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Compact dual-band millimeter-wave antenna for 5G WLAN

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Abstract

This paper presents a novel compact dual-band printed antenna with an omnidirectional radiation pattern for 5G WLAN. The antenna element comprises a star-shaped patch with six disc-shaped elements at the top and a defected ground structure at the bottom, having a radius of 3.77 mm for both. The proper feeding point and alignment with its element parameters help to achieve good impedance matching. The proposed antenna has a single center feed, a low profile, and a straightforward compact structure without any feeding complexity. A high reception fidelity antenna with comparable bandwidth and moderate gain is presented. The prototype radiator was printed on a 4 mm radius and a 1.6 mm thick dielectric substrate (Rogers RT/Duroid 5880), with a dielectric constant of 2.2. The designed antenna is fabricated and measured to validate the simulation result. The measured impedance bandwidth of 1.3 GHz (27.5–28.8 GHz) and 2.2 GHz (32.45–34.65 GHz) with a respective measured gain of 1.1 and 3.2 dBi are achieved at 28 and 34 GHz. The simulated radiation efficiency of above 95% is achieved for both bands. A good agreement between simulated and measured results of the proposed work shows that the proposed antenna is suitable for 5G short-range WLAN communications.

Introduction

The rapid development in wireless communication that occurs in the last few decades causes a huge increase in data usage. Considerably more substantial bandwidth is exploited to increase the capacity and enable users to experience several gigabit-per-second data rates [1]. The lack of bandwidth in the present technology can be overcome by the millimeter-wave (mm-wave) frequency spectrum regulated by FCC for 5G technology. According to FCC's document, the local multipoint distribution system band is 27.5–28.35 GHz, 29.1–29.25 GHz, and 31–31.3 GHz. Also, the 32 GHz band (31.8–33.4 GHz) is under consideration [2]. A high-performance mm-wave antenna with wide bandwidth is required to support extensive high-speed high-data-rate wireless connectivity since the antenna elements are in close proximity [3]. One of the crucial problems of mm-wave due to its small wavelength is the increased link loss and path loss under different atmospheric conditions [1, 3]. So, a high gain antenna at the line of sight is preferred for broadcast applications.

Omnidirectional antennas with high efficiency are highly preferred antennas over the directional antennas for short-range [3] wireless communication due to their better signal reception [4]. An antenna with an omnidirectional radiation pattern offers a high degree of reliable connectivity in all directions, limited in directional antennas [5]. The required gain for an omnidirectional antenna is comparatively less than the directional antenna in 5G WLAN communication. To enhance the omnidirectional antenna's radiation gain, it has to be loaded with electromagnetic-band gap (EBG) as a superstrate in patch and ground, and use it as a superstrate. Metamaterial and metasurface [6], negative permeability metamaterial [7], and dielectric resonator [8] are also some of the few methods to improve the radiation gain. Today, there is an integration of different wireless applications in a single device. So, a compact microstrip patch antenna with dual or multi-band is the best solution for this [5, 9–16]. Over the past decades, numerous dual-band antennas with good omnidirectional radiation patterns have been reported for Wireless Local Area Networks (WLANs), particularly in 2.4/5 GHz [5, 9–12, 17]. One of the commonly used techniques is defected ground structures (DGS) to introduce multiple bands in a single antenna, which excite additional resonances in a patch radiator [5]. DGS are usually slots cut inside the ground plane. It will change the surface current distribution by creating resonant gaps [18]. In this work, the antenna geometry is developed based on DGS by introducing slots [11] in the ground plane. The proper design of DGS gives two different frequency bands in the 5G spectrum.

Very few mm-wave antennas with the omnidirectional radiation pattern have been reported to the best of the author's knowledge. A single-band antenna with an omnidirectional

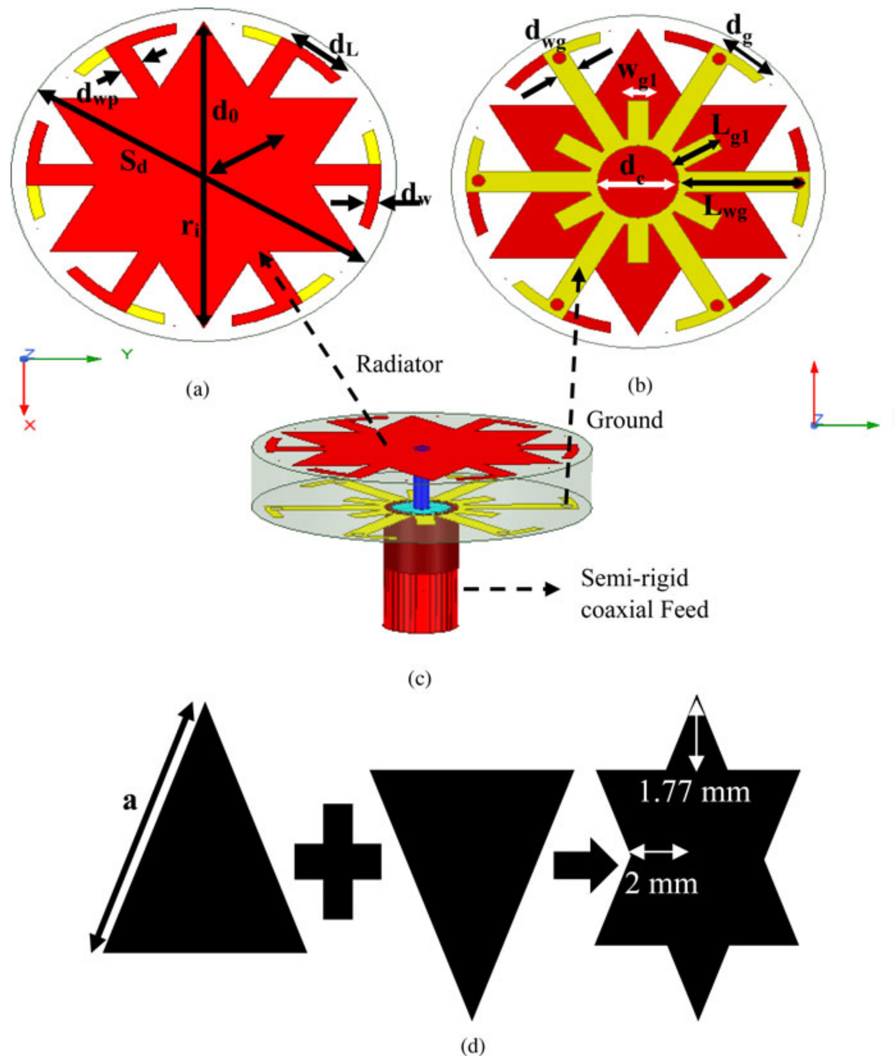

Fig. 1. Structure of the proposed antenna. (a) Top view. (b) Rear view. (c) Pin-type view. (d) Graphical demonstration of formation of the proposed star-shaped patch antenna.

radiation pattern [19] and a dual-band antenna with an omnidirectional radiation pattern [15, 16] are proposed for 5 G applications. These antennas have good bandwidth and moderate gain, but the design is complex and has a larger size. The works in [20, 21] report omnidirectional circular polarized radiation characteristics in the mm-wave band at 38 and 37 GHz, respectively, but both the works report problems such as bulky structure, installation difficulty, and high cost. The designs given in [4, 13, 22] are circular polarization omnidirectional antennas that are proposed for 5G applications. It suffers from minimal bandwidth and complex geometry. In [23], two monopole omnidirectional MIMO antenna designs of size $26 \times 9 \times 11\ mm^2$, having 5 and 5.7 dBi gain at the frequencies 27 and 39 GHz, are proposed, respectively. In [24], modeling of a dual-band monopole omnidirectional antenna design using H-slotted DGS assisted by ANN for 5G sub-6 GHz applications is presented. A multi-band rectangular dielectric resonator omnidirectional antenna, having a stacked radiator with semi-circular slots etched on the left and right sides of an upper radiator, is proposed for a future 5G wireless communication system [8]. Some works have been recently released [25, 26] by different authors on designing 5G antennas/arrays. A millimeter-wave low-profile wideband magnetoelectric monopole antenna with the vertically polarized end-fire radiation is presented. It is the combination of a pair of the top-loaded electric monopoles with a thin open-ended substrate integrated waveguide with the extended lower broad wall. It is a high gain directional array antenna with 60% of impedance bandwidth [27].

A compact novel dual-band omnidirectional printed antenna for 5G wireless communication systems is reported in the present research work. The proposed antenna geometry is designed with a star-shaped patch [28] attached with six disc-shaped elements [17] at the top. The star patch decides the frequency band at 34 GHz, and the six-disc shape elements at the top and bottom with respect to parameter values give the frequency band at 28 GHz with good impedance matching. The feeding point and the DGS in the ground provide an omnidirectional radiation pattern at 28 and 34 GHz bands. The respective realized gain of 28 and 34 GHz frequencies is 1.1 and 3.2 dBi.

Design of antenna geometry

The proposed compact dual-band patch antenna structure for 5G WLAN communication is shown in Figs 1(a–c). The detailed dimensions of the prototype antenna are given in Table 1. A star-shaped radiator is placed at the top of the round-shaped substrate with six disc-shaped elements attached. The substrate used here for the design is Rogers RT/Duroid 5880, having a dielectric constant of 2.2 with a thickness of 1.6 mm and $\delta = 0.001$. The star-

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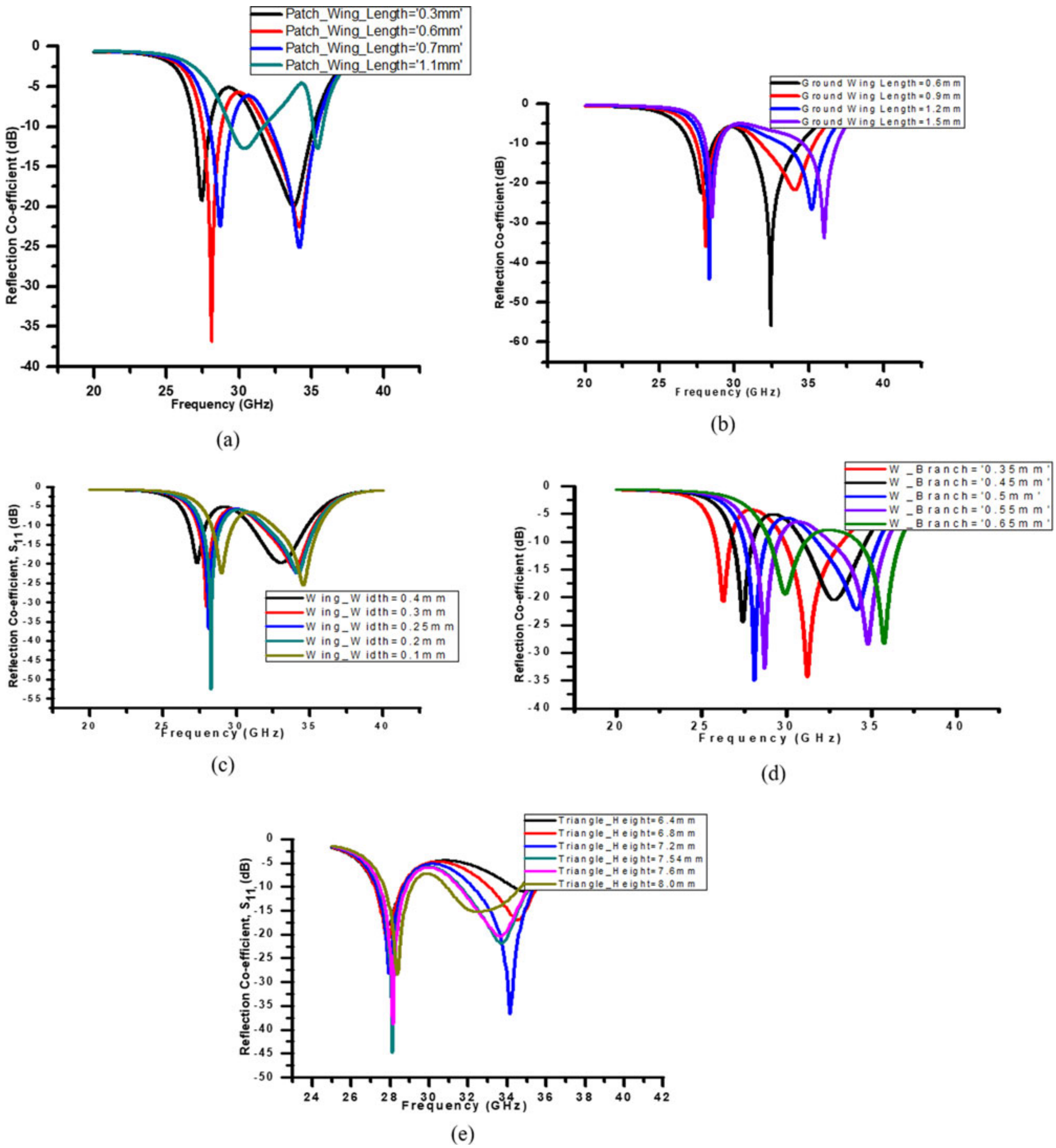

Fig. 2. Parametric study on (a) wings length at patch (d_L), (b) wings length at ground (d_g), (c) wings width both in patch and ground (d_w), (d) branch width (d_{wp}, d_{wg}). Parametric study on (e) triangular patch radius (height).

Table 1. Antenna design parameters [unit: millimeters]

Parameter	r_i	r_0=d_0/2	sd	d_L	d_{wp}	L_{g1}
Dimension	2	3.77	8	0.99	0.5	1.1
Parameter	d_c	d_w	w_{g1}	d_g	d_{wg}	L_{wg}
Dimension	1.8	0.25	0.45	0.75	0.5	2.87

shaped radiator is formed by combining two equilateral triangles with side length, "a = 6.53 mm", where both of its center lie at the same point. Its details are shown in Fig. 1(d).

The star-shaped patch's radius "r" (3.77 mm) will decide the resonance frequency at 34 GHz. The six $\lambda/4$ elements determine the second resonant frequency of 28 GHz. The combination of these two elements produces a dual band in the proposed antenna geometry. The resonance frequency of the star-shaped patch is

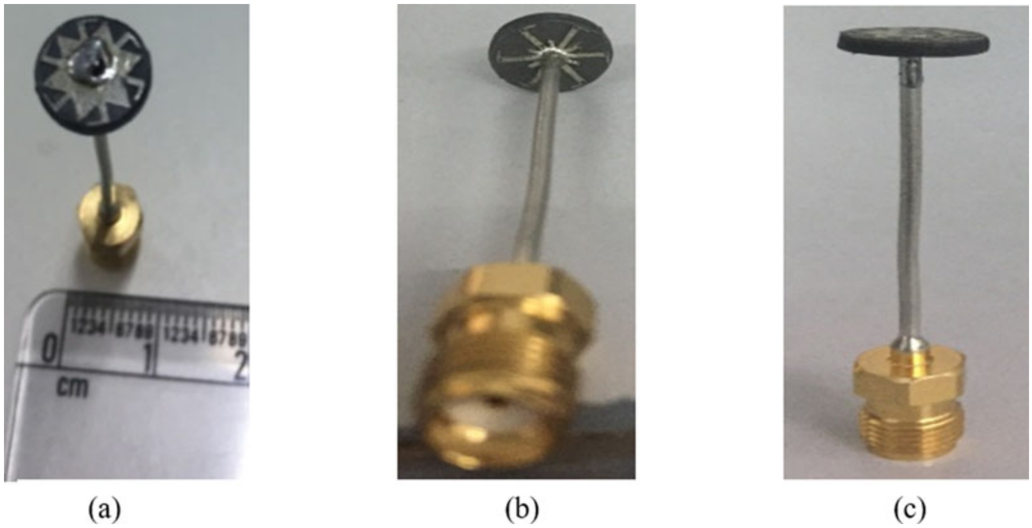

Fig. 3. Photos of prototype antenna. (a) Front view. (b) Rear view. (c) Side view.

calculated using the triangular patch antenna equation [29] as given in equation (1).

$$\frac{CK_{nm}}{3r\sqrt{\varepsilon_r}}. \tag{1}$$

Here C is the frequency of light. For T11 mode $K_{nm} = 1.84118$. The value of ε_r (dielectric constant) will decide the size of the radiator, and the star radius "r" determines the resonance.

The impedance matching of the antenna is achieved for 50 Ω by varying the dimensions of disc-shaped element parameters. Branch length of the element in both patch and ground is equivalent to the tip of the star, and it is fixed for 28 GHz. The dimensions of branch width (d_{wp}, d_{wg}), wings width (d_w), and wings length (d_g, d_L) will decide the impedance matching and fine-tuning of the frequency. Also, the wing length determines the surface current distribution between the patch and the ground, which causes an excellent omnidirectional radiation pattern. The arc shape on the wings of dipoles gives a uniform radial distribution of surface current that improves the radiation. Six small branches have a width of 0.45 mm placed at the inner side of the patch on the ground side. Suppose any extension of this branch toward the outer triangle does not give a 34 GHz frequency. So, proper ground geometry is necessary for dual resonant frequency. The 0.3 mm slot in the ground dipole is exploited to fine-tune the surface current in the clockwise direction. It gives a better omnidirectional pattern at 28 GHz with realized gain of 1.1 dBi. In 34 GHz, most of the current distribution is at the center of the star-shaped patch. It gives an omnidirectional pattern at 34 GHz with a realized gain of 3.2 dBi.

Moreover, the antenna structure is simple to fabricate and compact in size. The antenna is fed by a 50 Ω, 047 semi-rigid coaxial cable [9]. The maximum operating frequency of this cable is 40 GHz. The K-connector is soldered to the end of the cable; it also works up to 40 GHz. Both the cable and the connector are manufactured by Taoglas CAB.058 [30].

Parametric study

A detailed parametric study on triangular radius and different dipole parameters is done here, and its corresponding analyzing graphs are shown in Fig. 2. Figure 2(a) shows the variations of dipole parameters patch wing length (d_L) and how it affects the lower frequency at 28 GHz. From the figure, it is clear that the upper frequency remains the same with these variations. Figure 2(b) shows the variation of ground wings length (d_g) cause variation for the upper frequency at 34 GHz by keeping the frequency at 28 GHz. Upper frequency shifts right by the increase of ground wings length. Wings width (d_w) both in patch and ground will give proper impedance matching for the lower frequency at 28 GHz shown in Fig. 2(c). Branch width (d_{wp}, d_{wg}), both in patch and ground, is one of the main parameters that cause the shifting of both frequencies. It is well apparent in Fig. 2(d). If the branch width increases, frequency shifts to the right and *vice versa*. The fine-tuning on triangular height shown in Fig. 2(e) will cause the frequency variation in 5G bands at 34 GHz. It is not affecting much the lower frequency at 28 GHz. The proper impedance matching and resonance frequency matching are achieved by fine-tuning triangle height and dipole parameters, specifically wings width and wings length, on both the patch and ground sides. Branch width variation on both patch and ground sides provides a frequency with variation within a limited fixed frequency range. This design is a single-layer structure without much design parameters complexity. The antenna is designed and optimized using the 3D electromagnetic simulation tool.

Results and discussions

The prototype of the proposed compact dual-band antenna with an omnidirectional radiation pattern is fabricated and studied experimentally. The photos of the fabricated proposed dual-band antenna with an omnidirectional radiation pattern are given in Fig. 3. Figure 4 shows the comparisons between the simulated and the measured reflection coefficient ($S11$) characteristics. The measurement is carried out using an N9951A Microwave Analyzer. The measured bandwidth for the first resonance frequency at 28 GHz is 1.3 GHz (27.5–28.8 GHz) and for the second resonance frequency at 34 GHz is 2.2 GHz (32.45–34.65 GHz). The measured results show 4.64 and 6.55% of impedance bandwidth at 28 and 34 GHz, respectively. From Fig. 4, it is observed that both simulated and measured results have good agreement. The omnidirectional radiation pattern of the proposed antenna

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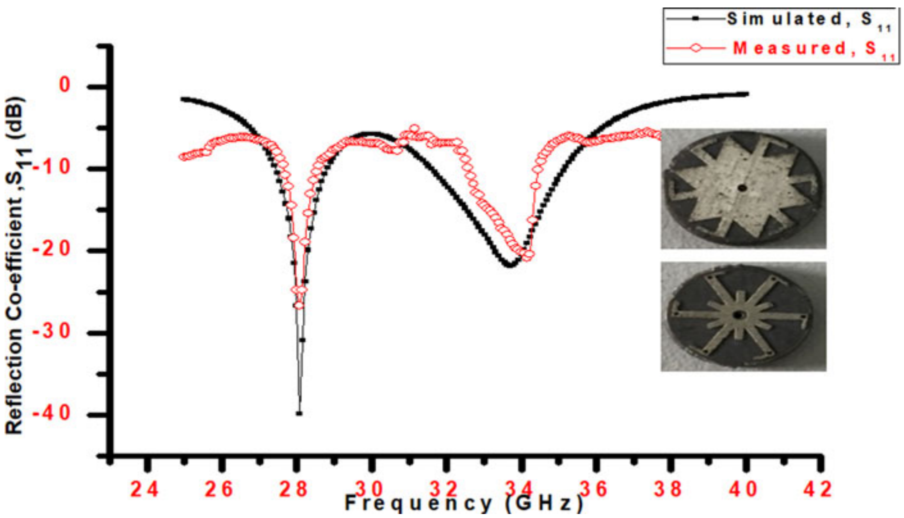

Fig. 4. Simulated and measured reflection coefficient for the proposed work.

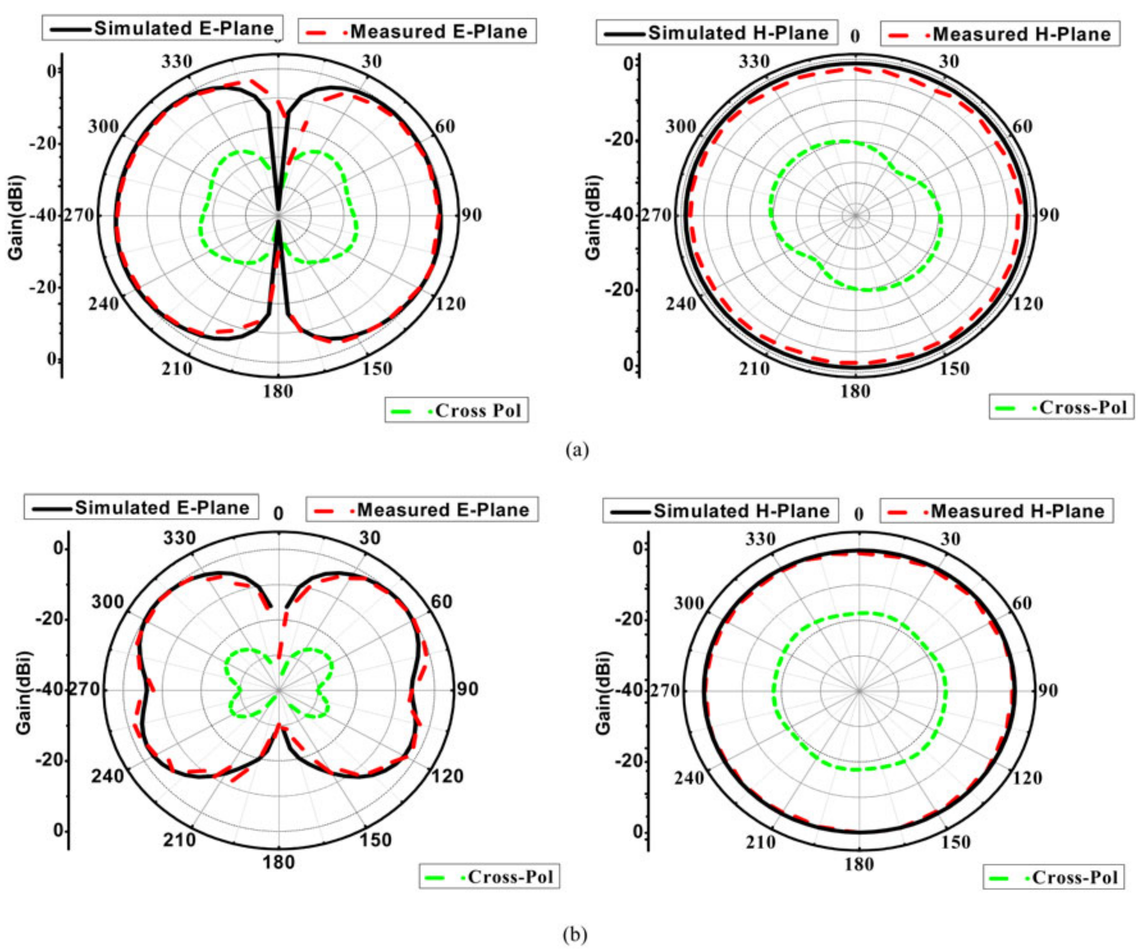

Fig. 5. Simulated and measured far-field radiation pattern at (a) 28 and (b) 34 GHz for both E and H-planes.

is validated with the simulated patterns given in Fig. 5, which shows the radiation patterns obtained at 28 and 34 GHz, respectively. The cross-polarization is <−20 dB in the two orthogonal planes (XOZ and YOZ planes) in both frequency bands, so the proposed antenna offers better performance. The radiation pattern for both E and H-planes for both observed resonance frequencies is measured inside the anechoic chamber at the center for the electromagnetic lab (CSIR-National Aerospace). The dipole-shaped radiation in the E-plane and omnidirectional radiation in the H-plane are observed at dual frequencies.

The radiation pattern for the azimuth plane for both the lower band (28 GHz) and upper band (34 GHz) is omnidirectional.

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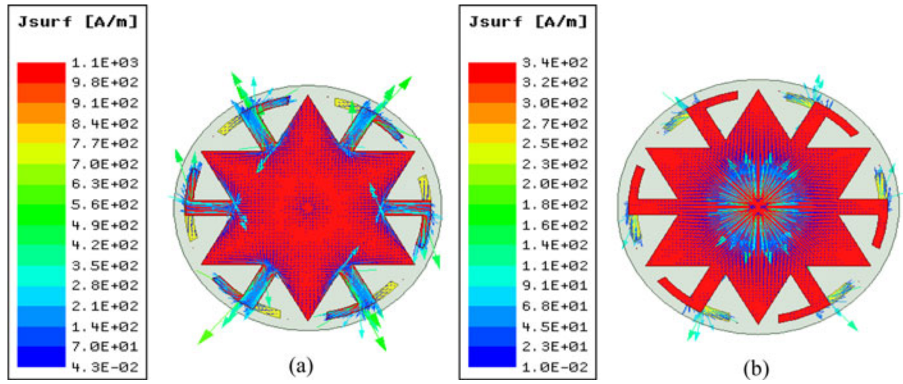

Fig. 6. Surface current distribution of proposed antenna at (a) 28 GHz and (b) 34 GHz.

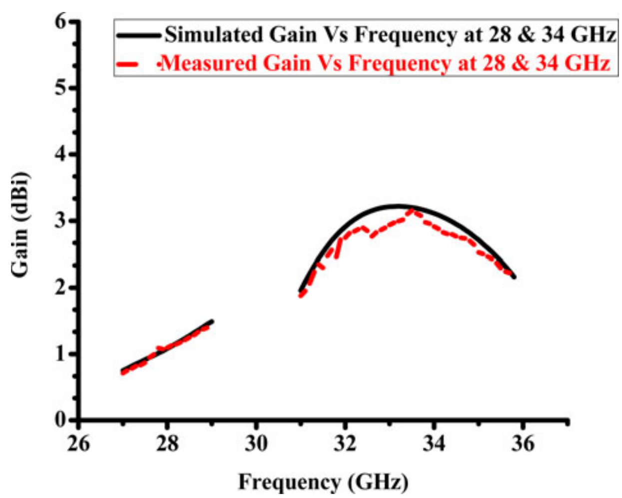

Fig. 7. Simulated and measured gain for both resonance bands.

Therefore, the signal reception fidelity for the presented antenna is relatively high and can detect the signal coming at any angle in the azimuth plane. The measured realized gains for 28 and 34 GHz are 1.1 and 3.2 dBi, respectively. The considerable gain variation is due to the insertion loss of the feed and soldering. Here a simulated radiation efficiency of above 95% is achieved for both bands due to the use of low loss substrate and by maintaining the compact size. The simulated directivity of the antenna is 1.146 and 3.33 dBi for resonance frequency 28 and 34 GHz, respectively. The simulated and measured reflection coefficient and antenna gain have a good agreement, which can be observed in Figs 4 and 5. These parameters indicate that the simulated radiation efficiency is almost near the original value.

Figure 6 shows the surface current distribution of the proposed antenna for both resonance frequencies. At 28 GHz, the maximum current distribution is observed at the inner circle of the star patch. But for 34 GHz, the maximum current distribution is achieved at the edges of star-shaped patch and disc-shaped elements. These two different current distributions are achieved with the help of proper placing of disc-shaped elements and the DGS method with its accurate parameter values, which is obtained through a parametric study. Figure 7 shows simulated gain at both resonance bands.

A comparison of configuration features and operating characteristics of the reported and proposed dual-band omnidirectional millimeter-wave antenna is summarized in Table 2. It is evident from the comparison that the proposed work offers miniaturized size, better efficiency, and comparable bandwidth with most of

Table 2. Comparison between the proposed antenna and previous works

Ref.	Operating. frequency (GHz)	Dielectric constant, ε_r	Dimensions.	10 dB BW (GHz)	Radiation pattern	Peak gain (dBi)	Efficiency (%)
[4]	26.5–28.7	2.2	Diameter 3.44 mm	2.2	OCP	2.2	95
[18]	26–40	3.4	16×16 mm^2	14	OMD	4	NA
[19]	24–29.5	2.2	8×8 mm^2	5.5	OMD	3.2	80
[20]	37.9–38.55	–	–	0.65	OCP	1.5	NA
[21]	36.7–37	2.2	Bulky	0.3	OCP	3.2	NA
[22]	27.5–28.35	6.1	5.6×5.6 mm^2	1.3	OCP	–	NA
[14]	37.5, 47.8	2.2	8×15 mm^2	0.4,0.7	OCP	5,5.7	88,93
[16]	26.6–29.2, 36.95–39.05	2.2	12×14 mm^2	2.55,2.1	OMD	1.27,1.83	78,76
[31]	21–31, 36–39	2.2	15×15 mm^2	10,4	OMD	5.3,5.4	93, 94
This work	27.5–28.8, 32.45–34.65	2.2	Diameter 8 mm	1.3,2.2	OMD	1.1, 3.2	95,96

OCP, omnidirectional circular polarized; OMD, omnidirectional radiation.

the works. Also, the proposed work has a dual-band with an omnidirectional pattern.

The salient features of the proposed antenna are,

i The proposed dual-band patch antenna achieves compactness with the minimum size of 8 mm diameter in contrast to [14, 16, 18–22, 31]. Despite compactness, it also covers the dual-band resonating frequencies such as 28 and 34 GHz used for 5G WLAN application, unlike in [4, 18–22].

ii The obtained bandwidth is 1.3 and 2.2 GHz, for 28 and 34 GHz, respectively, it is better than [14, 20–22].

iii The proposed antenna design with the defective ground structure and center feeding method is very simple with [4, 14, 19–22] less complexity of design and fewer design parameters.

iv The proposed design achieves overall simulated efficiency of 96% for resonant bands 1.3 and 3.4 GHz, respectively, which is better compared with all the existing literature along with moderate peak gain.

Conclusion

A star-shaped dual-band patch antenna attached with six disc-shaped elements and proper DGS has been proposed for 5 G WLAN communication. The proposed antenna has a single center feed, a low profile, and a straightforward compact structure without any feeding complexity. An antenna prototype has been fabricated and measured to validate the simulation and theory. The design procedures of the proposed antenna with the impact of design parameters are discussed. The designed antenna covers a 5G 28 GHz band from 27.5 to 28.8 GHz with a realized gain of 1.1 dBi. It also covers 5G 34 GHz band from 32.45 to 34.65 GHz with a realized gain of 3.2 dBi. So, due to omnidirectional radiation and reasonable gain performance at dual frequencies, the designed antenna can be used for future high data rate 5G short-distance wireless communication systems.

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