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DESIGN AND ANALYSIS OF DEFECTED GROUND STRUCTURE BASED MICROSTRIP ANTENNA FOR X-BAND RADAR APPLICATION

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Abstract— In this paper, a compact (32 × 32 × 1.6 mm^3), microstrip line-fed based with dual operating band is presented for X-band (8-12 GHz) application and mostly applicable for radar application. The proposed design was drawn on low-cost FR-4 dielectric substrate ($\varepsilon_r = 4.4$, tan $\delta = 0.02$ and h = 1.6) of P-shaped radiating patch and defected ground structure (DGS). The proposed antenna has return loss is below -10 dB at both exhibited bands, and finding that the first operating band has impedance bandwidth is 14.67% (8.40-9.73 GHz), resonating frequency is 8.8 GHz with 3.32 dBi 3D peak gain and second operating band has impedance bandwidth is 8.80% (10.86-11.86 GHz), resonating frequency is 11.53 GHz with 3.27 dBi 3D peak gain are obtained respectively, and peak radiation efficiency of first and second operating band is 86.5% and 83.4% are obtained respectively. The group delay time of the proposed antenna is varying between -0.90 ns to 0.40 ns (< 0.5 ns) and VSWR of the proposed antenna is close to 1 and less than 2 are obtained. The proposed design and model of antenna has been analyzed with HFSS simulation tool.

Keywords— Radiating Patch, Return Loss, Radiation Pattern, Group Delay, VSWR and Radiation Efficiency

1. Introduction

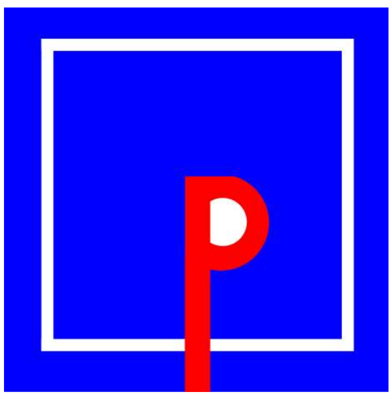
Importance in wireless handheld devices has led to an increasing demand to incorporate more communication services. The key features of a microstrip patch antenna for wireless applications are ability to integrate in small and handheld communication devices. To overcome the limitations of a microstrip patch antenna, the researchers are focused to improve the antenna parameters such as return loss, bandwidth, gain, and radiation efficiency [1-2]. However, it is difficult to improve several parameters simultaneously therefore, a trade-off is required by inserting the antenna structure with stub, slit, and slot, truncating corners of radiating patch, loading radiating patch with high frequency active devices, and introduction of defected ground structure (DGS) [3-4]. There are many researches in progress in overcoming these disadvantages in order to make full use of advantages such as ease in design, ease in manufacturing and low cost in manufacturing these compact Microstrip antennas [5]. The performances of these antennas are dependent upon their physical configuration. Various methods to improve the performance of antenna on their physical configuration are suggested by the researchers [6]. Microstrip patch antennas are fed by two methods that are categorized into contacting and non-contacting method. In contacting methods, RF power is fed to the radiating patch directly by using the connecting link which is the Microstrip line. In non-contacting method, electromagnetic field coupling is conducted by transmission of power from Microstrip line to radiating patch. In Microstrip line, different type of feed techniques are used there are coaxial probe (both contacting schemes), aperture coupling and proximity coupling (both non-contacting schemes) [7, 8 & 9]. In recent years, the demand for modern wireless communication has increased manifolds and it has prompted scientists and engineers to design devices capable of handling multiple applications within a single device [10]. Microstrip antennas are unduly renounced antennas for transmitting and receiving electromagnetic waves. These antennas have ability to integrate with printed and active devices [11-12]. These antennas find applicability in military applications like missile, fighter planes and rockets as well as commercial applications like global positioning system (GPS), radar applications, remote sensing and direct broadcasting [13-14]. These days, the avail of micro strip antennas are not only bounded in single band operations but also scaled for multiband operations [15-16]. Defected ground structure (DGS) is prominently used in high frequencies antenna design to reduce the antenna size and to enhance the bandwidth [17]. The slots and notches in the ground plane disturb the current distribution in the ground plane and increase the effective inductance and capacitance of input impedance that results to enhancement in bandwidth [18-19]. In former decennary several multiband antennas for radars and satellite communications are introduced.

In the modern years the improvement in modern wireless communication system needs low profile, light weight, high gain and high efficiency features like radar, mobile, satellite, GPS and etc.[20-21]. It has several gorgeous feature such as, light weight, low cost, imitate capability to shaped surface, compatibility with included circuitry and thin profile antennas that are proficient of preserving high recital over a wide spectrum of frequencies [22-23]. Although the many benefits of typical microstrip antenna they also have restrictions, narrow bandwidth, low gain, and relatively large size [24-25]. In recent years a remarkable development is noticed for the indoor and outdoor wireless communication systems due to most of the work on microstrip antenna system is reported for the WLAN (wireless local area network) and WiMax (word wide interoperability for microwave access), LTE (long term evolution) and 5G/6G communication systems [26-27]. Faster transmission rate along with better communication signal quality enable the system and desirable for the bands like X, Ku, K also. Systematic design method of a multiple antenna system using the theory of characteristic modes is reported in [28]. In the past few decades, many techniques have been introduced for bandwidth enhancement such as increasing the planar area, substrate thickness [29], modifying feeding techniques [30], using defected ground structures [31], using shorting pins [32], and using parasitic patches [33]. Electromagnetic band gap (EBG) structures have garnered more attention as bandwidth and gain enhancement technique in the design of ultra-wideband antennas [34]. DGS can be considered as one of the most efficient bandwidth enhancement technique because it improves the radiation efficiency by suppressing the ground [35].

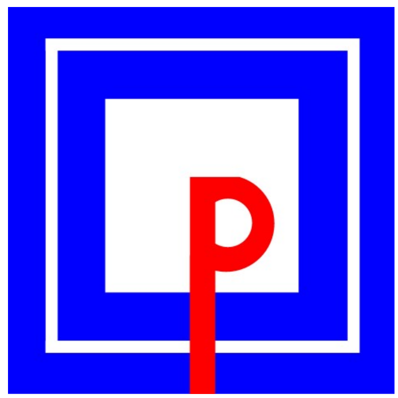
In this paper, a defected ground dual-band operated in the frequency range of 8-12 GHz has been presented. The rectangular defect in the ground plane is responsible for dual-band behavior of designed antenna. The proposed antenna is in terms defected square track structure employed through on the ground plane, P-shape radiating patch, improved antenna characteristics like bandwidth, impedance matching ($Z_{in} = Z_o = 50\ \Omega$), gain and group delay (< 0.4 ns). The designed antenna is simulated using HFSS simulation software and has good antenna characteristics.

2. Antenna Design & Evolution of the Proposed Design Model

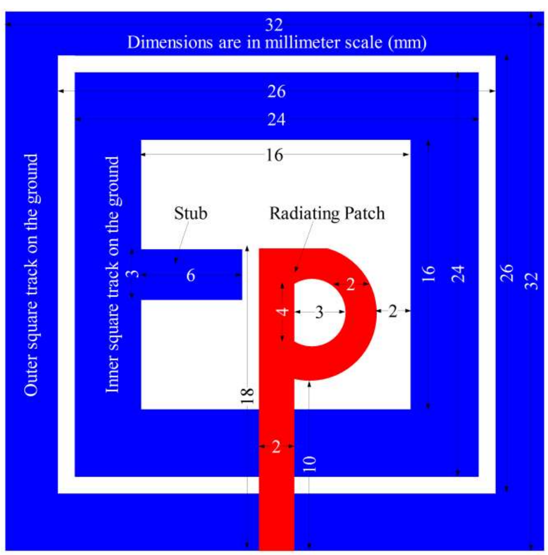
Antenna dimensions of the proposed antenna are well labeled with millimeter (mm) scale in Figure 1. The layout and geometry of the proposed antenna with orange color radiating patch and blue color ground layout is shown in Figure 1 (a-c). The proposed antenna with the dimension of $32 \times 32 \times 1.6\ mm^3$ is simulated on a 1.6-mm-thick FR4-epoxy substrate with dielectric constant of 4.4 and loss of tangent tan $\delta = 0.02$.



(a)



(b)



(c)

Fig. 1: Schematic the geometry of (a) Antenna -1, (b) Antenna-2, and (c) Antenna-3 (proposed)

Introduction of stub (3 × 6 mm^2) on the ground plane plays vital role in optimizing impedance matching, as discussed later. The evolution of antennas (Antenna-1 to Antenna-3) [cf. Figure 1 (a-c)] in terms of return loss, and gain is parametrically analyzed. The behavior of inner square ground plane (24 × 24 mm^2), and perturbation stub (3 × 6 mm^2) at the ground plane of antennas is observed by simulating individual antenna as shown in Figure 2 (a-b), respectively. However, introduction of slot reduces the overall area of the ground plane as well as it changes the overall inductive and capacitive behavior of the equivalent lumped element circuit of the antenna. Antenna-1 exhibits dual bands starting from 8.46 to 11.8 GHz, but peak gain is negative at first operating band (cf. Figure 2 (a-b) and table 1). In antenna-2, a square slot (16 × 16 mm^2 without stub) is introduced, which shifts the operating bands toward lower frequency side, that is, to (8.40 to 11.86 GHz), resulting into dual bands and also peak gain is negative at first operating band (cf. Figure 2 (a-b) and table 1). The stub (3 × 6 mm^2) in antenna-3 (proposed) increases the gain as compared to Antenna-1 and Antenna-2. Hence, Antenna-3 is considered as the optimum and proposed design of the antenna.

In P-Shaped radiating patch of side length L_P with slots or stub are loaded on the radiating patch. The radiating patch is fed with a 50 Ω micro-strip feed line on the top of the bottom substrate. Feed length (L) and width (W) are optimized to match the 50 Ω characteristics impedance with antenna impedance. The optimized design parameters of the proposed antenna geometry are enumerated in Figure 1. Microstrip antennas with rectangular or square patches can be simply modeled as sections of transmission lines, and the transmission line model can be used to analyze a rectangular microstrip patch antenna. The dimensions of the conventional microstrip patch antenna have been evaluated using the mathematical equations below. The dimensions of conventional P-shaped radiating patch and square of outer or inner ground geometry of the antenna (Antenna-3, cf. Figure 1) are calculated with the given equation 1, 2, 3, 4 and 5 respectively [14-19]:

$$W = \frac{c}{2f}\sqrt{\frac{2}{\varepsilon_r+1}} \tag{1}$$

$$L = L_{ef} - 2\Delta l \tag{2}$$

$$L_{ef} = \frac{c}{2f\sqrt{\varepsilon_{re}}} \tag{3}$$

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

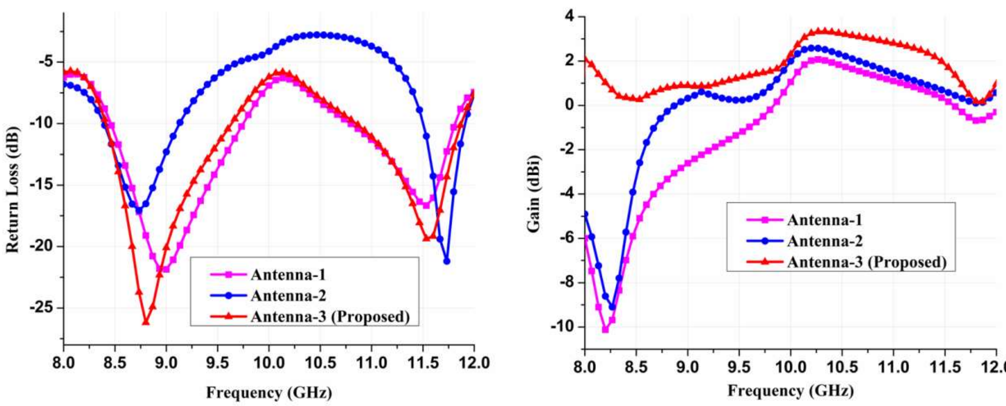
$$\Delta l = 0.412h\frac{(\varepsilon_{re}+0.3)\left(\frac{W}{h}+0.264\right)}{(\varepsilon_{re}-0.258)\left(\frac{W}{h}+0.8\right)} \tag{5}$$

Where, ε_r is the dielectric constant of substrate and f is the center frequency, L_{ef} is the patch effective length and Δl is the normalized extension in length, ε_{re} is the effective substrate dielectric constant, and and h is the thickness of substrate and the normalized extension in length (Δl).

Parametric analysis of defects/shapes created on the ground plane has been performed to achieve optimized geometrical configuration and antenna parameters. The performance of antenna is analyzed in terms of return loss, gain, current distribution, and radiation pattern.

3. Results & Discussion

The proposed design is specifically analyzed in terms of surface current distribution, return loss, radiation pattern, gain, radiation efficiency, and group delay. The proposed antenna is designed and simulated using HFSS software for high frequency application arrange of 8 GHz to 12 GHz frequency. From the simulation of proposed antenna, dual resonating bands are obtained at resonance frequency of 8.80 GHz and 11.53 GHz with impedance bandwidth of 14.67 % and 8.80 % respectively shown in figure 2 (a) & table 1.

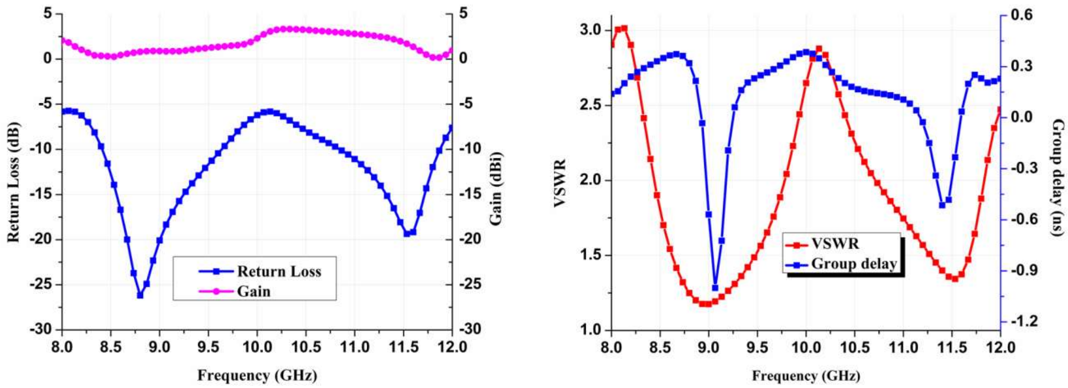


(a) (b)

Fig. 2: Schematic of (a) Simulated returns loss versus frequency curve, and (b) Simulated gain versus frequency curve of the Antenna-1, Antenna-2 & Antenna-3

Figure 2(b) show the gain versus frequency plot of the Antenna-1, Antenna-2 and Antenna-3. Also Figure 3 (a) depicts the simulated antenna gain response of the proposed antenna and it is observed that the maximum peak gain is 1.94 dBi. The stable gain (0.96-1.94 dBi) of the proposed antenna makes the antenna the best choice for X-band applications and particularly for the modern radar application.

A perusal of table-1 and figure 2 (a-b), and 3 (a) clearly shows that the operating band and gain characteristics of the proposed Antenna (Antenna-3) are enhanced as compared to Antenna-1 and Antenna-2. For modern radar applications is required to significant return loss less than -10 dB and gain more than 0 dBi [7-9], whereas variation of the proposed antenna in terms of return loss is less than -10 dB and peak gain is more than 0 dBi, with larger values since required significant and also larger as well as compared to Antenna-1 & Antenna-2. These mentioned parameters make the proposed design suitably potential for modern radar application.



(a) (b)

Fig. 3: Schematic of (a) simulated Return loss & Gain versus frequency curve, and (b) VSWR and Group delay versus frequency curve of the proposed Antenna

Table 1: Comparative Performance of Antenna-1, Antenna-2, and Antenna-3

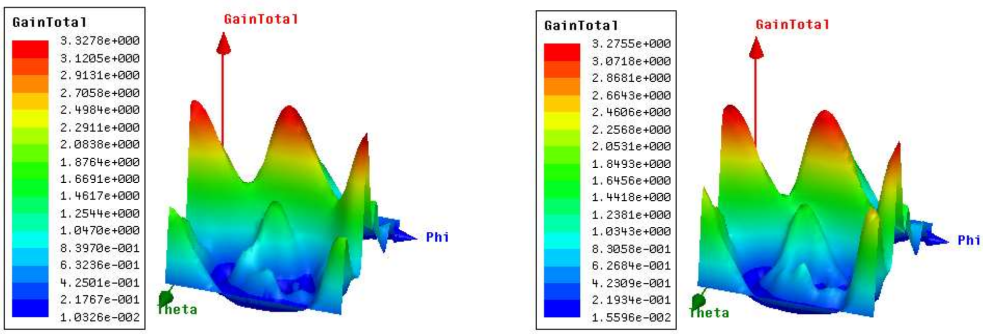
Antenna	Operating Band/ Bandwidth(GHz)	Impedance Bandwidth (%)	Resonance Frequency (GHz)	Reflection Coefficient (dB)	2D Peak Gain (dBi)	3D Peak Gain (dBi)
Antenna-1	(8.46-9.73)/1.27	13.96	09.06	-21.08	-1.17	0.24
	(10.8-11.8)/1	8.84	11.53	-16.67	0.16	0.29
Antenna-2	(8.40-9.06)/0.66	3.78	08.73	-17.07	-0.59	1.21
	(11.53-11.86)/0.33	2.82	11.73	-21.19	0.18	1.33
Antenna-3 (Proposed)	(8.40-9.73)/1.33	14.67	08.80	-26.17	0.96	3.32
	(10.86-11.86)/1	8.80	11.53	-19.36	1.94	3.27

The group delay shows the degree of distortion in transmitted and received signal as a function of frequency and it is mathematically defined [6-18] as in equation (6):

$$\text{Group delay} = d\psi/d\omega \quad (6)$$

The group delay time of the proposed antenna is varying between -0.90 ns to 0.40 ns as shown in Figure 3 (b) which is acceptable for distortion-free transmission. The flat and consistent group delay response is desirable for efficient transmission of pulse through microstrip patch antenna in radar applications. A good group-delay response depends on the symmetry and feed point of the antenna and shows the degree of distortion in transmitted/received pulses. For efficient pulse transmission group delay less than 0.5 ns are desirable.

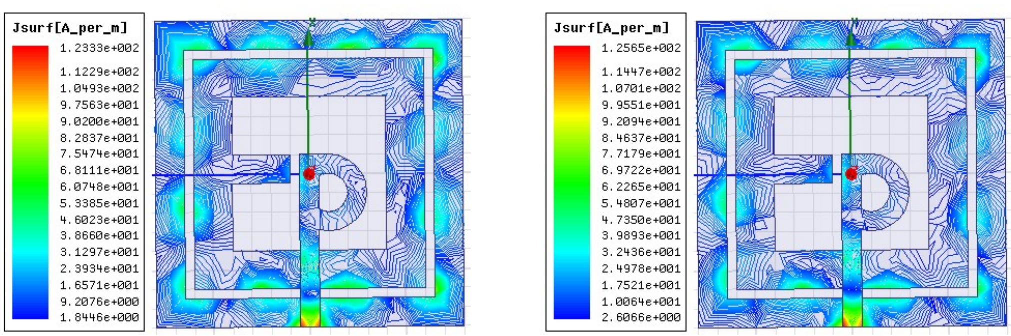
The simulated VSWR of the antenna is illustrated in the Figure 3(b). It is clearly visible that the simulated VSWR is less than 2 throughout the operating frequency. The effect of higher frequency is more pronounced and as the frequency increases the input impedance is lowered. This effect is corroborated with the result of VSWR is observed for both operating band of the proposed antenna is close to 1 and it is less than 2, which is indicative of the fact the antenna is properly matched.



(a) (b)

Fig. 4: Representation the 3D gain of proposed antenna at (a) 8.80 GHz, and (b) at 11.53 GHz

The 2D (Two Dimensional) and 3D (Three dimensional) plot of antenna gain is illustrated in Figures 2 (b) and 3 (a), and Figure 4 (a) & (b) respectively. In the proposed design model, while observing Fig. 4 (a) & (b), we witness two simulated 3D peak gains 3.32 dBi at 8.80 GHz and 3.27 dBi at 11.53 GHz observed respectively. Hence, proposed three dimensional gains are the ability of the antenna to radiate more and make it is potential for modern radar application.



(a) (b)

Fig. 5: Representation the surface current distributions of proposed antenna at (a) 8.80 GHz, and (b) 11.53 GHz

The radiating contrivance of the described antenna system was investigated the surface current distribution. This was absorbed on inspecting the antenna portions that are inducing the radiation appearances. Surface current density of the proposed antenna is 123.33 A/m & 125.65 A/m at 8.80 GHz & 11.53 GHz respectively is presented in Fig. 5 (a) & (b). The maximum surface current density of 125.65 A/m at 11.53 GHz is observed.

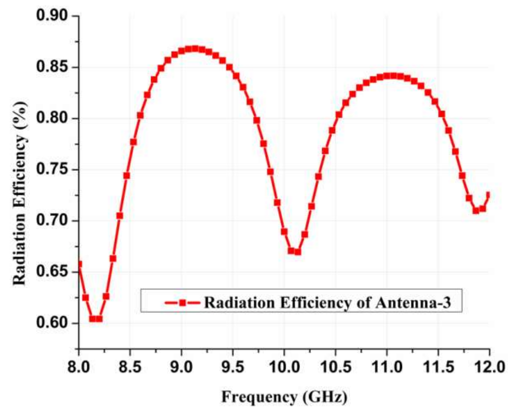
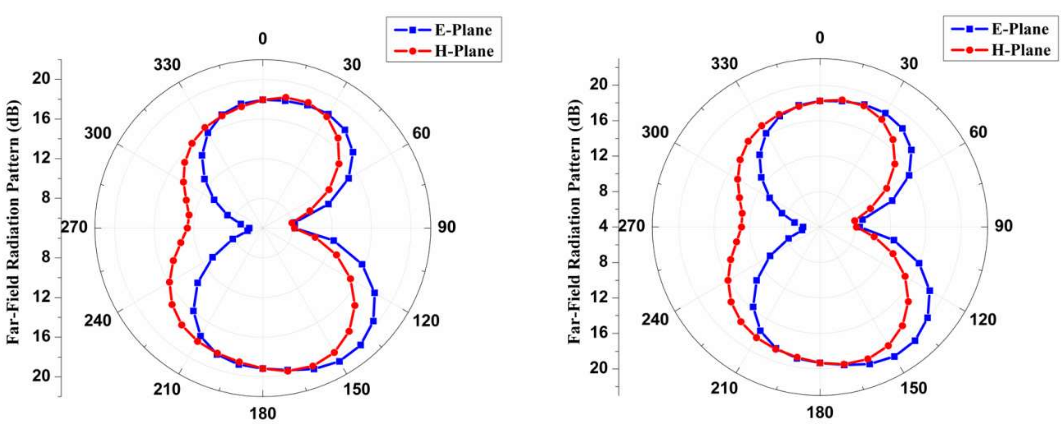


Fig. 6: Representation the simulated radiation efficiency of the proposed antenna

The simulated radiation efficiency plot of the proposed design is shown in Figure 6. Radiation efficiency plays pivotal role in terms of performance parameter of an antenna because it is the ratio of total power radiated to the total power supplied. The simulation yields to a maximum efficiency of 86.5 % for (8.40-9.73) GHz operating band and 83.4 % for (10.86-11.86) GHz operating band is observed at proposed antenna (cf. table 1).

The simulated far-field radiation pattern for the proposed antenna in the E-plane ($\varphi = 0^0$) and H-plane ($\varphi = 90^0$) at 8.80 GHz, and 11.53 GHz are shown in Figure 7 (a) & (b) respectively. The radiation pattern represents the magnitude of the radial electric field in dB.



(a) (b)

Fig. 7: Representation the simulated radiation pattern of proposed antenna at (a) 8.80 GHz, and (b) 11.53 GHz

For all resonating frequencies, the co-polarization level in the E-plane and the H-plane is higher than the cross-polarization level where the simulated radiation patterns are in good agreement as shown in Fig. 7 (a) & (b) respectively, it can be fairly concluded that the proposed antenna radiates more power in the Omni-directional due to the significant difference between co and cross- polarization level.

Table 2: A Comparative Overview of the Proposed Antenna

Ref. No.	Area of the Antenna (mm^2)	Substrate Used	3D Peak Gain (dBi)	Group Delay (ns)	VSWR	Radiation Efficiency (%)
[3]	3600	FR-4	2.67	< 0.5	NR	63
[4]	3025		NR	< 0.8	< 2	73
[17]	1500		3.14	< 0.6	< 5	NR
[26]	2025	Rogers RT/Duroid-5880	NR	< 0.5	NR	68
[28]	1575	FR-4	2.96	NR	< 2	74
[29]	1628		1.83	NA	NR	77
[32]	1024	Rogers RT/Duroid-5880	NR	< 0.9	< 4	NR
[34]	1764	FR-4	3.16	NR	< 2	81
[35]	1296		NR	< 0.5	< 2	67
Proposed	1024		3.32	< 0.4	< 2	86.5

A comparative overview of the proposed antenna in terms of area of the antenna, substrate material, 3D peak gain, group delay, voltage standing wave ratio (VSWR) and radiation efficiency is presented in table 2. The proposed antenna occupies a compact area, better 3D peak gain, lowest group delay time, perfect VSWR and better radiation efficiency as compared to antennas reported in references [3, 4, 17, 26, 28, 29, 32, 34 & 35]. Proposed antenna occupies the compact area as compared to reported references, the group delay time is less than 0.4 ns are acceptable for distortion-free transmission and VSWR is close to 1 and less than 2, which is indicative information of the antenna is properly matched, highly 3D peak gain are the ability of the antenna to radiate more and make it is potential for modern radar application.

4. Conclusion

In this paper, the proposed antenna performance is reported in Table 1 and the geometry is reported in Fig. 1. The dual-band performance in the range of 8.40–11.86 GHz and the structure of the proposed antenna are in the compact region, which is acceptable for distortion-free group delay transmission, and the acceptable VSWR is less than 2, which exactly matches the signal information of the antenna. Square track antennas create inductive and capacitive effects on the impedance, resulting in changes to the overall antenna parameters, such as lowering the resonant frequency and increasing the bandwidth as shown in Figures 2 and 3. The spurious impedance bandwidth of the first operating band is 14.67% at 8.80 GHz with a resonance frequency at 8.40–9.73 GHz and the impedance bandwidth of the second operating band is 8.80% at 10.86–11.86 GHz with a resonance frequency at 11.53 GHz. The 3D peak gain in the first and second operating bands is 3.32 dBi and 3.27 dBi, respectively. The peak radiation efficiencies of the first and second operating bands are achieved to be 86.5% and 83.4%, respectively. Due to its defective ground structure at high frequency for surface motion, the proposed antenna has enhanced 3D peak gain, making it a good candidate for X-band applications and especially for modern radar applications.

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