect in the ground plane of planar circuits and antennas. DGS is an etched periodic or non-periodic cascaded configuration defect in ground of a planar transmission line (e.g., microstrip, coplanar, and conductor-backed coplanar wave guide), which disturbs the shield current distribution in the ground plane because of the defects in the ground [8]. Owing to their excellent pass and rejection frequency band characteristics, DGS are chosen to be a part of patch antennas in order to improve their performances. Surface waves occur due to the trapping of total available radiated power along the surface of the antenna substrate. These waves reduce the antenna gain, efficiency, and bandwidth. All these problems can be evicted by using DGS structure in patch antenna, which supports wideband operation [6, 7].

The coplanar waveguide (CPW)-feeding mechanism has many advantages over microstrip-type feed lines, such as low dispersion, low radiation leakage, the ability to effectively control the characteristic impedance, and the ease of integration with active devices [9–17]. The purpose of this work is to enhance the gain of compact circular patch antenna using the specific strategy of DGS technique and compare it with the conventional patch antenna (without DGS).

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II. CPW-FED BROADBAND ANTENNA ON FR4

Figure 1(a) shows the conventional CPW-fed circular patch antenna without DGS and Fig. 1(b) depicts the geometry of the proposed CPW-fed circular patch antenna with DGS. These patch antennas have equal cross-sectional areas. The width of the central strip of CPW antennas is of 3 mm, and the gap between the central strip and ground planes is 0.5 mm. There are two symmetric ground planes with dimensions of 7 mm × 8 mm lying on both side of the central strip. Figure 1(b) shows antenna with DGS of two circular slots etched of radius, "$r_1 = 2.5$ mm" each, in order to enhance the gain of the antenna. Since the antenna is made to design for higher frequencies for wireless and X-band applications, the size of the antenna is kept compact enough to fit the portable devices. The antenna is also fabricated on low cost "FR4" (flame retardant woven glass reinforced epoxy resin) substrate, which makes it cost-effective for various users.

The optimized design parameters obtained for the proposed patch antenna are $L = 18$ mm, $W = 20$ mm, $g = 0.5$ mm, $W_f = 3$ mm, $W_g = 8$ mm, $L_g = 7$ mm, $L_f = 7.23$ mm, $r_c = 5$ mm, $r_1 = r_2 = 2.5$ mm, and $r = 2$ mm. Dielectric substrate (FR4 epoxy) has relative dielectric constant ε_r of 4.4, loss tangent of 0.02, and thickness "h" of 1.6 mm.

These antennas have a single-layer metallic structure on one side of the substrate (top) whereas the other side (bottom) is without any metallization. The circular disc is fed via CPW feed, which in turn is connected through a standard 50-Ω Sub Miniature Version A Connectors (SMA) connector. Figure 2 shows the fabricated patch antennas.

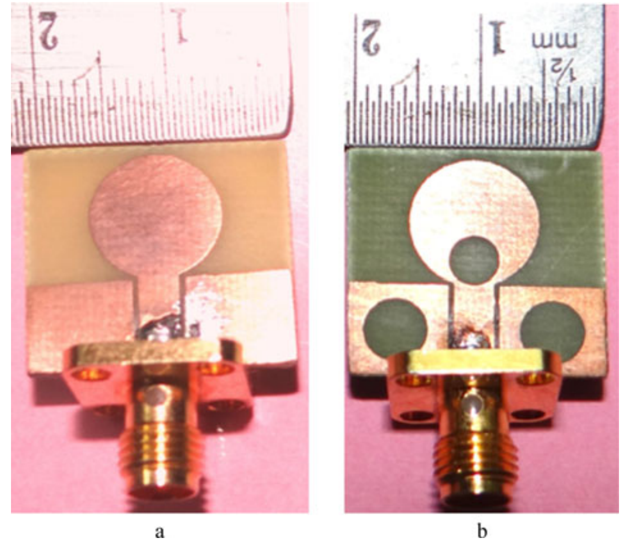

Fig. 2. The fabricated prototypes of antennas (a) conventional CPW fed circular patch antenna without DGS (b) proposed CPW-fed circular patch antenna with DGS.

III. DESIGN OF CIRCULAR MONOPOLE ANTENNA

The lower band edge frequency of a conventional circular printed monopole antenna with radius "r" can be evaluated from following equation [16]:

$$f_l = \frac{72}{\left(2r + \frac{r}{4} + p\right)y} \text{GHz}. \tag{1}$$

Here, "y" is a factor accounting the role of dielectric material in reducing the lower band edge frequency by increasing the effective dimensions of the antenna and "p" is the gap between the circle and the ground plane, which is $p = 0.23$ mm in our case and $y = 1.15$ (for FR4). The lower band edge frequency with our design for $r_c = 5$ mm comes out 5.45 GHz, which is near by the simulated and measured values.

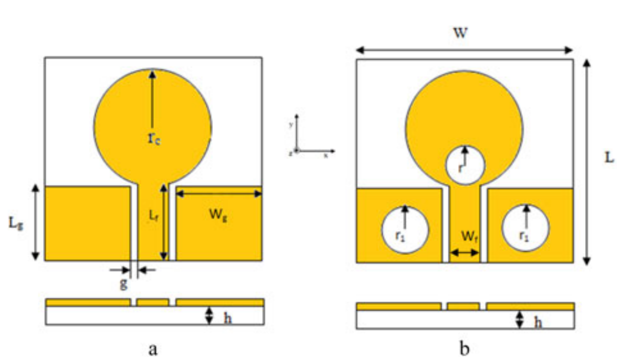

Fig. 1. The geometric design of antennas (a) conventional CPW-fed circular patch antenna without DGS (b) proposed CPW-fed circular patch antenna with DGS.

The characteristic impedance of CPW line with finite-width ground plane on the FR4 dielectric substrate of height "h_d" (see Fig. 3) is given by Simons [17]:

$$Z_o = \frac{30\pi}{\sqrt{\varepsilon_{re}}} \frac{K(k)}{K(k')} \Omega\,. \tag{2}$$

Here, "K" is the complete elliptical integrals of first kind. The arguments k and k' are dependent on the geometry of the CPW line

$$k = \frac{c}{b}\sqrt{\frac{b^2 - a^2}{c^2 - a^2}} \text{and}\, k' = \sqrt{1 - k^2} = \frac{a}{b}\sqrt{\frac{c^2 - b^2}{c^2 - a^2}} \tag{3}$$

and the effective dielectric constant (ε_{re}) of the CPW line is given as

$$\varepsilon_{re} = 1 + \frac{1}{2}(\varepsilon_r - 1)\,\frac{K(k)}{K(k')}\frac{K(k_1')}{K(k_1)}. \tag{4}$$

Here,

$$k_1 = \frac{\sinh\left(\frac{\pi c}{2h_d}\right)}{\sinh\left(\frac{\pi b}{2h_d}\right)} \sqrt{\frac{\sinh^2\left(\frac{\pi b}{2h_d}\right) - \sinh^2\left(\frac{\pi a}{2h_d}\right)}{\sinh^2\left(\frac{\pi c}{2h_d}\right) - \sinh^2\left(\frac{\pi a}{2h_d}\right)}}, \tag{5}$$

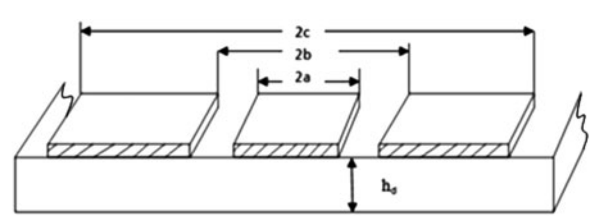

Fig. 3. The CPW with finite dielectric height (h_d) and finite ground planes.

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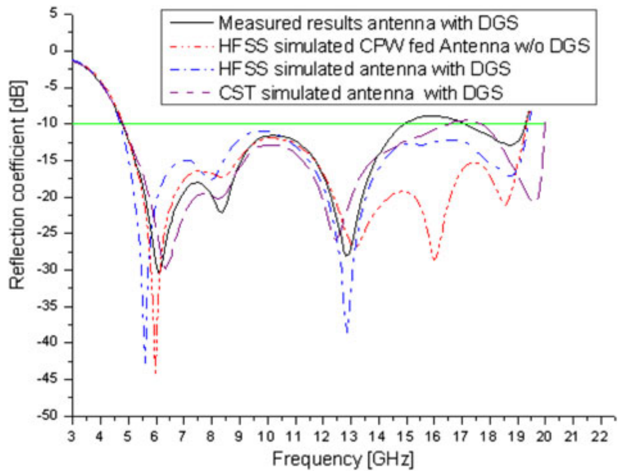

Fig. 4. Simulated and measured reflection coefficients of proposed antennas.

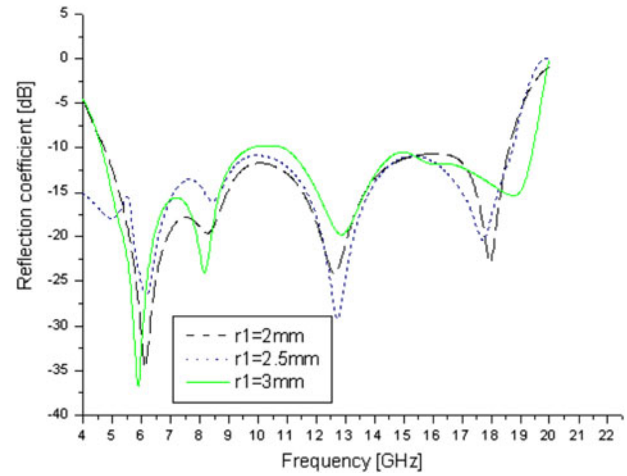

Fig. 6. Effect of the variation of radius of the circular slot "r_1" on ground plane (radius of DGS).

$$k'_1 = \sqrt{1 - k'_1} = \frac{\sinh\left(\frac{\pi a}{2h_d}\right)}{\sinh\left(\frac{\pi b}{2h_d}\right)} \sqrt{\frac{\sinh^2\left(\frac{\pi c}{2h_d}\right) - \sinh^2\left(\frac{\pi b}{2h_d}\right)}{\sinh^2\left(\frac{\pi c}{2h_d}\right) - \sinh^2\left(\frac{\pi a}{2h_d}\right)}}. \quad (6)$$

These equations are used to ascertain the physical parameters of the proposed CPW designs and designed antennas are simulated using HFSS EM simulation software and results were verified in CST MWS. The CPW central metal strip width, length, and the gap (g) of the distance between the strip and the coplanar ground plane are fixed at 3, 7.23, and 0.5 mm, respectively, in order to achieve 50-Ω CPW feed line. The designed antenna with DGS has the circular patch of radius $r_c = 5$ mm, which has a circular slot of radius 2 mm in the lower side of circular patch to enhance impedance bandwidth.

IV. RESULTS AND DISCUSSIONS

The broadband CPW-fed antennas with and without DGS are designed and simulated on HFSS and CST MWS. The fabricated antennas are characterized with Rohde and Schwarz vector network analyzer ZVA40 for reflection coefficient versus frequency, which has been compared with the simulated results in Fig. 4.

The simulated results of reflection coefficient versus frequency are in good agreement. The conventional CPW-fed antenna has huge impedance bandwidth but the gain is not significant for higher frequencies above 13 GHz. In the proposed antenna, we have introduced DGS in symmetrical ground planes. This proposed antenna as compared to conventional antenna achieves a significant impedance bandwidth of 100% ranging from 5 to 15 GHz with respect to the central frequency at 10 GHz. In literatures, we do not find improvement in radiation pattern characteristics in 12–15 GHz band for a compact design, as reported in this paper, as most of the works are limited to Ultra Wide Band (UWB) regions. The compact size and achieved broadband from 5 to 15 GHz make these antennas a good candidate for upper UWB applications and futuristic UWB as well.

We find a slight variation between the simulated and experimentally measured results at higher frequencies. This can be due to the dielectric losses introduced at high

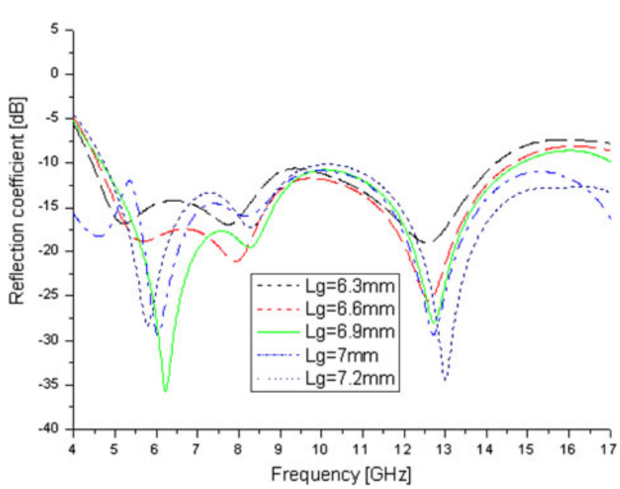

Fig. 5. Effect of variation of length of ground plane.

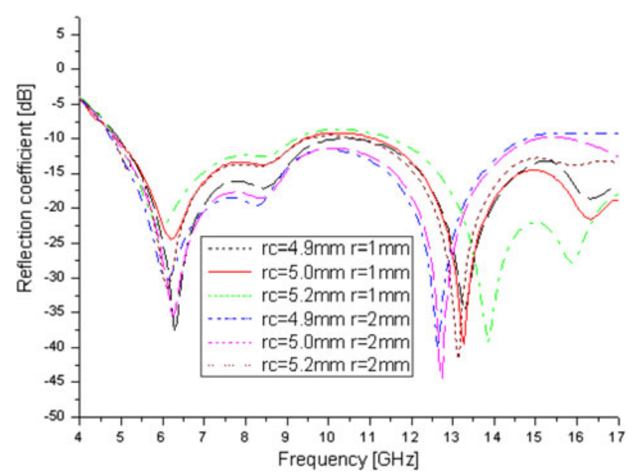

Fig. 7. Simulated result of the proposed antenna with various radii of main circular patch "r_c" and "r".

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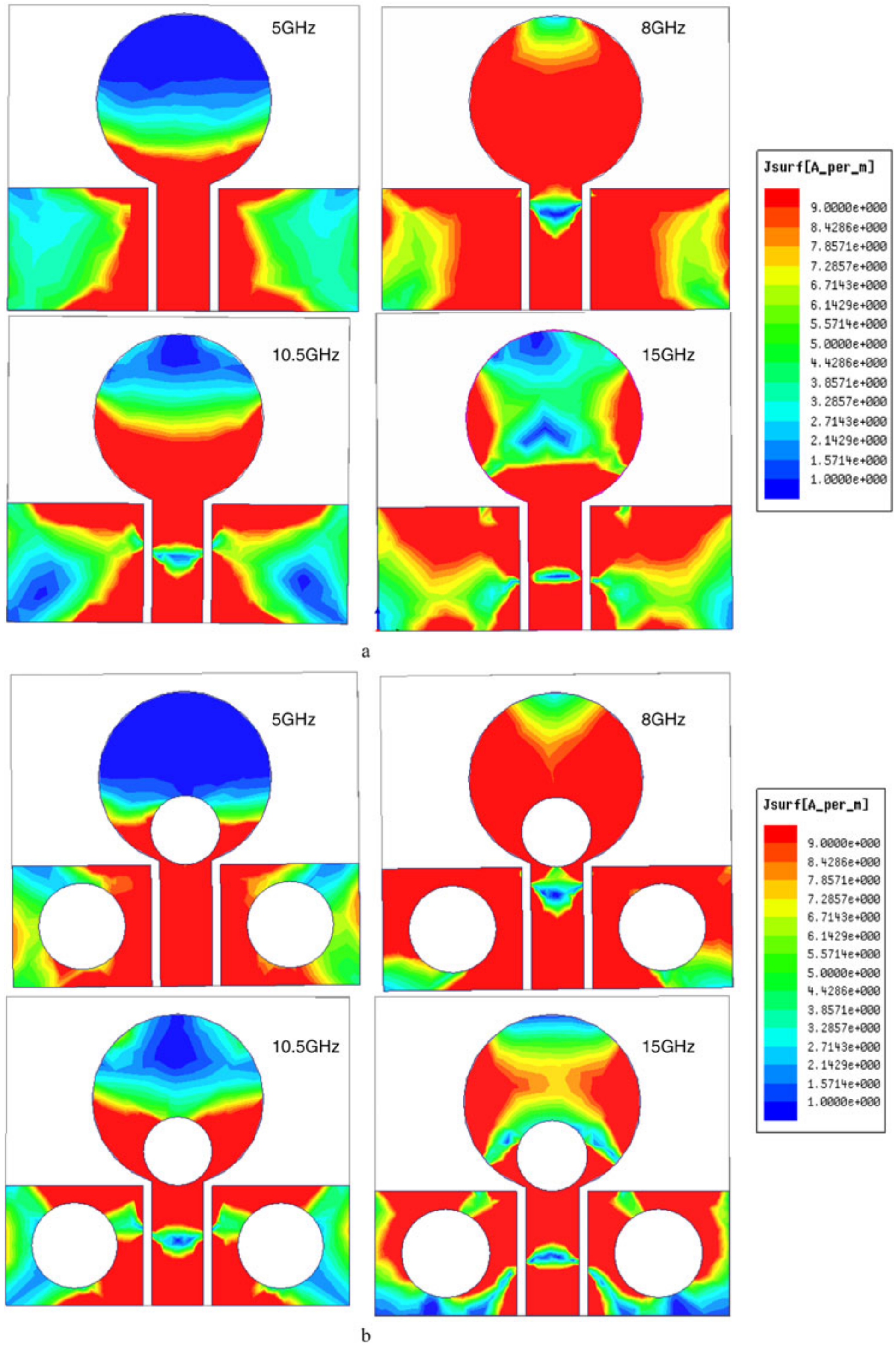

Fig. 8. Simulated current distributions of the proposed antennas at various frequencies: (a) antenna without DGS, (b) antenna with DGS.

frequencies or uncertainty of the purchased dielectric constant of the substrate. In order to achieve a good impedance matching we need to optimize the gap between the radiating circular patch and ground plane [16]. Hence, we start analysis with varying length of the ground planes "L_g" keeping all the parameters same. Figure 5 shows the effect of ground plane length on the proposed antenna with DGS. As per the simulated results most desired wideband is obtained at $L_g = 7$ mm. For lower values lesser than 7 mm the antenna is not able to radiate properly for frequencies below 5 GHz and gives poor impedance matching. For value of $L_g > 7$ mm, i.e. 7.2 mm as shown in Figure 5, the antenna has no significant value of S_{11}. The parametric analysis is performed on the radii of the circular slots r_1 (see Fig. 6), which acts as DGS and change the current distribution in the ground plane of the patch antenna. This change in surface current distribution increases the gain of antenna at higher frequencies. From Fig. 7, it is found that optimum radius of the circular DGS

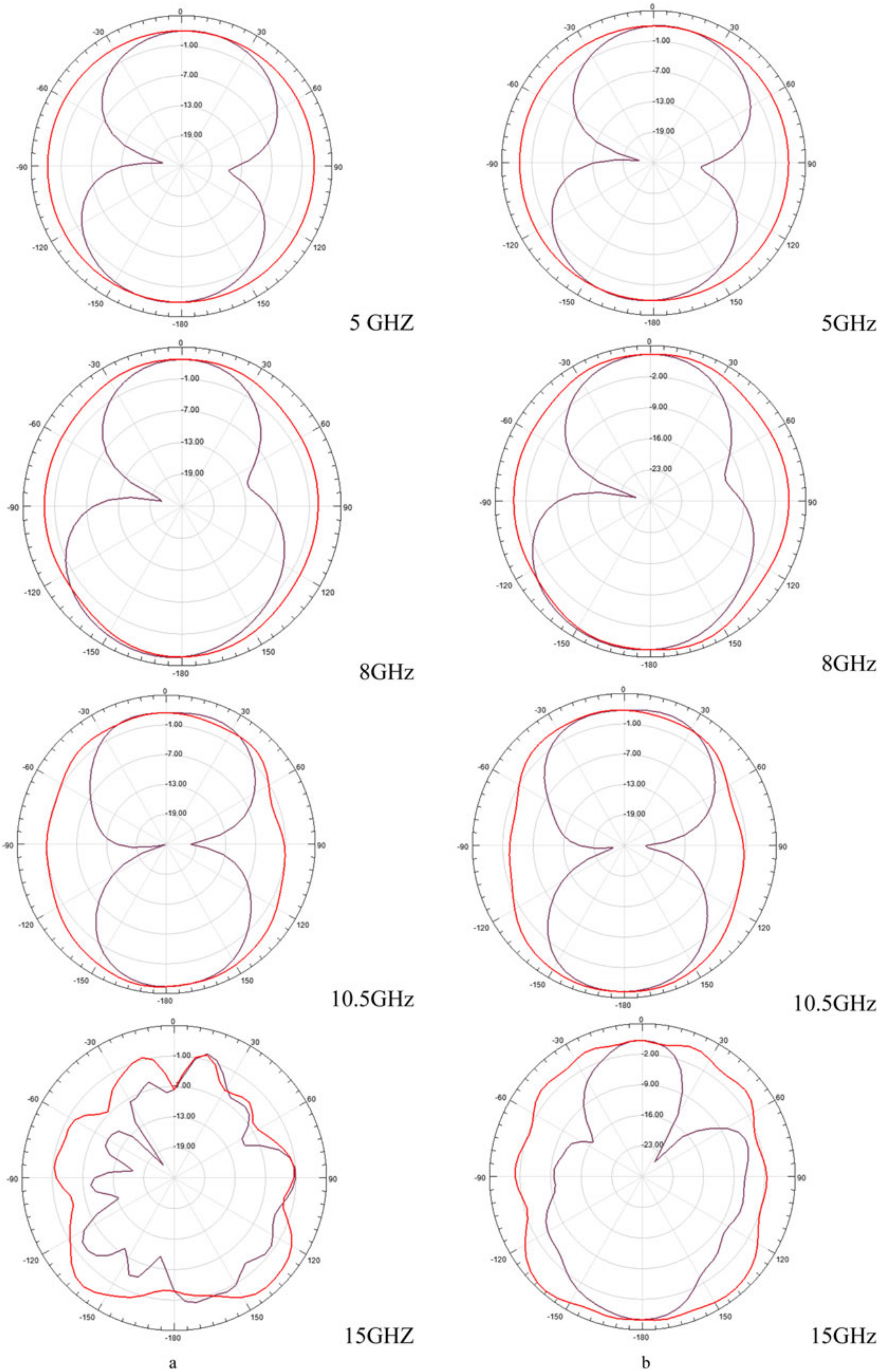

Fig. 9. Stimulated radiation patterns of the proposed antennas (*x–z* plane, omnidirectional-*H* plane, and bidirectional-*E* plane) (a) without DGS (b) with DGS at four different frequencies.

is 2.5 mm, which gives broad impedance bandwidth as compared to 2 mm, whereas on increasing the value by 0.5 mm makes antenna non-resonating for 9.8–10.2 GHz band.

Figure 7 shows the results of parametric analysis performance on the radii "r" and "r_c" to improve reflection coefficient versus frequency characteristics around 10 GHz. It is observed that when the radius of the circular slot "r" is 1 mm the impedance matching is poor and improves when it is increased to 2 mm. We have also found that the value of "r_c" below 5 mm results in decrease in impedance bandwidth, while increasing its value for "r_c" to 5.2 mm, results in poor impedance matching. Hence, we have opted the values of "r_c" = 5 mm and "r" = 2 mm.

We have also analyzed the current distribution in the antenna at various frequencies, as shown in Fig. 8. The current value is high along central metallic strip of the CPW feed and lower edge of the main circular patch "r_c" of the proposed antennas. In the ground planes, the current value is more on the upper edge near the circular patch "r_c" (along the x-direction). This explains that the impedance matching of the antenna is also dependent on gap between CPW central feed strip and ground plane as well as gap between the upper edge of ground plane and patch. These gaps are very important parameter for proper signal coupling from feed line to patch. This explains the importance of optimized dimensions of the ground plane [16].

Figure 9 shows the radiation patterns of the proposed antennas (CPW-fed antenna with and without DGS) at selective frequencies of 5, 8, 10.5, and 15 GHz, respectively.

From the radiation patterns shown in Figure 9, we see that gain and radiation characteristics of the proposed antenna with DGS have improved considerably as compared to conventional antenna (without DGS) at 15 GHz. The gain has increased to 7 dB and the H-plane radiation pattern has become nearly omnidirectional. At higher frequency, the ripple occurs in radiation pattern due to edge reflections.

It is noted that the radiation patterns of the antenna with DGS in the H-plane (x–z plane) are nearly omnidirectional in entire band of 5–15 GHz and radiation patterns in the E-plane (y–z plane) resembles figure of eight and are bidirectional. Table 1 shows the comparison between peak gains of the conventional CPW-fed patch antenna and antenna with DGS at higher frequencies from 12 to 15 GHz. A significant improvement in gain is noticed with antenna having DGS. This is due to reduction of surface waves at these higher frequencies. Figure 10 shows the peak gain of the proposed antennas for the frequency band 5–15 GHz. Maximum gain of the antenna with DGS is 3.88 dB at 7 GHz. It can be seen that antenna with DGS has stable radiation patterns (see Figure 9) and achieves improved gain at higher frequencies (see Figure 10). The gain of the antenna is significantly high for practical applications.

Table 1. The peak gains of the proposed antennas at higher frequencies.

Frequency (GHz)	Gain of antenna (without DGS) (in dB)	Gain of antenna with DGS (in dB)
12	2.210	2.28
13	0.998	3.739
15	−4.432	3.111

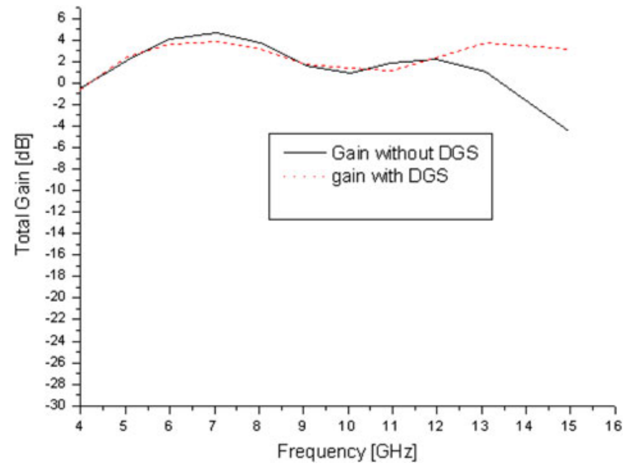

Fig. 10. Peak gain of the proposed antennas.

V. CONCLUSION

CPW-fed circular patch antenna has been designed, fabricated, parametrically analyzed, and characterized to obtain high gain with the defected ground structure. The antenna offers impedance bandwidth of 100% and gain enhancement in higher frequency ranges as compared to the conventional circular patch antenna. The wideband has been achieved by optimizing the dimensions of the ground planes and the radius of the slot "r" in circular patch. Inserting circular DGS of optimized radius in ground plane of conventional CPW-fed antenna has resulted in gain enhancement. The measured impedance bandwidth (VSWR $<$ 2) of proposed antenna is 10 GHz. It covers the C, X, and upper UWB. The antenna offers gain improvement of 2.74 dB at 13 GHz and 7 dB at 15 GHz. The antenna design is simple and can be easily mounted and packaged with other microwave devices and circuits. The antenna has stable radiation pattern and high gain in entire band. The proposed antenna structure can be used for futuristic wireless systems.

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