A Compact CPW-Fed Planar Stacked Circle Patch Antenna for Wideband Applications

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Abstract

The article investigates the performance of planar and compact CPW-fed microstrip patch antenna that offers 10 dB impedance bandwidth over the wide frequency range between 2.59 and 7.61 GHz. The parametric analysis of various design variables is included to acquire the final design of proposed antenna. The prototype exemplary of designed antenna is experimentally tested to obtain the return loss, VSWR, radiation response and gain characteristics. The close agreement is acquired between simulated and experimental results. The projected antenna has compact size of $0.61\lambda_0 \times 0.44\lambda_0 \times 0.027\lambda_0$ mm^3 and offers a 10 dB wide impedance bandwidth of 5.02 GHz. Thus, it may be considered suitable for variety of wireless applications including WLAN, Wi-MAX, fixed satellite services, wireless point-to-point applications etc.

Keywords Microstrip patch antenna · CPW-feed · Wideband antenna · Stacked circle patch

1 Introduction

The wireless communication systems & devices are hugely trending in this modern era. Specifically, those devices which are compact in size and offer exclusive quality voice & data communications, are in massive demand. These modern systems require efficient antennas that possess features such as light weight and wide impedance bandwidth.

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Microstrip patch antennas are one among the promising candidates that assure inherent advantages such as small dimensions, light weight, less fabrication expenditure, planar structure etc.[1, 2]. However, their major drawback of narrow impedance bandwidth deteriorates their widespread use in variety of wireless applications [3, 4]. Additionally, the conventional patch antennas are composed of metallic ground planes on reverse side of dielectric substrate that adds to the manufacturing cost. Also the coaxial probe feeding technique, a widely prevalent feeding method, enhances the complexity with hampering of conformability in structures. The coplanar waveguide (CPW) fed ground planes in patch antennas have emerged as an effective solution to above mentioned restrictions [4–8].

Several researches have been reported for compact size CPW-fed microstrip patch antennas that exhibit the wide impedance bandwidth. Sharma et al. proposed an ultra-wideband CPW-fed patch antenna that has acquired the compact dimensions by using defected crown shaped substrate [5]. R.B. Hwang introduced a novel CPW-fed T-shaped microstrip radiator to result in the broad impedance bandwidth between 2.205 and 3.68 GHz (65% relative bandwidth w.r.t. centre frequency) [9]. Liu and Yeh designed a CPW- fed rectangular antenna with slots embedded in it, which resonates in dual frequency bands (2.21 GHz & 6.25 GHz). The upper resonant region exhibited a wide impedance bandwidth between 3.73 and 7.86 GHz [10]. Jui-Han Lu inserted a U-shaped coupling slot in the CPW-feed line for reducing the resonant frequency, thus achieving size miniaturization for proposed antenna design. Further observation was made that the shift in resonant frequency is function of the vertical arm length of U-shaped slot [11]. Singh & Singh introduced a CPW-fed hexagonal shaped printed monopole antenna with '+' shaped defected ground structure to reflect the wide bandwidth characteristics between 3.5 and 9.0 GHz [12]. Das et al. designed a low profile CPW-fed microstrip antenna that exhibit circular polarization and 10 dB wide impedance between 1.28 and 4.5 GHz, specifically for wearable wireless devices [13].

The present research introduces a design of coplanar ground fed planar stacked circle patch antenna with the minuscule dimensions of $36 \times 26 \times 1.6 \ mm^3$. A rectangular slot is embedded in the microstrip feed line to enhance the bandwidth of proposed design. Additionally, parametric variation is attempted for coplanar ground length, embedded rectangular slot length and its position in feed line for the performance optimization. The optimized proposed design offers a wide impedance bandwidth of 5.02 GHz between the frequencies 2.59 and 7.61 GHz. The rest of article is framed as below: the proposed design and its specifications are included in Sect. 2. The discussion on parametric variation of different design variables is provided in Sect. 3. The results & its discussions constitutes the Sect. 4 with brief summarizing conclusion presented as Sect. 5.

2 Intended Antenna Layout and Design

The proposed antenna, as shown in Fig. 1, is composed of four circular patches that are connected on same plane to realize the overall design. All four circular patch elements have same diameter as L_{P2}. These circular elements are attached to each other via rectangular strips ($L_{P1} \times W_{P1}$) to create a novel shape. The patch radiator is fed by the rectangular microstrip feed line of size ($L_F \times W_F$). A rectangular slot ($L_S \times W_S$) is etched in the feed line at specific position L_{S1}, to increase the impedance matching over wide frequency band. Parametric analysis is performed for the selection of appropriate slot length and slot position. A 50 Ω SMA (Subminiature version-A) connector is affixed at feed line edge for

Fig. 1 Proposed planar stacked circle antenna design
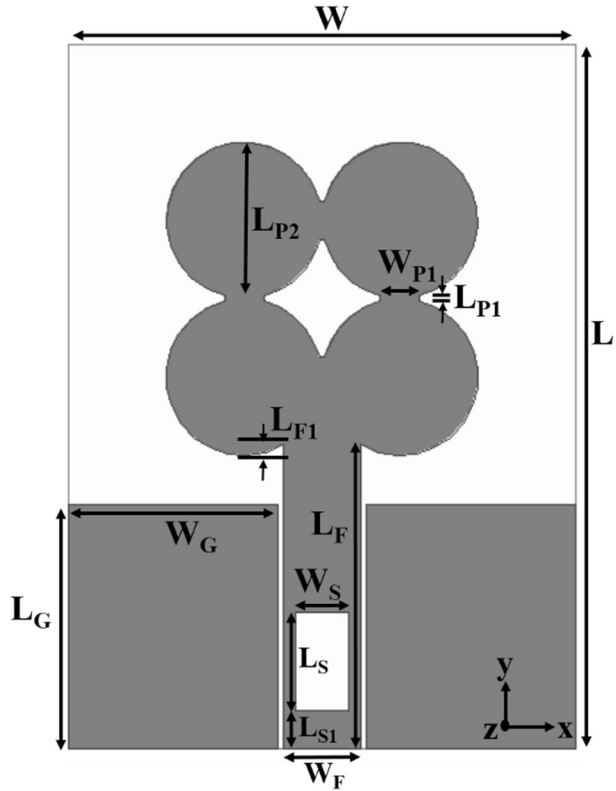
providing the excitation signal. The coplanar rectangular ground plane ($L_G \times W_G$) is provided on the both sides of microstrip feed line at the uniform gap of 0.3 mm. The anticipated antenna design is constructed on single-sided copper clad FR4-Epoxy substrate with dielectric constant of 4.4 and height as 1.6 mm. The substrate chosen is robust, cost effective & readily available in market. As printed monopole structure is selected for the proposed antenna design, following Eq. (1) can be used to predict its lower resonant frequency [14, 15]:

$$f_r = \frac{14.4}{l_1 + l_2 + g_1 + \frac{A_1}{2\pi l_1 \sqrt{\frac{\varepsilon_r + 1}{2}}} + \frac{A_2}{2\pi l_2 \sqrt{\frac{\varepsilon_r + 1}{2}}}} GHZ \tag{1}$$

where l_1 and l_2 represents the length of ground plane and radiating patch, respectively. g_1 indicates the gap between patch radiator and ground plane. A_1 and A_2 denotes the area of ground plane and radiating patch, respectively. All l_1, l_2, g_1, A_1 and A_2 are in centimeters. ε_r is dielectric constant of the substrate.

As per Eq. (1), for estimation of lower resonant frequency for the proposed antenna, the required parameters are calculated as given below:

Length of ground plane $l_1 = L_G$,
Length of radiating patch $l_2 = 2L_{P2} + L_F - L_{F1}$.
Gap between patch and coplanar ground plane $g_1 = L_F - L_{F1} - L_G$.
Area of ground plane $A_1 = 2[L_G W_G]$.

Table 1 Dimensions of proposed planar stacked circle antenna design

Parameters	L	W	L_G	W_G	L_{P1}	W_{P1}	L_{P2}
Units (mm)	36	26	12.5	10.7	0.25	5	8
Parameters	L_F	W_F	L_{F1}	L_S	W_S	L_{S1}	–
Units (mm)	15.5	4	0.5	5	2.75	2	–

Fig. 2 Input impedance characteristics for the proposed antenna design
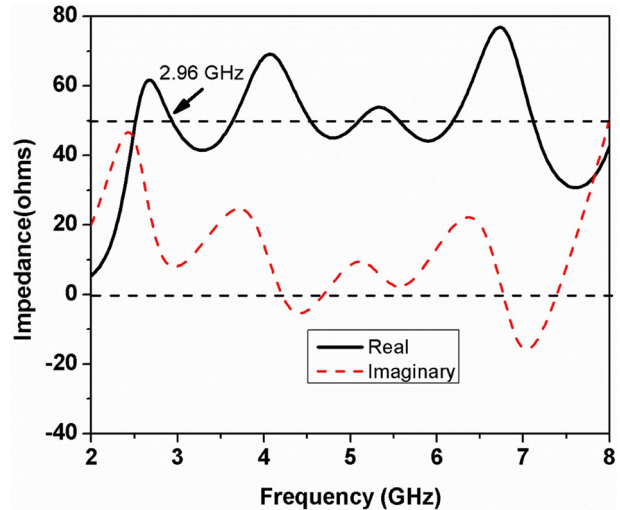
Area of radiating patch $A_2 = 4\left[\pi\left(\frac{L_{P2}}{2}\right)^2\right] + 4[L_{P1}W_{P1}] + L_F W_F - L_S W_S$.

From the data given in Table 1, the lower resonant frequency is calculated to be 2.95 GHz using Eq. (1). When the proposed antenna is designed using 3-D electromagnetic simulator named as HFSS (high frequency structure simulator), the first resonance is observed at 2.96 GHz (as shown in Fig. 2) that accurately matches with calculated resonant frequency as per Eq. (1).

3 Parametric Analysis of Design Variables

Certain design variables in the proposed antenna design must have optimum values to result in the wide impedance bandwidth. The parametric analysis is performed for these design variables to get their optimum value. The first significant design parameter is length of coplanar ground plane i.e. L_G. Figure 3 indicates the simulated return loss versus frequency graph against various values of the ground plane length, L_G. The length of ground plane is varied between 12.0 and 14.5 mm at the uniform intervals of 0.5 mm. It is inferred from the graph that the minimum return loss with widest 10 dB impedance bandwidth is retrieved when length of coplanar ground plane is selected as 12.5 mm. With the further increase in ground plane length, the return loss increases and there is decline in achieved impedance bandwidth. With ground plane length to highest value of 14.5 mm,

Fig. 3 Simulated return loss versus frequency for various ground plane lengths, L_G
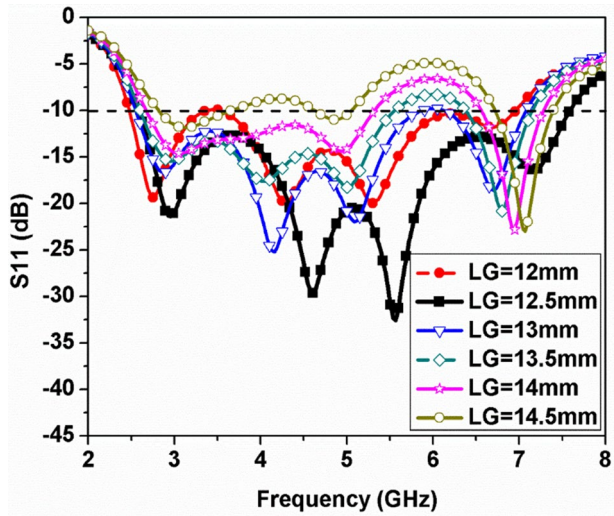
approximately entire operating region is shifted above 10 dB range, which is absolutely unacceptable. Thus, the final selected value of ground plane length is 12.5 mm.

Another design variable that is parametrically varied and analysed is rectangular slot length, L_S. The slot length is altered from 1 to 9 mm at the uniform intervals of 2 mm each (shown in the Fig. 4). The return loss is also analysed without rectangular slot in the feed line. It is observed in Fig. 4 that without any rectangular slot, the return loss at 3.6 GHz and 6.7 GHz is approximately close to 10 dB which has to be reduced. Thus, a rectangular slot is inserted in microstrip feed line to decrease the return loss at these frequencies for attaining wide impedance bandwidth. It is perceived from the graph analysis that when slot length (L_S) is kept at 5 mm, the return loss at 3.6 GHz and 6.7 GHz is reduced to its minimum. However, when L_S is increased beyond 5 mm, the return loss value at 6.7 GHz frequency is deteriorated again. Thus, the optimum value of rectangular slot length is selected

Fig. 4 Simulated return loss versus frequency against different values of slot length, L_S
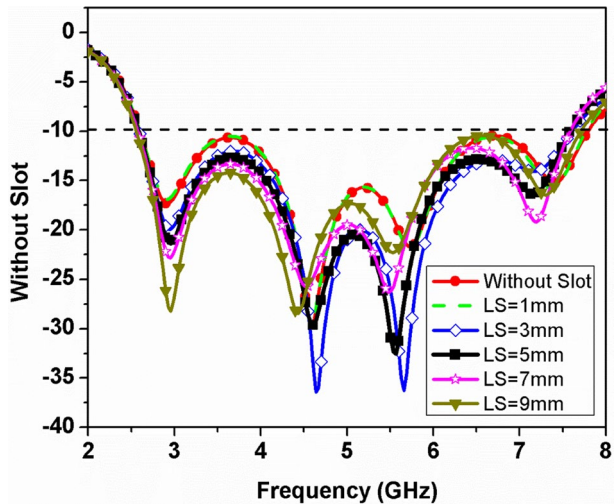
as 5 mm. As width of feed line is 4 mm only, there is not much variation possible in the alteration of rectangular slot width, W_S. Thus, the optimum slot width W_S is chosen as 2.75 mm after few trials in simulation.

For the proposed design, the rectangular slot ($L_S \times W_S$) acts a half-wavelength line resonator, whose length can be estimated as below:

$$L_N = 2(L_s + W_S) \tag{2}$$

The resonant frequency for this resonator can be empirically approximated as [15]:

$$f_r = \frac{v}{2XL_N X \sqrt{\varepsilon_{reff}}} \tag{3}$$

where v is speed of light, ε_{reff} is effective dielectric constant of substrate. Due to lack of ground plane below the substrate in proposed CPW-fed antenna design, its effective dielectric constant can be taken as half of actual dielectric constant (4.4 for FR4-Epoxy substrate) i.e. 2.2. From the data available in Table 1, L_N is calculated to be 15.5 mm. When substituted in Eq. (3), resonant frequency obtained is 6.5 GHz. This calculated frequency is quite close to the simulated frequency (6.7 GHz) in Fig. 4 at which return loss is close to 10 dB value. Thus, introducing rectangular slot with dimensions '$L_S X W_S$' in microstrip feed line has improved return loss near 6.7 GHz (resonance) and 3.7 GHz (half of resonance) region, thus contributing to the wide impedance bandwidth.

Apart from dimensions of the inserted rectangular slot, its location in feed line is of equal significance. As per the available length of feed line, the position of rectangular slot (L_{S1}) is varied between 2 and 12 mm at intermediate intervals of 2 mm each. The return loss performance against different values of L_{S1} is presented in Fig. 5. As inferred from the graph, when slot position is kept at 2 mm, the minimum return loss is acquired with widest 10 dB impedance bandwidth of 5.02 GHz. However, if the position of slot is shifted towards patch area, the performance is depreciated due to increase in the return loss. Also, the achieved 10 dB impedance bandwidth is decreased. Thus, the optimum location of inserted rectangular slot is chosen as 2 mm.

Fig. 5 Simulated return loss vs. frequency against different values of slot position, L_{S1}
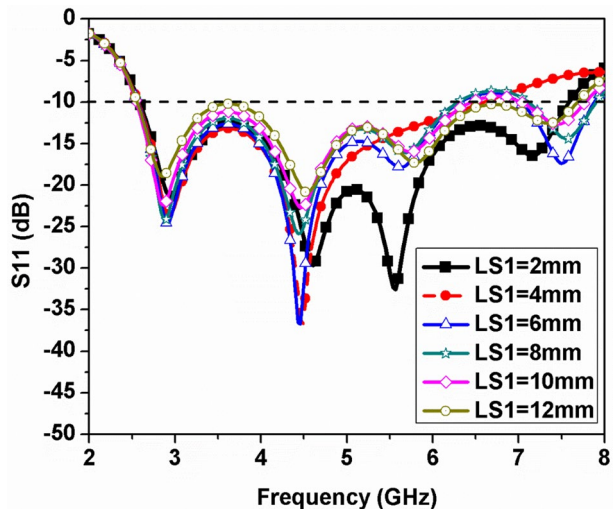
Figure 6 represents the simulated surface current distributions for proposed antenna at the four resonant frequencies viz. 2.96 GHz, 4.61 GHz, 5.57 GHz and 7.19 GHz, respectively.

There is current disturbance observed around the rectangular slot in feed line at 2.96 GHz and 7.19 GHz respectively. At these frequencies, the surface current in feed line is shifted in the opposite direction due to presence of the rectangular slot. Due to this current disturbance, the return loss is reduced around these frequency regions for anticipated antenna (also shown as parametric analysis against 'L_S' in Fig. 4), thus attributing towards the 10 dB impedance bandwidth between 2.59 and 7.61 GHz.
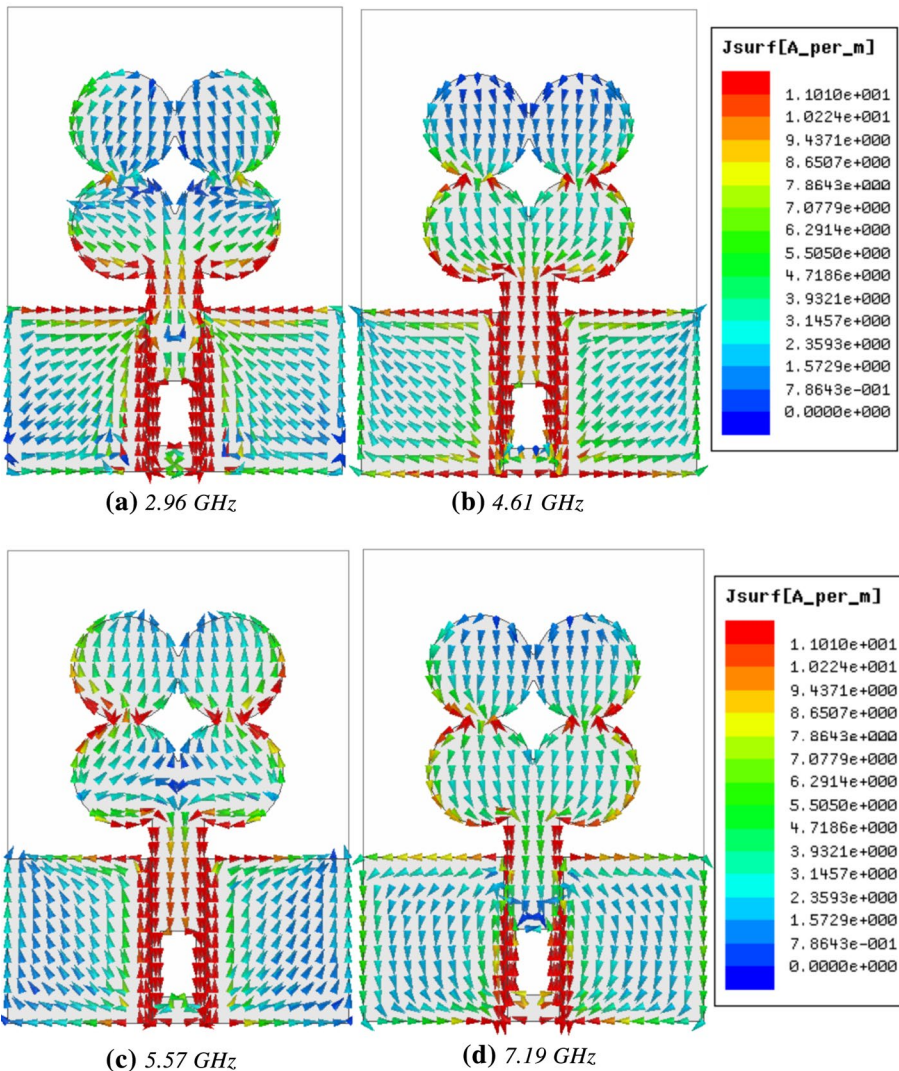

Fig. 6 Surface current distributions for proposed antenna at **a** 2.96 GHz **b** 4.61 GHz, **c** 5.57 GHz **d** 7.19 GHz

4 Results and Discussions

The exemplary prototype of the proposed antenna is fabricated and experimentally tested
to verify the simulated results. Figure 7a demonstrates front view of fabricated prototype
antenna design with FR4-epoxy as its substrate whereas Fig. 7b indicates the experimental setup of anticipated antenna design in anechoic chamber for measurement of radiation
pattern.

The fabricated antenna structure is tested using vector network analyser (Rohde &
Schwarz, 10 MHz–20 GHz) for the measurement of return loss & VSWR. Figure 8 compares the simulated and experimentally measured return loss for proposed antenna structure. The simulated 10 dB bandwidth of 5.02 GHz is acquired between 2.59 and 7.61 GHz

Fig. 7 a Prototype of fabricated
planar stacked circle patch
antenna **b** experimental setup for
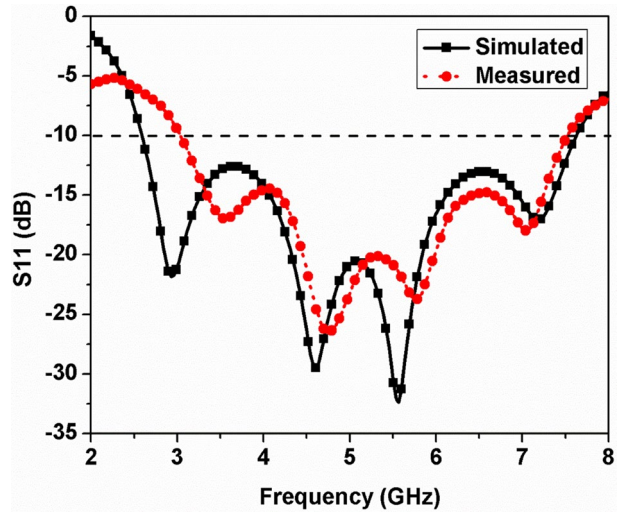radiation pattern measurement in
anechoic chamber
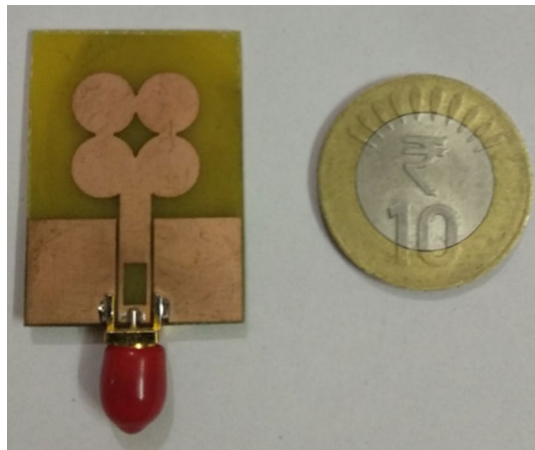
(a)
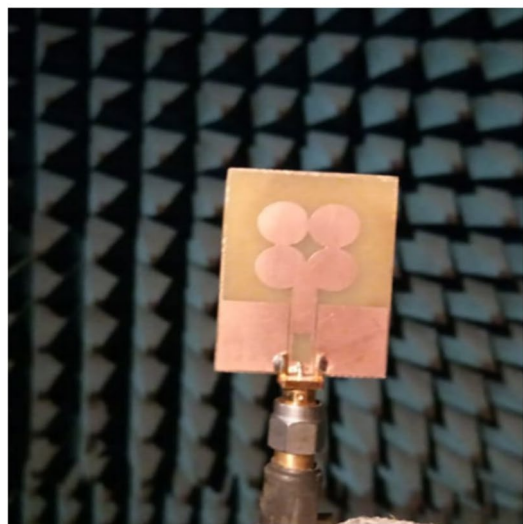
(b)

Fig. 8 Simulated & measured return loss versus frequency for planar stacked circle patch antenna

frequency range. The four resonances are obtained at 2.96, 4.61, 5.57 and 7.19 GHz with corresponding return loss observed as -21.8, -29.4, -32.3 and -17.1 dB, respectively. On the other hand, measured 10 dB return loss lies between 3.02 and 7.52 GHz. Resonances are observed at frequencies 3.56, 4.73, 5.75 and 7.10 GHz with their respective return loss as -17.1 dB, -26.7 dB, -23.9 dB & -17.9 dB. It is clearly observed that there is close agreement achieved between the simulated & measured return loss.

Figure 9 exhibits comparison between simulated and measured VSWR against frequency. VSWR has ideal value as 1 in case of perfect impedance matching between transmission line and antenna feeding location. However, VSWR value below 2 at any particular resonant frequency is an industry acceptable standard. It is exhibited from Fig. 9 that simulated VSWR lies below 2 for continuous frequency range between 2.59 and 7.61 GHz and experimentally measured VSWR results closely match with the simulated results. The

Fig. 9 Simulated & measured VSWR versus frequency for planar stacked circle patch antenna
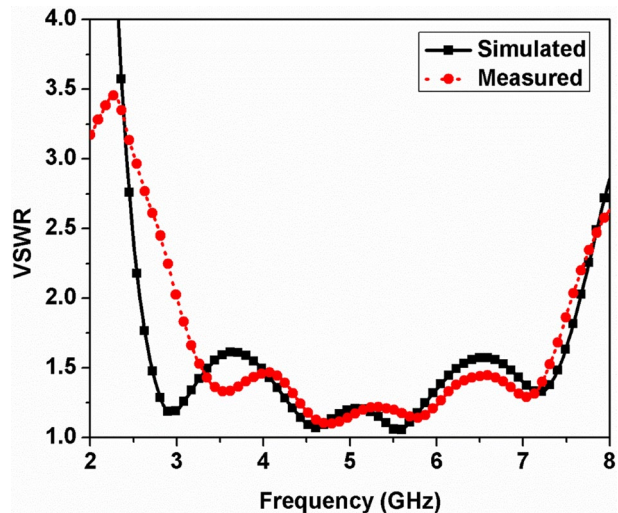
minor disparity between simulated and measured results exists due to the possible fabrication inaccuracies for proposed antenna design. Additionally, soldering procedure and its high temperature may slightly hamper the measured results but still acceptable agreement is acquired with the simulated results.

Radiation pattern is a graphical parameter to represent the directional variation of radiation intensity from any antenna. Figure 10 plots the comparison between simulated and measured radiation patterns for two principal planes termed as E-plane and H-plane. Four frequencies among the achieved wide impedance bandwidth are selected for observing the E-plane and H-plane radiation patterns. The considered frequencies are 3.23 GHz, 4.73 GHz, 5.75 GHz and 7.23 GHz. It is observed from plotted graphs in Fig. 10 that E-plane radiation is nearly omnidirectional at almost all measuring frequencies. On the contrary, radiation of H-plane is approximately bidirectional with maximum intensity concentration towards elevation angle (θ) of 0° and 180°. It is inferred from these patterns that anticipated antenna virtually radiates maximum in broadside direction. Also, radiation symmetry is realized among the measured radiation patterns at different frequencies.

Figure 11 presents comparison between simulated & measured gain for the considered CPW-fed patch antenna. As the figure clearly reveals that close agreement is attained between both the simulated and measured results. The simulated realized gain for operating band ranges between 2.5 and 8.9 dB while measured gain varies between 1.6 and 9.3 dB for the tested prototype antenna. Table 2 presents comparison between the proposed antenna and some relevant literature works which provided the wide impedance bandwidths using
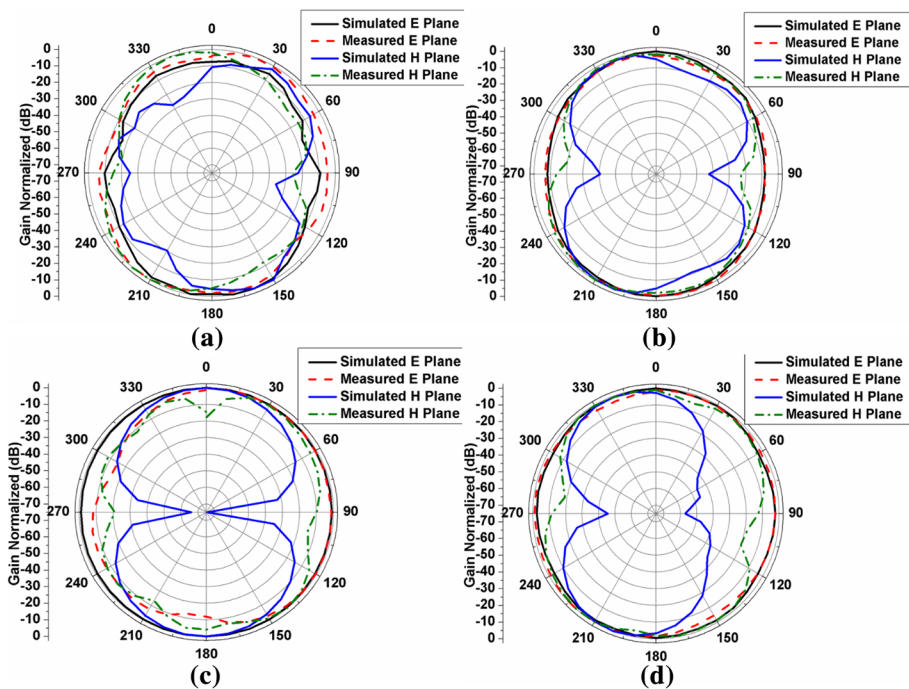

Fig. 10 **a** Simulated & measured radiation pattern (E-Plane & H-Plane) at 3.23 GHz **b** Simulated & measured (E-Plane & H-Plane) at 4.73 GHz **c** Simulated & measured (E-Plane & H-Plane) at 5.75 GHz **d** Simulated & measured (E-Plane & H-Plane) at 7.34 GHz

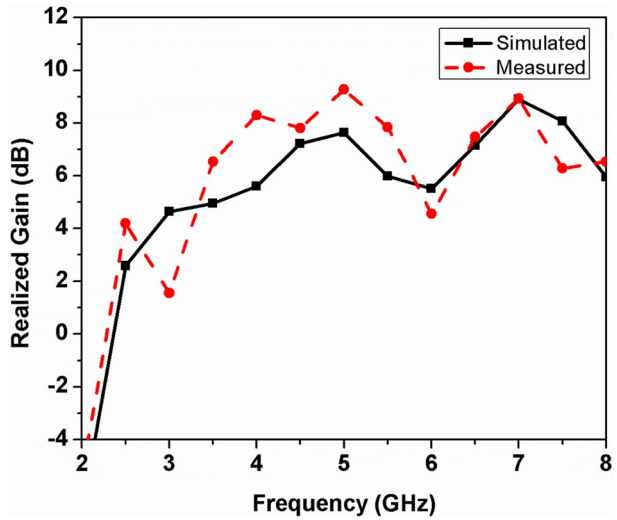**Fig. 11** Simulated & measured gain versus frequency for planar stacked circle patch antenna

Table 2 Comparison of the proposed antenna design with relevant literature works

Reference	Size, mm^2	Operating frequency range, GHz	Percentage bandwidth, %	Maximum gain, dBi
[13]	$75 \times 63 = 4725$	1.28–4.5	111.4	3.5
[16]	$35.05 \times 29 = 1016.5$	4.25–6.31	39.7	–
[17]	$56.9 \times 56.9 = 3237.6$	1.8–2.0	10	8.9
[18]	$50 \times 30 = 1500$	3.07–4.11	28.9	–
[19]	$35.24 \times 26.4 = 930.3$	3.424–6.274	58.8	5.51
[20]	$25 \times 20.5 = 512.5$	4.27–7.58	55.9	4.39
[21]	$54 \times 54 = 2916$	1.78–5.64	104	Above 2.9 dB for operating range
[22]	$38 \times 38 = 1444$	3.62–7.32	67.6	5.6
[23]	$36 \times 36 = 1296$	3.57–4.63	26.7	5.6
Present work	$36 \times 26 = 936$	2.59–7.61	98.3	9.3

variety of techniques. This comparison illustrates that the proposed antenna has compact dimensions and has achieved the wider impedance bandwidth of 5.02 GHz. Thus, the proposed wideband stacked circle antenna can be suitable for various wireless applications such as Wi-MAX standards (3.3 GHz, 3.5 GHz, 5.8 GHz), WLAN standards of 802.11 a/h/j/n/ac/ax (5 GHz ISM band), dedicated short range communications (5.8/5.9 GHz), fixed satellite services (3.4–3.7 GHz, 4.5–4.8 GHz and 6.725–7.025 GHz), fixed point-to-point applications (6.425–7.125 GHz) etc.

5 Conclusion

A planar and compact microstrip patch antenna design is introduced which connects the four circular patches of equal diameter. A rectangular slot is loaded in the microstrip feed line along with CPW ground plane to result in the wide impedance bandwidth. The parametric analysis is conducted against coplanar ground length, embedded rectangular slot length & its position to get the optimized design. The optimized design exhibited the simulated wide impedance bandwidth between 2.59 and 7.61 GHz that agreed well with the measured impedance bandwidth of 3.03 and 7.52 GHz. Nearly broadside radiation is observed for measured radiation patterns at the different frequencies. Thus, the proposed design is suitable for multiple wireless applications owing to its compact dimensions along with nearly symmetrical radiation behaviour attained over the wide frequency range.

Compliance with Ethical Standards

Conflict of interest The authors declare that they have no conflict of interest.

Ethical Approval This article does not contain any studies with human participants or animals performed by any of the authors.

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