DESIGN AND ANALYSIS OF PEDESTAL FAN SHAPED MICROSTRIP PATCH ANTENNA FOR X/KU/K-BAND APPLICATIONS

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Abstract: For this communication, we designed a compact (20×20 mm2) pedestal fan shaped microstrip patch antenna with improved gain and bandwidth for X (8-12 GHz), Ku (12-18 GHz) and K (18-27 GHz) bands for radar and satellite applications. The entire antenna (designs 1 to 4) is designed and simulated on FR-4 epoxy substrate ($\varepsilon r = 4.4$, $\tan \delta = 0.02$ and $h = 1.6$ mm) and carried out by 3D electromagnetic (EM) simulation software. The proposed antenna (design-4) is performed with higher gain and bandwidth than the reported antennas, the two layered of stacking techniques being played a major role for improved performance. The proposed antenna covers (10.96–11.83) GHz for X-band, (12.26–14.00) GHz for Ku-band, and (15.30–23.53) GHz for Ku and K-band. The proposed antenna resonates at 11.40 GHz, 13.13 GHz, 16.16 GHz, 17.46 GHz and 20.06 GHz with peak gains of 9.17 dBi, 13.29 dBi, 10.07 dBi, 2.55 dBi and 11.83 dBi, respectively. The proposed antenna gain varies in the range of (2.55-13.29) dBi, VSWR varies in the range of (0-0.15), group delay varies between (-0.40 to 0.50) ns and radiation efficiency up to 85% is achieved during entire operating frequency band.

Index Terms- X/Ku/K-band, reflection coefficient, gain, VSWR, group delay, radiation efficiency

1. Introduction

Microstrip patch antennas have provided many advances in the advancement of wireless communication systems. Its salient features such as planar configuration, lightweight, low profile, low cost, and easy operation make it a suitable candidate for wireless communication systems [1-2]. Antennas with multiple operating bands are a new trend. Researchers are focusing on microstrip patch antennas with dual-band, triple-band, quad-band, pent-band [3-6], etc. A single antenna with multiple bands can be useful for many applications. Both the implementation cost and the area occupied by that antenna would be low. Currently, researchers are focusing on the smaller-sized antenna with multiple bands [7-8].

Researchers and scientists are always in favor of achieving higher gain and bandwidth. They use various methods for the improvement of these two important features like gap coupling, parasitic patch, defected ground, EBG (electromagnetic band gap structure), stacking, MIMO, meta-material, etc. [9-10]. In which slot utilization is the simplest and most confirmed method to improve bandwidth and gain. In this paper, slots are used to improve gain and bandwidth. Large-bandwidth microstrip patch antenna at high frequency such as X/Ku/K is in high demand. UWB (ultra-wideband) antennas are becoming popular in advanced communication

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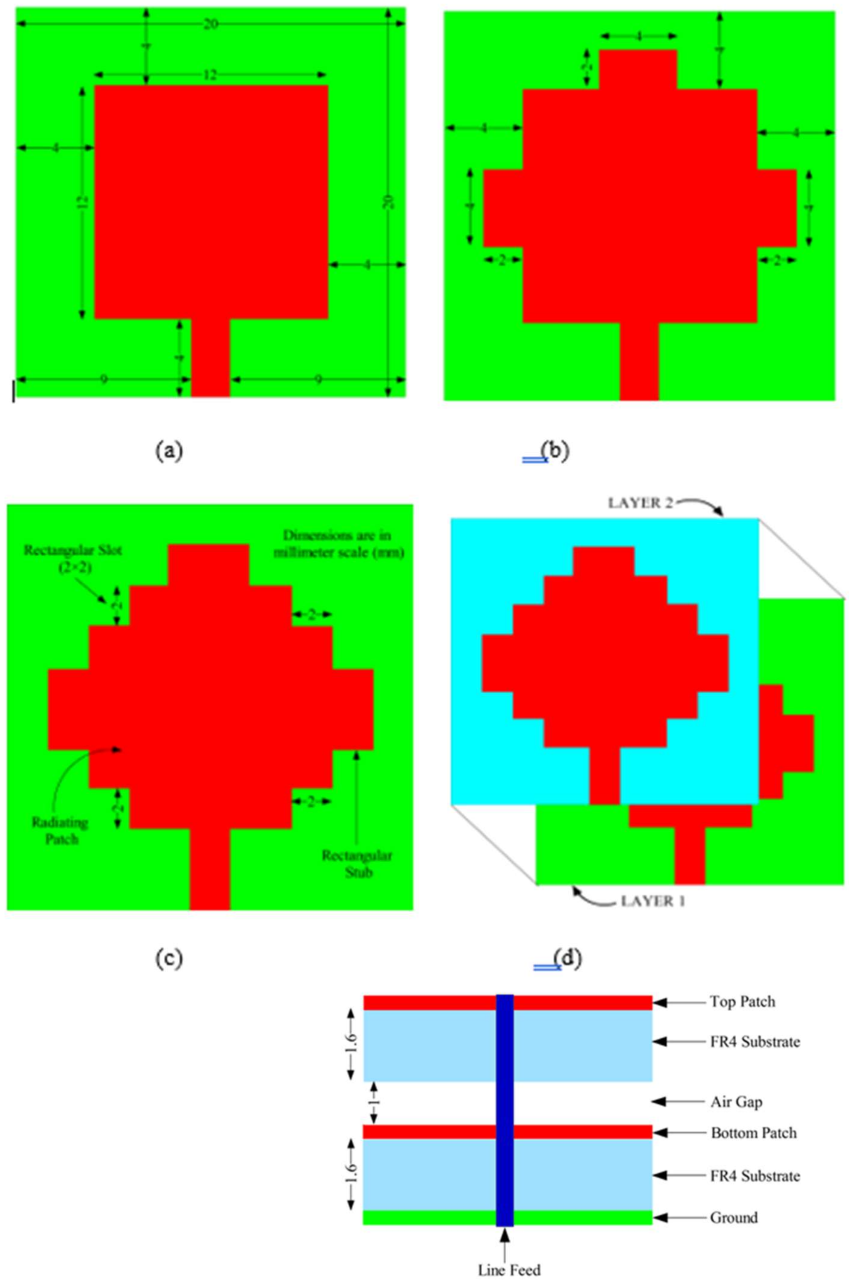
systems since their adaptation by Federal Communication Commission (FCC) in 2002 [11-12]. According to FCC, an intentional radiator (antenna), at any point in time,has a fractional bandwidth equal to or greater than 0.20 or has a UWB bandwidth equal to or greater than 500 MHz, regardless of the fractional bandwidth [13]. A compact UWB patch antenna with defected ground structure for Ku/K band applications is presented in ref [14]. A slotted circular ultra-wideband (UWB) microstrip patch antenna has been reported in ref [15]. It operates in the 4.0-40 GHz range. This antenna can be used in UWB communications with C-band, X-band, Ku-band, Ka-band, WLAN, and future wireless applications [16]. A compact ultra-wideband antenna structure with defected ground is presented in ref [17]. This design has the capability to operate between 1.5 GHz and 10.75 GHz with four notch frequencies [18]. This is why researchers have shifted their focus from the lower to the higher bands [19]. Microstrip patch antenna with optimal structure with high gain and bandwidth is still a struggle for researchers in each operating band [20-21]. An ultra-compact triple band antenna for X/Ku/K band applications is presented in ref [22].

In this paper, the goal of implementing and achieving a modest and innovative antenna, the novelty of the proposed antenna has a lesser size (20×20 mm2) with enhanced gain and bandwidth as compared to reference Antenna's (cited in table 2).

2. Evolution of Antenna Design

The dimensional structure (20×20 mm2) of the entire antenna (designs 1 to 4) has a red colour representing the top-view, green colour represents the bottom-view, and blue colour represents the substrate, the entire antenna is fed by a 50Ω microstrip feed line (cf. Figure 1). The entire antenna (designs 1 to 4) is designed and simulated on FR-4 epoxy substrate (εr = 4.4, tan δ = 0.02 and h = 1.6 mm) and carried out by 3D electromagnetic (EM) simulation software.



(e)

Fig.1: (a), (b), (c) and (d) represent the top (red colour), bottom (green colour) and FR4 substrate (blue colour) of Design-1, 2, 3 and 4 respectively, and (e) represent the side-view of the proposed antenna (Design-4)

The systematic growth of designs 1, 2, 3, & 4 is displayed in Figure 1.a, 1.b, 1.c, & 1.d respectively and the ground geometry of the entire designs 1 to 4 are the same, the figure 1.e represent the side-view geometry of proposed antenna (design 4). Design 1 was succeeded by deforming a simple rectangular shaped radiating element (12×12 mm2) (cf. Figure 1.a). Design 2 was succeeded with the help of design 1, in which we added three rectangular stubs (4×2 mm2) in radiating elements of top and side portions (cf. Figure 1.b). Design 3 is achieved by design 2, which has etched quad rectangular slots (2×2 mm2) at the adjacent corners of the radiating element (cf. Figure 1.c). The proposed antenna or pedestal fan shaped microstrip patch antenna (design 4) is obtained through design 3, which has attachment of the two layers of stacking with the same radiating elements of design 3 (cf. Figure 1.d), the reason behind stacking techniques for the enhancement of the gain, and the attachment of the rectangular stub and scratching the rectangular slot played the major role in enhancing the operating bandwidth.

3. Parametric Analysis of the Proposed Design

The pedestal fan shaped microstrip patch antenna is fed with a 50 Ω micro-strip feed line on the top of the bottom substrate. Feed length (L_f) and width (W) are improved to match the 50 Ω characteristics impedance with antenna impedance. The dimensions of the pedestal fan shaped radiating patch along with the ground geometry of the antenna (cf. Figure 1) is calculated with the given equations 1, 2, 3, 4, 5, 6, 7 and 8 respectively [9-18].
The patch-width (W) is calculated by the equation:

$$W = \frac{c}{2f}\sqrt{\frac{2}{\varepsilon_r+1}} \quad (1)$$

Where, ε_r is the dielectric constant of substrate and f is the center frequency, length of patch is calculated by the equation:

$$L = L_{ef} - 2\Delta l \quad (2)$$

Where, L_{ef} is the patch effective length and Δl is the normalized extension in length:

$$L_{ef} = \frac{c}{2f\sqrt{\varepsilon_{re}}} \quad (3)$$

Where, ε_{re} is the effective substrate dielectric constant is given by:

$$\varepsilon_{re} = \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{2}\left[1+\frac{12h}{W}\right]^{-1/2} \quad (4)$$

Where, h is the thickness of substrate and the normalized extension in length (Δl) is given by:

$$\Delta l = 0.412h\frac{(\varepsilon_{re}+0.3)\left(\frac{W}{h}+0.264\right)}{(\varepsilon_{re}-0.258)\left(\frac{W}{h}+0.8\right)} \quad (5)$$

Feed line length (L_f) is calculated by using below equation:

$$L_f = \frac{\lambda g}{4} \quad (6)$$

Where λg is guided wavelength and it is given by:

$$\lambda g = \frac{\lambda}{\sqrt{\varepsilon_{re}}} \quad (7)$$

Radiation efficiency (η) of the antenna is calculated by given equation:

$$\eta = \frac{\text{Gain}}{\text{Directivity}} \times 100\ \% \qquad (8)$$

4. Results and Discussion

The proposed antenna has been simulated in terms of reflection coefficient or return loss, gain, voltage standing wave ratio (VSWR), group delay, radiation efficiency, surface current distribution, radiation pattern etc. The entire antenna (designs 1 to 4) is designed and simulated on FR-4 epoxy substrate (εr = 4.4, tan δ = 0.02 and h = 1.6 mm) and carried out by 3D electromagnetic (EM) simulation software.

The design 1 has succeeded the triple operating bands are (10.53-11.10) GHz, (11.40-12.70) GHz, and (17.90-23.53) GHz with resonated at 10.96 GHz, 11.83 GHz, 19.63 GHz, and 21.80 GHz and peak gains are -10.30 dBi, -0.58 dBi, 1.97 dBi, and -3.82 dBi obtained respectively. Design 2 has obtained dual operating bands (11.83-12.70) GHz, and (18.33-20.50) GHz with resonated at 12.26 GHz, and 19.63 GHz and peak gains are 4.6 dBi, and -3.54 dBi respectively (cf. fig. 2 and table-1). Design 3 has obtained triple operating bands are (13.56-17.03) GHz, (17.90-19.63) GHz, and (20.50-21.36) GHz with resonated at 14.86 GHz, 16.60 GHz, 19.20 GHz, and 20.93 GHz and peak gains are -0.55 dBi, 2.64 dBi, 5.45 dBi, and 8.59 dBi respectively (cf. fig. 2 and table-1).

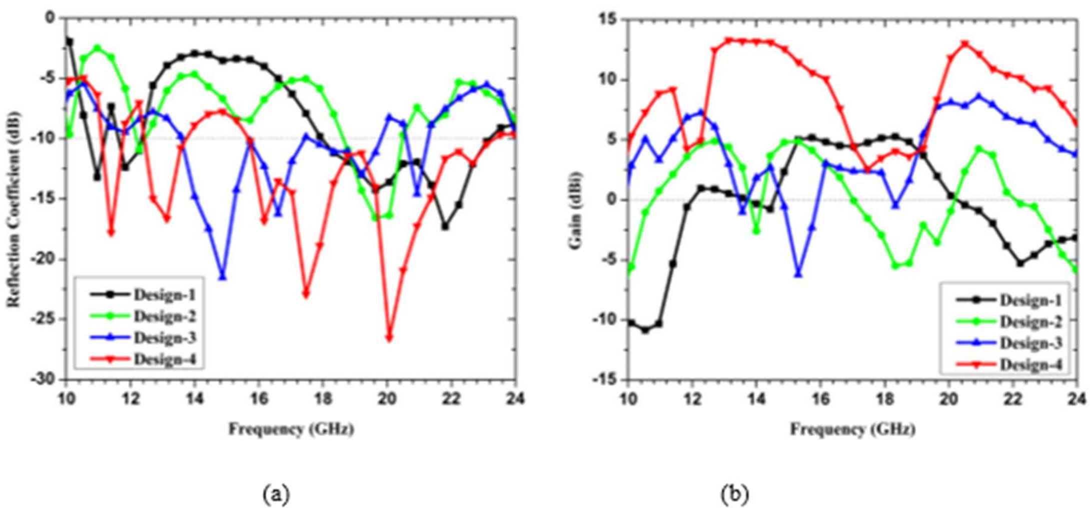


Fig.2: (a) and (b) represent the reflection coefficient (return loss) and gain of design-1, 2, 3 and 4 respectively

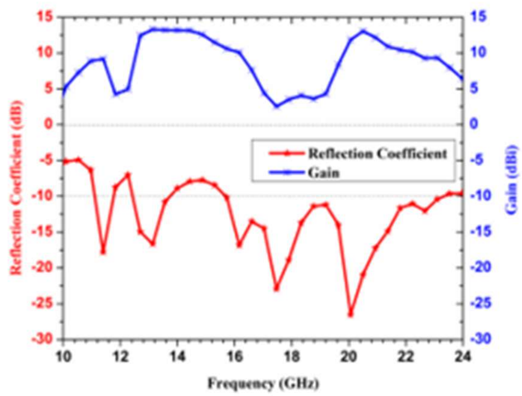
Table 1: Performance characteristics of the Antennas (Design 1 to 4)

Antenna	Operating band (GHz) / Bandwidth (GHz)	Resonant frequency (GHz)	Reflection Coefficients (dB)	Peak Gain (dBi)
Design-1	(10.53-11.10)/0.57	10.96	-13.20	-10.30
	(11.40-12.70)/1.3	11.83	-12.37	-0.58

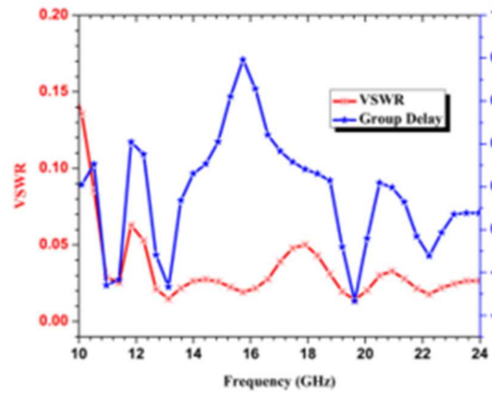
	(17.90-23.53)/5.63	19.63	-14.26	1.97
		21.80	-17.30	-3.82
Design-2	(11.83-12.70)/0.87	12.26	-10.94	4.6
	(18.33-20.50)/2.17	19.63	-16.56	-3.54
Design-3	(13.56-17.03)/3.47	14.86	-21.51	-0.55
		16.60	-16.23	2.64
	(17.90-19.63)/1.73	19.20	-12.98	5.45
	(20.50-21.36)/0.86	20.93	-14.59	8.59
Design-4 (Proposed)	(10.96-11.83)/0.87	11.40	-17.80	9.17
	(12.26-14.00)/1.74	13.13	-16.64	13.29
	(15.30-23.53)/8.23	16.16	-16.82	10.07
		17.46	-22.94	2.55
		20.06	-26.54	11.83

The proposed antenna (design 4) has obtained triple operating bands are (10.96-11.83) GHz, (12.26-14.00) GHz, and (15.30-23.53) GHz with resonated at 11.40 GHz, 13.13 GHz, 16.16 GHz, 17.46 GHz, and 20.06 GHz and peak gains are 9.17 dBi, 13.29 dBi, 10.07 dBi, 2.55 dBi, and 11.83 dBi respectively (cf. fig. 2, 3.a, and table-1), the proposed maximum/minimum peak gain 13.29/2.55 dBi has obtained. The proposed antenna covers the three frequency bands of X (8-12) GHz, Ku (12-18) GHz, and K (18-27) GHz, the proposed antenna has covers the radar and satellite communication frequency range and higher gain and bandwidth are played the good agreement of radar and satellite communication.

The Table-1, represent the data in the term of the operating band (GHz) with bandwidth (GHz), resonant frequency (GHz), reflection coefficient or return loss (dB), and peak gain (dBi) of antennas. The simulated analyses of design 1 to 4 in terms of reflection coefficient are represented in figure 2.a. The figure 2.b represents the gain parameter of the designs 1 to 4. In Table 1, we examined these antennas (designs 1 to 4) and compared all these antennas; the proposed antenna (design 4) is superior in terms of bandwidth, peak gain, and reflection coefficient. In the inspection of fig.2, 3(a) and table 1, the proposed band and gain are higher as compared to reported antennas (designs 1, 2 & 3).



(a)



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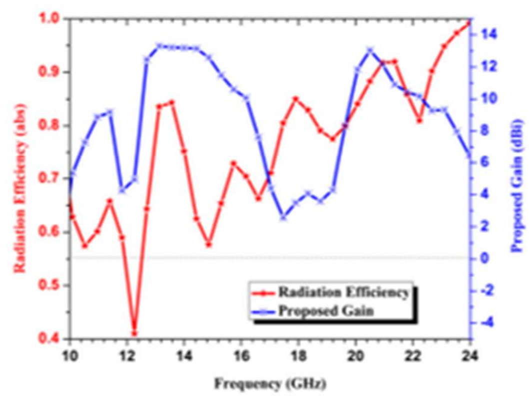

(c)

Fig.3: (a), (b), and (c) represent the reflection coefficient (return loss) and gain, VSWR and group delay, and radiation efficiency and gain of design-4 (proposed antenna) respectively

The group delay (GD) demonstrates the grade of alteration in transmitted and received signal as a role of frequency. Simulated group delay is gained from the phase of |S11| is presented in equation (9).

$$GD \approx \frac{\{\text{Phase}\ [S11\ (f2)] - \text{Phase}\ [S1\ \ (f1)]\}}{[2\pi\ (f2-f1)]}$$

(9)

The proposed group delay is varying between -0.40 ns to 0.50 ns at entire resonating bands as shown in figure 3(b), which is acceptable for distortion-free transmission. The simulated VSWR (voltage standing wave ratio) of the proposed antenna is demonstrated in figure 3(b). It is obviously visible that the simulated VSWR is close to 0 and less than 0.15 throughout the operating frequency. This outcome is verified by being the result of VSWR being detected for entire operating bands of the proposed antenna is analytical of the element is well matched. The radiation efficiency is calculated by the equation (8). The efficiency is the ratio of gain and directivity of the antenna [16]. The simulated radiation efficiency is displayed in figure 3(c), which has indicated the determined efficiency is up to 85 %, obtained at the entire operating frequency band.

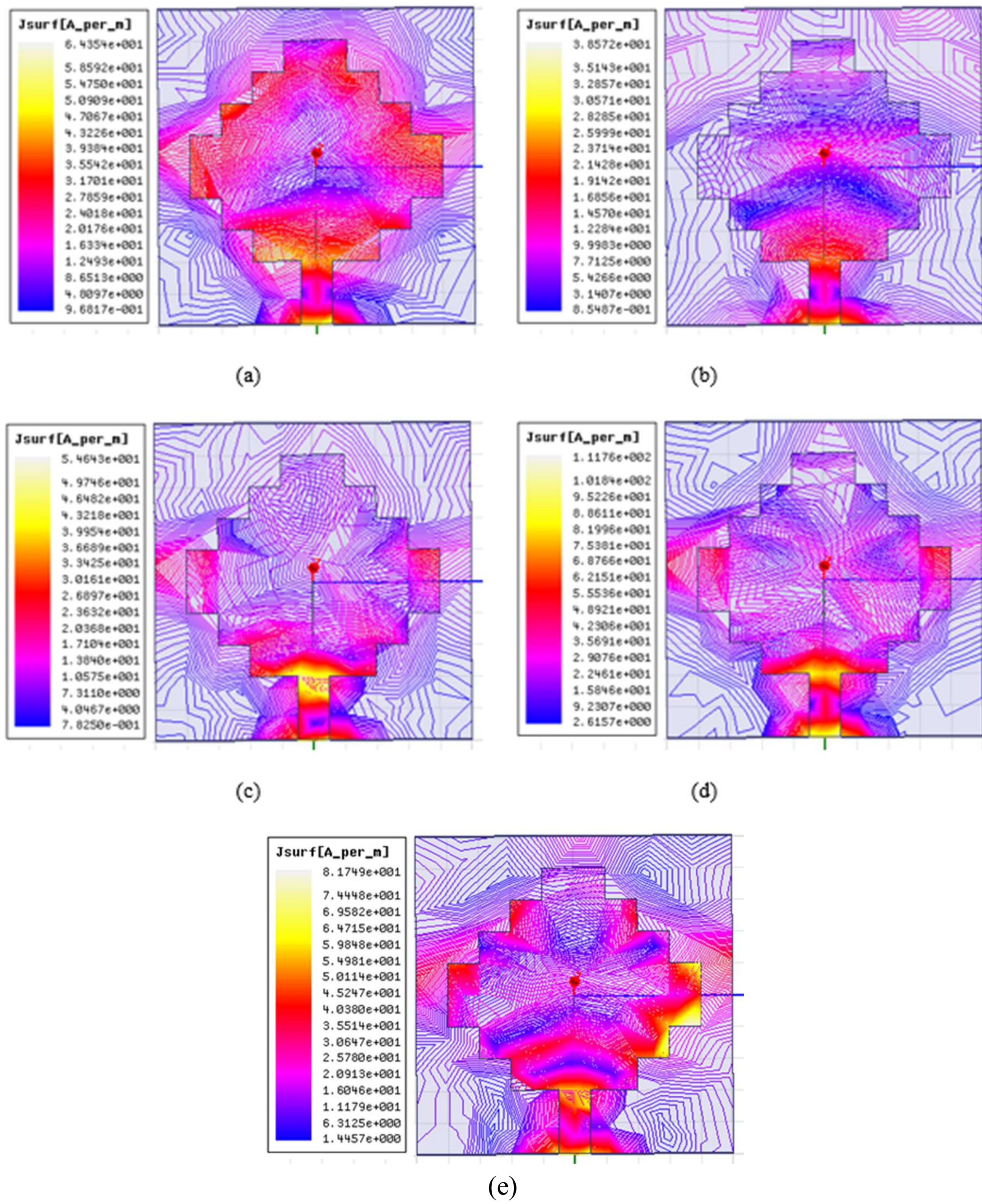

Fig.4: (a), (b), (c), (d), and (e) represent the surface current distribution at 11.40 GHz, 13.13 GHz, 16.16 GHz, 17.46 GHz, and 20.06 GHz respectively of design-4 (proposed antenna)

The simulated surface current distribution of the proposed antenna is categorized at 11.40 GHz, 13.13 GHz, 16.16 GHz, 17.46 GHz, and 20.06 GHz with 64.35 A/m, 38.57 A/m, 54.64 A/m, 111.76 A/m, and 81.74 A/m respectively, and has been entirely demonstrated in Figure 4 (a-e) respectively.

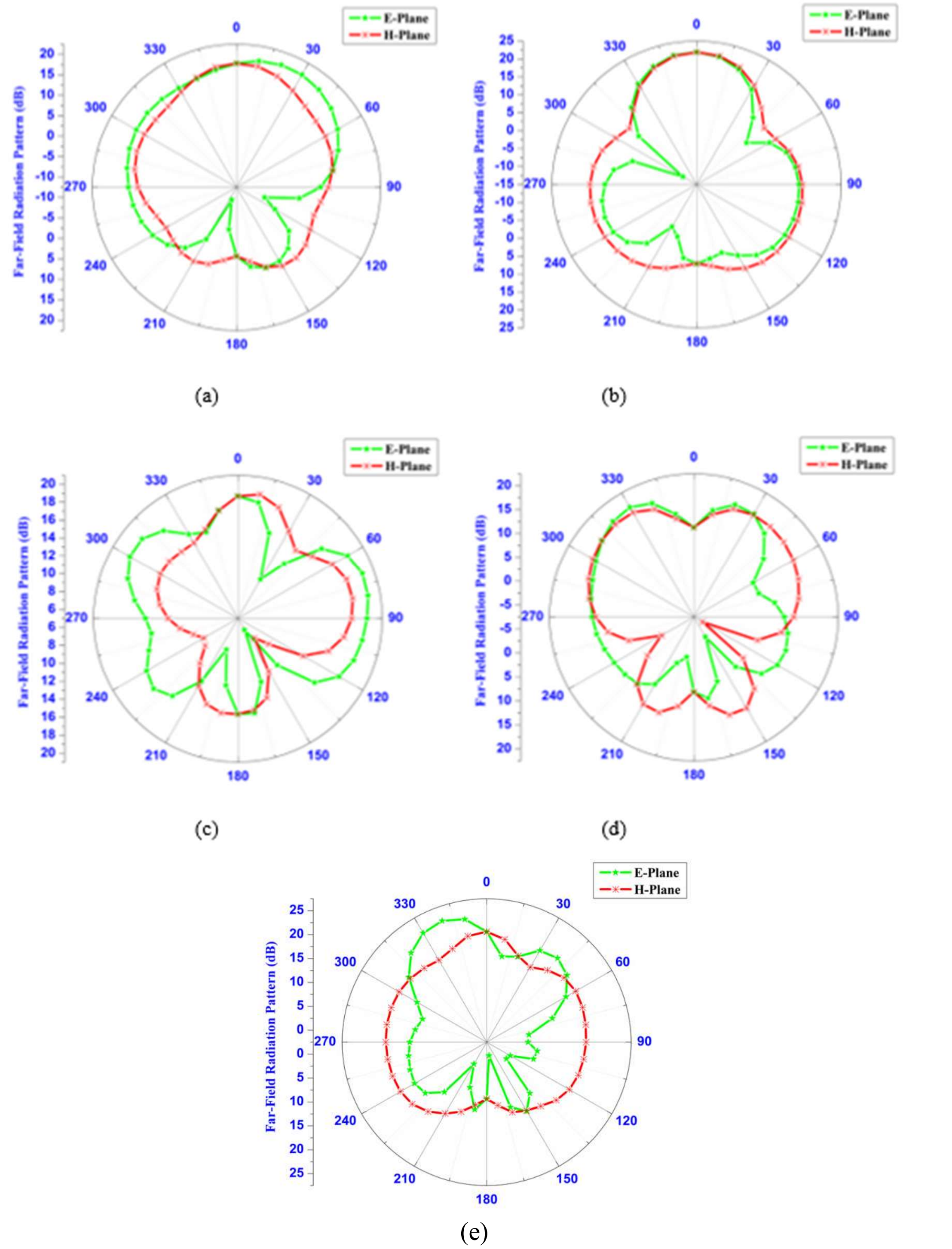

Fig.5: (a), (b), (c), (d), and (e) represent the far-field radiation pattern at 11.40 GHz, 13.13 GHz, 16.16 GHz, 17.46 GHz, and 20.06 GHz respectively of design-4 (proposed antenna)

Figure 5 (a-e) illustrates the proposed antenna is simulated Co/Cross polarization far-field radiation patterns in both the E-plane & H-plane, when the elevation axis corresponds to the polar axis (Phi = 0o) for the antenna's coordinate system. The simulated far-field radiation pattern is presented at 11.40 GHz, 13.13 GHz, 16.16 GHz, 17.46 GHz, and 20.06 GHz. The proposed antenna is intended for entire resonating frequencies are suitable for omnidirectional broad radiation pattern characteristics. The omnidirectional radiation patterns are operational for vehicular applications along with radar and satellite communications.

5. Comparative Analysis with References

The comparative analysis of proposed antenna with reported literature in terms of dimensions of antenna, operating band, resonant frequency, peak gain, VSWR, and radiation efficiency is mentioned in table 2. The proposed design is smaller in size and much superior performance in standings of operating band, bandwidth, peak gain, VSWR, radiation efficiency than other reported antennas in the literature [10-17].

Table 2: A comparative overview of the proposed antenna with reported antenna

Ref.	Dimension of Antenna (L×W) mm^2	Operating Band (GHz)	Bandwidth (GHz)	Resonant Frequency (GHz)	Peak gain (dBi)	VSWR	Radiation Efficiency (%)
[10]	24×24	14.3-16.2 17.4-18.9 19.3-19.8	1.9 1.5 0.5	15.15 18.2 19.5	5.6 3.5 3.1	NR	60
[12]	27×27	11.67-14.05 18.19-19.75	2.38 1.56	12.94 19.04	3.1 4.13	< 2	NR
[13]	25×25	15.35-19.65	4.3	16.8	6.2	NR	NR
[14]	20×20	17.15-18.53	1.38	17.75	7.8	NR	70
[15]	35×35	11.76-12.71	0.95	12.2	7.6	< 2	65
[16]	30×30	14.75-18.23	3.48	16.21	3.54	NR	NR
[17]	25×35	15-64-17.82	2.18	16.43	2.65	NR	NR
Proposed	20×20	(10.96-11.83) (12.26-14.00) (15.30-23.53)	0.87 1.74 8.23	11.40 13.13 16.16 17.46 20.06	9.17 13.29 10.07 2.55 11.83	< 0.15	85

6. Conclusion

The purpose of this pedestal fan shaped microstrip patch antenna designed a compact (20×20 mm2), with enhanced gain and bandwidth for X, Ku, and K bands applications and particularly for radar and satellite applications. The proposed design is simulated on FR-4 epoxy substrate (εr = 4.4, tan δ = 0.02 and h = 1.6 mm) and carried out by ANSOFT HFSS 13 electromagnetic solver. The proposed antenna is performed with higher gain and bandwidth than the reported antennas, the two layered of stacking techniques being played a major role for improved performance. The proposed antenna gain varies in the range of (2.55-13.29) dBi, VSWR varies in the range of (0-0.15), group delay varies between (-0.40 to 0.50) ns and radiation efficiency up to 85% is achieved during entire operating frequency band. The Omni-directional radiation pattern of the proposed antenna is beneficial even for vehicular applications along with radar and satellite communications.

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