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Original Article

Design and Analysis of Microstrip Patch Antennas for Sub-6GHz 5G: A Comparative Study of Substrates and Feeding Techniques

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Abstract *- In this paper, Microstrip patch antennas were designed at a center frequency of 3.7GHz, and the performance parameters were analyzed using three different feeding techniques on two different substrates. The antennas were designed using Direct, Inset and Quarter wave feeds on FR4 substrate having a dielectric constant (ε_r) of 4.4 as well as using low loss RT-Duroid substrate with Dielectric constant 2.2 by keeping the constant size of 60mm*60mm*1.6mm. The antennas' performance variations regarding Return Loss (S11), voltage standing wave ratio (VSWR), Gain, Radiation Efficiency, Bandwidth, and Impedance were analyzed using the ANSYS HFSS simulator. The analysis shows S11 of -21.2316 dB, -32.1585 dB, -22.9989 dB and -22.27 dB, -29.2056 dB, and -21.45 dB, respectively, for the Direct, Inset, Quarter wave feeds on FR4 and RT Duroid substrates respectively at 3.7GHz. The study shows that better impedance matching was obtained using an Inset Feed than the other two, with VSWR values of 1.0506 and 1.0718, for the equal length and width of the substrate and ground plane. The gain of the antennas was found to be 4.72 dBi,4.3 dBi,4.33 dBi and, 8.08 dBi, 8.05 dBi, and 8.10 dBi, respectively. The moderate radiation efficiencies of 65.06%,50.84% and 51.54% were obtained for the design using a lossy FR4 substrate. The study reveals that the design on low-loss RT Duroid substrate improves the Radiation efficiency and the Gain but minimizing the bandwidth compared to the design on FR4 substrates.*

Keywords *- Microstrip Patch Antenna (MSPA), Sub-6 GHz, FR4, HFSS, Rogers RT/Duroid 5880.*

1. Introduction

Rapid technological advancements have shown the path for high data rates, low latency, and enhanced capacity through 5G. Microstrip patch antennas play a critical role in the sub-6GHz band of 5G due to their compact structure, lightweight, ease of fabrication and meeting the requirements of real-world communications. Many researchers have implemented an MSPA for 5G applications using different techniques such as variations in substrate, feeding, introducing slit/slots, stacking the patches/substrates to achieve better results in the form of Gain, Bandwidth, Radiation efficiency, VSWR etc. Research on combining different techniques has a significant role in determining the requisite performance. This work mainly focuses on the design of MSPA by combining variations in three different techniques and two substrates over a constant length and width of the ground plane and substrate. The structure of MSPA includes a metallic surface at the top and bottom with the substrate in between. The substrate is dielectric, whereas the radiating patch and ground plane are conductors. The radiating patch can have shapes like rectangular, triangular, circular, pentagon, hexagon, etc. Most commonly, rectangular patches are used with various performance improvement techniques such as feeding techniques, Defective Ground Structures (DGS), slots and slits etc. The primary task of the antenna is to transmit or receive electromagnetic waves effectively at the desired frequencies.

In the 5G scenario, particularly in the sub-6 GHz band, which has below 6GHz frequencies, microstrip patch antennas are well applicable due to their characteristic features. The trade-off between capacity and coverage in 5G sub-6 GHz is better than millimetre-wave frequencies that confirm long-distance transmission and penetration via obstacles such as buildings and large structures. This results in a reliable and high data rate for multiple users.

The main challenge in the 5G sub-6 GHz Microstrip patch antenna design is to obtain better performance parameters with less volume and cost that meets the user demands such as wide bandwidth and high gain, which are very crucial for modern devices such as WiFi modules, Internet of Things (IoT) equipment and smartphones. The main problem today's researchers face with the MSPA is that improving one performance parameter affects the other. Hence, the design of optimised performance MSPAs is a challenging task.

In addition, the compact structure of microstrip patch antennas makes them a good choice for incorporating them into base stations, mobile phones and different 5G devices. Also, advancements in the fabrication and material sciences have made the development of conformal, flexible, and semi-flexible microstrip patch antennas possible. The efficiency of the microstrip patch antennas is one more critical parameter in sub-6GHz 5G applications. Efficient radiation signifies that a good amount of power has been radiated, which is a prime factor for maintaining the signal strength.

The paper's organisation has six sections: Section 1 discusses the need for a microstrip patch antenna in 5G sub-6GHz and its characteristic features. A review of the literature is presented in Section 2. The proposed antenna design methodology with the corresponding mathematical equations is in Section 3. The results of the proposed antennas are discussed in Section 4. Section 5 presents the conclusion, and then the future scope is presented in Section 6.

2. Review of Literature

A microstrip patch antenna with a flag structure has been designed using RT Duroid substrate (ε_r =2.2) resonating at 2.4GHz. [1]. The Defected Ground Structure and rectangular slots were used to achieve a wide bandwidth and decrease the resonant frequency. The structure of the ground plane was L-shape, and Slit had been introduced on the Patch. The implemented antenna gives a Bandwidth of 200MHz and a good radiation efficiency of 92%.

This paper proposed an Omnidirectional Dual Band Circular Patch antenna [2]. The Radiating Patch is circular and consists of a star-shaped slot at the mid, resulting in operating at two bands (2.45 GHz and 5.2 GHz). Truncated Arc and partial ground structures were added to improve the Bandwidth and reflection coefficient. A gain of 2.5dBi and 4.63dBi were obtained with a radiation efficiency of 98.5% and 95%. The designed antenna was suitable for Wireless Body Area Networks due to its semi-flexible nature.

An Inset-Fed Microstrip Patch antenna designed on an RT/Duroid 5880 substrate (ε_r =2.2) operating at 3.5GHz [3]. The antenna shows a good radiation efficiency of 89.56% with a -13.772dB reflection coefficient.

T-shaped feeding acting as a stepped impedance structure is used with a circular-shaped patch operating at a frequency of 3.2GHz and is designed for harmonic suppression [4]. Two arms were included parallel to the T-shaped feeding structure. The gain of 7.5dBi is realized with an improvement in the Bandwidth. The antenna's performance shows its ability to work in integrated wireless communication due to its compact size, harmonic suppression, Null radiation at out-band and Wider bandwidth.

In this work, a circularly polarised patch antenna was designed using slots and coupled strips to widen the 3-dB Axial Ratio Beam Width (ARBW) [5]. The measured values of the S11 matched adequately with the computer-simulated values, which were less than -10dB between 2.36 GHz and 2.48 GHz. The simulated and measured ARBW values were 241o and 244o respectively. The antenna can be used in wireless applications at high-elevation angles.

The tri-polarized microstrip patch antenna operating at 2.65GHz is proposed [6]. The Left-Hand Circular Polarisation (LHCP) was obtained by incorporating the slots with the excitation of the set of radiative modes on a single patch. Shorting vias were used to mitigate or suppress the unwanted modes at the patch's edges. In the same way, with the help of slots and shoring, vias Right Hand Circular Polarization (RHCP) and Linear polarisations were achieved on a quarter and Half patch. Finally, all the individual patches were fabricated on a single structure by maintaining an isolation greater than 20 dB.

Microstrip Patch antennas operating at 2.4GHz with different structures consisting of a single layer, Double layer of substrate, diagonally slotted and corner slotted sections were designed [7]. The FR4 Epoxy material as a substrate having a height of 1.5mm and ε_r =4.4 has been used for the design. The gain of the single, double layer, diagonally slotted, corner slotted designs vary between 0.16dBi to 1.38dBi, with the bandwidth varying between 80 MHz and 120 MHz. The results emphasize that the diagonally slotted Microstrip Patch Antenna (MSPA) provides a better reflection coefficient than the other structures.

The MSPA, using three different substrates with dielectric constants of 4.3 (FR4), 2.2 (RT-5880), and 3 (TLC-30), were designed [8]. Also, the thicknesses of all the substrates used differed, with the values 1.6, 1.575mm and 1.58mm, respectively. The findings of the work show that the variations in dielectric constant height (thickness) of substrates greatly impact the antenna gain and bandwidth. The TLC-30 gives better radiation efficiencies when compared to the other two substrates used in the design. The Direct Fed MSPA is implemented on an FR4 substrate (ε_r =4.4) with a height of 1mm in the LED3 simulator [9]. The ground plane has H-shaped metal with two slots.

The Ultra-Wide Band (UWB) microstrip patch antenna was implemented over an FR4 substrate of ε_r =4.4 using a simulator CST microwave studio [10]. The initial design of the antenna was resonating at 6.7GHz. The variations in the shape of the ground plane due to the introduction of slots resulted in improved bandwidth up to 5.7GHz. Due to wide bandwidth, the single antenna covers WiFi, WiMAX, Bluetooth, and WLAN applications.

The Direct Fed MSPA is designed at 1.176GHz on a FR4 Substrate (ε_r =2.33). The IE3D simulator was used. The 0.021 GHz bandwidth and 6.3 dBi of gain were observed from the results. The return loss was found to be -29.752dB [11].

The Inset Fed MSPA is designed at 2.4GHz with a 4.4 dielectric constant material such as FR4. The Patch width is varied to get the different bandwidths [12].

The Direct Fed MSPA, along with an H-shaped slot on the patch, was proposed using different substrates at a frequency of 2.4GHz. The analysis of the results shows that the antenna with FR4 substrate gives a significant return loss of -23.68dB [13].

This inset fed MSPA operating at 3.5GHz is designed using an RT Duriod substrate (εr=4.3) with 0.1mm thickness [14]. The structure was simulated in ANSYS HFSS, and the result shows a return loss of -19.89dB, directivity of 6.7 dBi, VSWR of 1.22, and a bandwidth of 128.9 MHz.

An Inset-Fed MSPA with a T-shaped slot on the radiating patch operating at 948MHz was proposed in the paper [15]. The antenna consumes low power; hence, it applies to UAV communications. The structure was designed using a Rogers RO 4003C substrate (ε_r =3.55). The return loss of the antenna was found to be -28.6 dB with a gain of 5.3dBi. The study reveals that introducing insets and slots enhanced the gain from 2 dBi to 5.3 dBi.

The coaxial-fed stacked MSPA was implemented on an FR4 dielectric substrate for GPS and WiFi applications. The upper and lower patches operated at 1.227 GHz and 2.4 GHz, respectively. The performance of the stacked patch antenna was correlated to the conventional single-patch antenna. The experimented antenna shows a better result of -15 dB/-24.8dB (S11), 1.49/2 (VSWR) and 50MHz of bandwidth at 1.227 GHz and 2.4 GHz respectively [16].

A Direct-fed MSPA operating at 4GHz is designed by varying the substrates' thickness and dielectric constant. The study takes three different substrates such as RT Duroid 5870 (ε_r = 2.33), Neltec NY9320 (ε_r = 3.2) and FR4_epoxy (ε_r = 4.4). The substrates' thickness varied, and the performance parameters were analysed [18]. The analysis shows that the increase in the thickness decreases the gain and directivity with the increase in bandwidth.

An Inset fed MSPA designed on an FR4 substrate with εr =4.3 with a thickness of 1.5mm using a CST microwave studio simulator operating at 2.25 GHz [18].

An Inset fed MSPA operating at 3.5GHz designed on FR4 substrate (εr =4.4) for Sub-6GHz 5G applications [19]. This paper's study reveals that a T-shaped slot on the patch top and the half ground plane increased the antenna performance, particularly S11 and VSWR.

A UWB MSPA with a staircase of structure and rectangular slot in the patch was proposed in [20]. The slot improved the antenna bandwidth (3.1 GHz- 16.7 GHz).

A rectangular MSPA operating at 3.5 GHz was designed using a FR4 substrate (εr =4.4, h=1.6mm). The antenna's bandwidth was enhanced by increasing the height of the substrate. The Designed antenna gives a very good return loss, Bandwidth, and gain of -43.52 dB, 2.3 GHz, and 2.646 dBi [21].

From the literature, it is observed that most of the research work concentrated on implementing the microstrip patch antennas to improvise any of the performance parameters (better gain, VSWR, S11, Bandwidth, multi-band, and wide-band operation etc) with the variations in the shape of the patch as triangular, flag, circular etc, introducing the slots/slits on the radiating patch, defected ground structures, feeding techniques (Coaxial, Aperture coupled, Direct etc.) and substrate materials. Currently, researchers are concentrating on bandwidth, gain enhancement, and incorporating Machine learning techniques, MIMO, particularly in MSPAs for 5G related applications. The proposed work focuses on improving the performance of microstrip patch antennas by combining the variations in substrate and feeding mechanisms by keeping the constant length, the width of the substrate and ground plane for the lower band of 5G implementations. Two substrates and three feeding techniques are used to implement the MSPAs at a frequency of 3.7GHz.

Table 1. Substrate parameters

Substrate	FR4	Rogers RT/duroid 5880
Dielectric Constant (ε_r)	4.4	2.2
Height (mm)	1.6	1.6
Loss Tangent	0.02	0.0009

3. Proposed Antenna Design

The MSPA design primarily depends on key parameters such as operating frequency, Dielectric constant (ε_r) and substrate height (h). These three parameters will be used to determine the length and width of the patch. The proposed design takes a constant length, the width of the substrate, and the ground plane with the value 60mm*60mm to implement an antenna using three different feeding techniques (Direct Feed, Inset Feed, and Quarter wave Feed). The antennas were designed considering two commercially available dielectric substrates, FR4 Epoxy and Rogers RT/duroid 5880. The details of the substrate parameters are listed in Table 1. Equations (1) to (7) will be used to find the various dimensions of the Direct fed Microstrip patch antenna. In addition to the first seven equations, equation (8) is used for finding the inset depth from the edge of the patch for inset fed microstrip patch antenna and equations (9) and (10) for finding the impedance of the quarter wave transformer in Quarter wave fed antenna. Table 2 details the Quarter wave Feed line's Inset Depth and Characteristic impedance. Figure 2 shows the general structure of the Direct, Inset and Quarter wave fed microstrip patch antennas. The flow chart representing the design process of the proposed microstrip antennas is shown in Figure 1. The simulation set-up consists of setting a radiation boundary(100mm*100mm*40mm) to capture maximum antenna far field radiations with air as a material. An adaptive mesh with a maximum of 20 passes obtained good convergence. Lumped port excitation is provided with an input impedance of 50 Ohms. The frequency sweep is taken from 2.5GHz to 4.5GHz with a step size 10MHz. PEC is assigned to the Patch, Feed, and Ground Plane, whereas dielectric material is assigned to the substrate.

The equation governs the width of the microstrip patch (1) as

$$W = \frac{C}{2f_r}\sqrt{\frac{2}{\varepsilon_r+1}} \tag{1}$$

Where C- Free space light velocity, ε_r – Substrate's Dielectric constant, fr -resonant frequency or Operating frequency.

The patch length can be calculated by equation (2) as

$$L = L_{eff} - 2\Delta L \tag{2}$$

Leff- Patch's effective length, given by equation (3)

$$L_{eff} = \frac{c}{2f_r\sqrt{\varepsilon_{eff}}} \tag{3}$$

Ɛeff – Substrate Effective dielectric constant given by the equation (4)

$$\varepsilon_{eff} = \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{2}\frac{1}{\sqrt{1+\frac{12h}{W}}} \tag{4}$$

h – substrate thickness, w – Patch width.

$$\frac{\Delta L}{h} = 0.412\,\frac{(\varepsilon_{eff}+0.8)}{(\varepsilon_{eff}-0.258)}\frac{(\frac{W}{h}+0.264)}{(\frac{W}{h}+0.8)} \tag{5}$$

Ground plane length and width were calculated using the equations (6) and (7).

$$L_{g=}L + 6h \tag{6}$$

$$W_g = W + 6h \tag{7}$$

Lg- Ground plane length, Wg - Ground plane width.

$$Z_{in}\,(y=0) = Z_{in}\,(y_0)\,\mathrm{COS}^2\left(\frac{\pi y_0}{L}\right) \tag{8}$$

Where $Z_{in\,(y=0)}$ is the input impedance of the patch at the edge, $Z_{in\,(y=y_0)}$ is the expected input impedance (50 ohms), and L is the Patch length.

Quarter wave Transformer Length and Width can be calculated by investigating the Characteristic impedance of the transformer for the corresponding Edge impedances of the Patch.

$$Z_{in} = \frac{Z_0^2}{Z_L} \tag{9}$$

Zin is the Patch's edge impedance, Z_L is the feedline impedance (50 ohms), and Z_0 is the characteristic impedance of a quarter wave transformer.

$$Z_0 = \sqrt{Z_{in} * Z_L} \tag{10}$$

The patch and feed line length and width parameters are calculated using the corresponding equations from equations (1) to (10). The calculated and optimized values were tabulated in Table 3. The optimization of direct fed microstrip patch antenna involves varying the Patch length and width by keeping the feed width constant in the proposed design.

Variations of inset depth and width, along with the patch length and width, were done in the case of the inset feeding mechanism. The alterations with the width of the quarter wave transformer, as well as the length and width of the patch, resulted in the optimum values of the performance parameters.

Table 2. Inset depth and characteristic impedance of Quarter wave feed line

Substrate	FR4	Rogers RT/duroid 5880
Dielectric Constant	4.4	2.2
Edge Impedance of the Patch (Z_{in})	243 ohms	144 ohms
Inset Depth (y_0)	6.609 mm	7.929394 mm
Characteristic impedance of Quarter wave Feed line (Z_0)	110.23 ohms	80.85 ohms

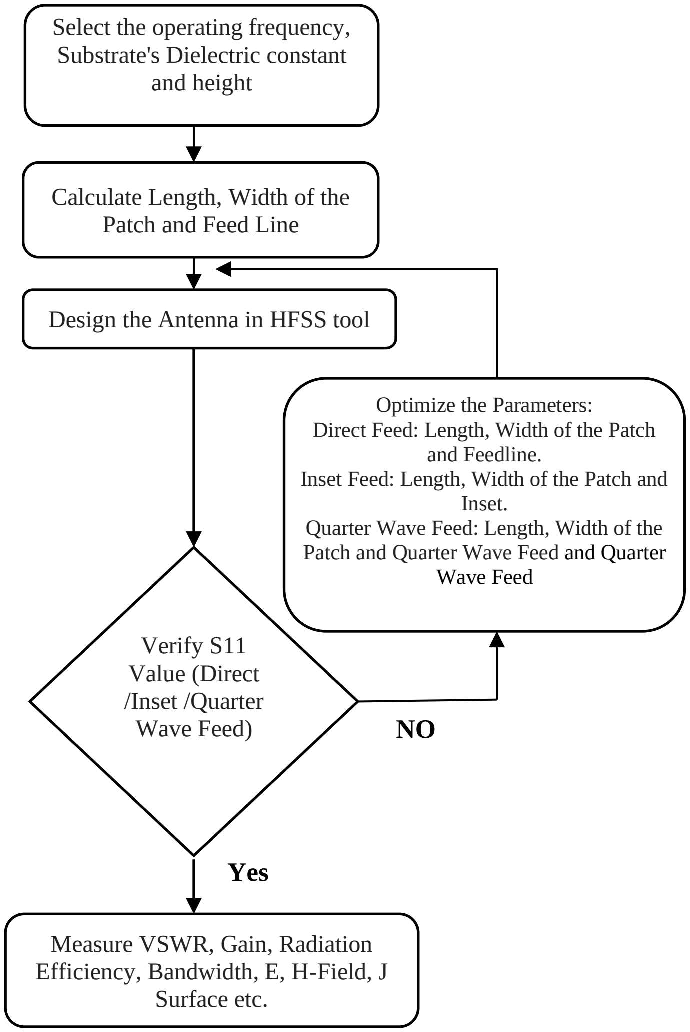


Fig. 1 Design process of proposed microstrip patch antennas

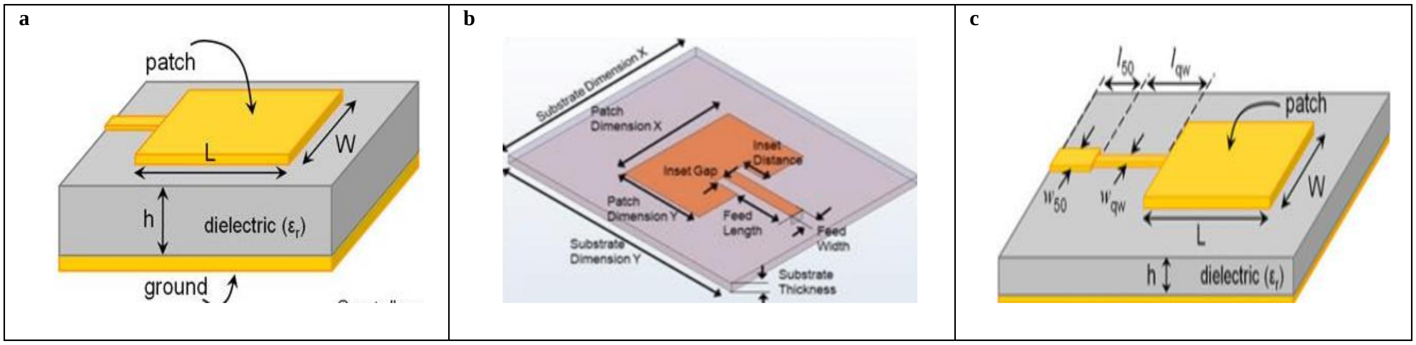


Fig. 2 General structure of Microstrip patch antennas: a. Direct Fed b. Inset Fed c. Quarter wave fed

The parametric variations of the design show that the patch width is increased to achieve the perfect resonance at the operating frequency with the equal length and width of the substrate and ground plane. In contrast, the length is decreased for both FR4 and RT Duroid substrates. The analysis shows that the Inset Width and depth of the antenna are decreased for the structure designed using the high dielectric constant substrate to get the proper impedance matching. Meanwhile, the depth and width of the inset are increased for the antenna structure made of a low dielectric constant substrate to get good impedance matching.

Table 3. Proposed microstrip patch antenna calculated and optimized values for Direct, Inset and Quarter wave Feeding using FR4 and RT Duroid Substrates

Substrate		**FR4**		**RT Duroid**	
Feeding Technique	**Parameters**	**Calculated Value (mm)**	**Optimized Value (mm)**	**Calculated Value (mm)**	**Optimized Value (mm)**
Direct Feed	Patch Length	18.8692	18.25	26.4691	25.3
	Patch Width	24.67218	35	32.05	32.25
	Feed Length	22.215	11	29.6366	17.5
	Feed Width	3.058	3.058	4.9298	1.2
Inset Feed	Patch Length	18.8692	18.82	26.4691	26.45
	Patch Width	24.67218	24.67218	32.05	32.5
	Feed Length	28	26.29	26	26
	Feed Width	3.058	3.058	4.9298	4.9298
	Inset Depth	6.609	5.7	7.929394	8.31
	Inset Width	6	5.5	7	7.9
Quarter Wave Feed	Patch Length	18.8692	18.03	26.4691	25.525
	Patch Width	24.67218	24.67218	32.05	32.1
	Feed Length	11.1076	11.1076	14.82	14.82
	Feed Width	3.058	3.058	4.9298	4.93
	QW Length	11.7426	13.3924	15.14	15.93
	QW Width	0.5345	1	2.215	1.15

4. Results and Discussion

The single microstrip patch antenna performance parameters such as return loss (S11), VSWR, Gain, Bandwidth, Radiation efficiency, Radiation Pattern, E-field, H-field, and Surface current density (Jsurf) were analysed individually for the different substrates using HFSS.

Return Loss (S11): S11 is the measure of power reflected compared to the input power. The typical value of the S11 for the antenna applications is -10dB and less. S11 of -10 dB indicates 90 percent of the power has been transmitted from the antenna, and only 10 percent is reflected.

VSWR: VSWR is the measure of impedance matching. The minimum value of the VSWR is 1, and the maximum value will be ꝏ. For the antenna, the VSWR value should be less than 2.

Gain: It measures the antenna’s capacity to drive the energy in the desired direction. It is measured by considering an isotropic antenna as a reference.

Bandwidth: It measures frequency range with S11 less than -10dB.

Radiation Efficiency: This signifies the ability of an antenna to convert the supplied input power into electromagnetic signals. Mathematically, it is the ratio of radiated to the total input power.

Radiation Pattern: Pictorial way of representing the antenna’s radiation concerning directions.

E-Filed, H-Field and Surface Current Density: The measure of current flow on the antenna surface per unit length. The E, H-field and Jsurf form the resonance.

Table 4. Performance parameters of MSPA with different feeding techniques on FR4 and RT duroid substrates

Feeding Technique	**Direct Feed**		**Inset Feed**		**Quarter Wave Feed**	
Substrate	**FR4**	**RT Duroid**	**FR4**	**RT Duroid**	**FR4**	**RT Duroid**
S11 (dB)	-21.2316	-22.27	-32.1485	-29.2056	-22.9989	-21.444
VSWR	1.1901	1.1677	1.0506	1.0718	1.1524	1.1850
Gain(dBi)	4.72	8.08	4.30	8.05	4.33	8.10
Bandwidth (MHz)	213	80.8	108	71.9	111.2	67.4
Radiation Efficiency (%)	65.06	98.62	50.84	98.31	51.50	98.39
Impedance (ohms)	1.050+0.1749i	0.8597+0.0319i	1.0493+0.0115i	0.9464+0.0409i	1.0634-0.1320i	1.1369+0.1188i

4.1. Analysis of the Performance Parameters of Designed MSPAs with Substrate as a Key Parameter

Table 4 shows the various performance parameters of the designed microstrip patch antennas with different feeding techniques on FR4 and RT Duroid substrates with the dielectric constants 4.4 and 2.2, respectively.

The parameters, as tabulated in Table 4, signify that, over a constant length of the substrate and the ground of the antenna, the design using an RT Duroid substrate gives a relatively better reflection coefficient for direct feed, whereas FR4 substrates perform comparatively well to the inset and quarter wave feeds. A VSWR value of less than 2 is considered significant for practical antenna applications, resulting in better radiation and minimum reflection.

The FR4 substrate gives a better VSWR value of 1.0506 for the Inset feed, but RT Duroid performs well for direct, quarter-wave feeds. Irrespective of the feeding techniques, the RT Duroid substrate antennas give an excellent gain, radiation efficiencies of above 8 dBi and 98.3 percent due to the dielectric properties of the substrate, such as low tangent loss, quick movement of the electromagnetic waves in the lower dielectric constant materials resulting in less confinement.

The surface waves in the high dielectric constant material produce less radiation, affecting the antenna's gain. For all these reasons, from the results, we can observe that the gain of the RT Duroid substrate antennas is 4dBi higher than the FR4 antennas. The MSPAs designed over an RT Duroid substrate, irrespective of the feed provided, are suitable for 5G applications in Industrial IoT, Remote Surveillance, Tracking and Navigation, Fleet management, etc., where gain and efficiency are critical parameters at the cost of increased size of the patch, moderate bandwidth.

The design also proves the material property of the low dielectric constant, tangent loss substrates. In contrast to the RT Duroid MSPAs, The MSPAs designed on FR4 substrate give comparatively 35MHz more bandwidth at the cost of reduced gain and efficiency due to their material properties, such as dielectric constant and loss tangents affecting the quality factor. The high dielectric constant substrates lead to low-quality factors, resulting in wider bandwidths and vice-versa. The experiment shows that antennas designed using FR4 as a substrate provide better bandwidth than those implemented using RT-Duroid substrates, irrespective of the feeding techniques.

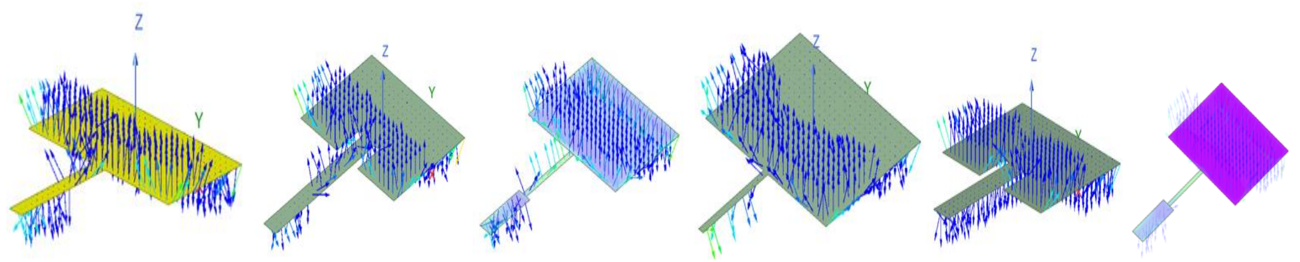
The experiment also implies that for bandwidth-critical 5G applications such as Live streaming, Industrial Automation, Augmented and virtual reality, remote surgery, etc. FR4 as a substrate is better for the antenna design than the RT Duroid. The real part of the impedance values is between 0.85 and 1.05. This signifies that the value of the real part is very close to 1, and the designed antennas are well matched with the characteristic impedance, thus resulting in better radiation from the antenna with minimal reflections on the source.

The imaginary part of the impedance is almost close to 0 with a minimum value of -0.1320i and a maximum of +0.1749i. The positive and negative values in the imaginary part indicate inductive and capacitive reactance.

4.2. Analysis of the Performance Parameters of Designed MSPAs with Feeding Technique as a Key Parameter

The microstrip antennas were designed using three different feeding techniques: Direct, Inset and Quarter wave feed. Table 4 shows that very good impedance matching of -32.1485 dB and -29.2056 dB was obtained for the inset feed microstrip patch antennas using FR4 and RT Duroid substrates compared to the other two. The inset feed results prove that the inset depth is moved to the 50 ohm point on the patch to obtain better matching.

In Direct feed, the 50-ohm feedline is directly connected to the edge of the patch, which has a higher impedance, resulting in difficulty in matching. The variations in the length of the quarter wave transformer lead to less accurate impedance matching. Due to this, the results of S11 for the direct fed and quarter wave microstrip patch antennas are not as good as the inset feed. The simulated results are shown in the Figures 3-7. The performance comparison of the various works with the present work is tabulated in Tables 5 and 6.



(a) **(b)** **(c)** **(d)** **(e)** **(f)**

Fig. 3 Electric Field Distributions at 3.7GHz (3a,3b,3c – for FR4 substrate, 3d,3e,3f – for RT Duroid substrate

Table 5. Comparison of various works with the proposed work on FR4 (4.4)

Technique used	Operating Frequency (GHz)	Return Loss (S11 in dB)	Gain (dBi)	Bandwidth (GHz)	Radiation Efficiency (%)	Antenna Size (mm^3)
Patch antenna with Parallel strips and slots **[5]**	2.42	<-10	3.42	0.12	60	60 × 60 × 1.575
Microstrip Patch with variation in substrate layers and positions of slots. **[7]**	2.4	-29.61	0.16	0.08	-	47×38.18×1.5
Inset Fed MSPA **[12]**	3.64-10.52	-20.211	3.04	6.68	-	80*60*1.6
Coaxial Fed stacked Dual-Band MSPA **[16]**	1.227/2.4	-15 /-24.8	4.22/2.39	0.05/0.09	-	85*85*1.6
Inset fed MSPA with T-Slot and half Ground Plane **[19]**	3.5	-38	3.4	0.15	-	37*37*1.6
Constant Length, Width of Substrate and Ground plane with direct, inset and quarter wave feeds. **[This Work]**	3.7	-21.2316/ -32.1485/ -22.9989	4.72/ 4.30/ 4.33	0.213/ 0.108/ 0.112	65.06/ 50.84/ 51.50	60*60*1.6

Table 6. Comparison of various works with the proposed work on Rogers RT5880 (2.2)

Technique used	Operating Frequency (GHz)	Return Loss (S11 in dB)	Gain (dBi)	Bandwidth (GHz)	Radiation Efficiency (%)	Antenna Size (mm^3)
Partial Ground along with Rectangular Slots [1]	2.48	-32.21	2.5	0.5	93	34 x 22 x 0.8
Circular Patch with a Star Slot in the middle [2]	2.45/5.2	-24/-21	2.5/4.63	1.396/2.02	98.5/95	47×30 × 0.787
Inset Fed MSPA [3]	3.5	-13.772	7.55	0.0236	89.56	100×100×0.077
Circular Patch with T Shaped feeding [4]	2.55	<-10	7.5	0.26	-	62 × 60 × 6.1
Inset Fed MSPA [14]	3.5	-19.89	-	0.1289	-	50*50*0.1
Constant Length, Width of Substrate and Ground plane with direct, inset and quarter wave feeds. **[This Work]**	3.7	-22.27/ -29.2056 / -21.444	8.08/ 8.05/ 8.10	0.0808/ 0.0719/ 0.0674	98.62/ 98.31/ 98.39	60*60*1.6

The antenna deployed in practical applications requires a minimum S11 of -10 dB and a VSWR of less than 2. The S11 values were less than -20dB, and the VSWR values were closer to the ideal value of 1 in all the implementations, more specifically, less than 1.2. The proposed MSPA implementations are compact when compared to the designs in [3],[4],[12],[16]. The feeding techniques directly impact the E-field distribution in the MSPAs. Figure 3 shows better electric field distribution in the inset, quarter wave than the direct feed. The inset feed design shows a better result regarding S11 and VSWR over a constant length, substrate width, and ground plane. Quarter feed gives an almost equal performance to Inset feed, but the design is complex. Even though the design is simple, achieving a proper impedance matching to reduce the spurious radiations is a challenge in Direct feed.

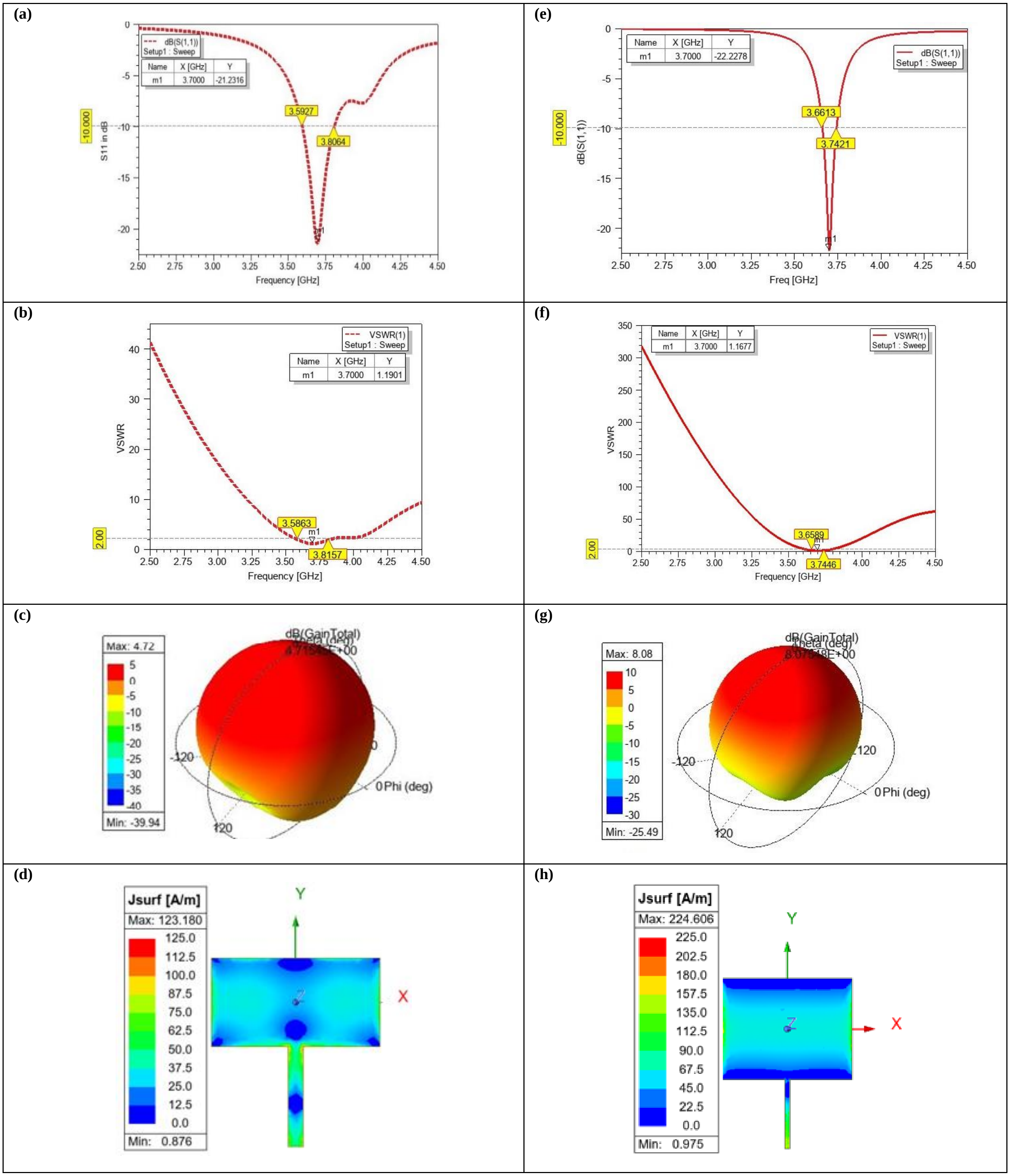


Fig. 4 Simulated results of the antenna designed on FR4 (left column) and RT Duroid (right Column) Substrates with Direct Feed. (Fig.4a,4e- Plot of S11 versus frequency, Fig.4b,4f- Plot of VSWR versus frequency, Fig. 4c,4g – 3D plot of Gain, Fig. 4d,4h- Surface Current Distribution)

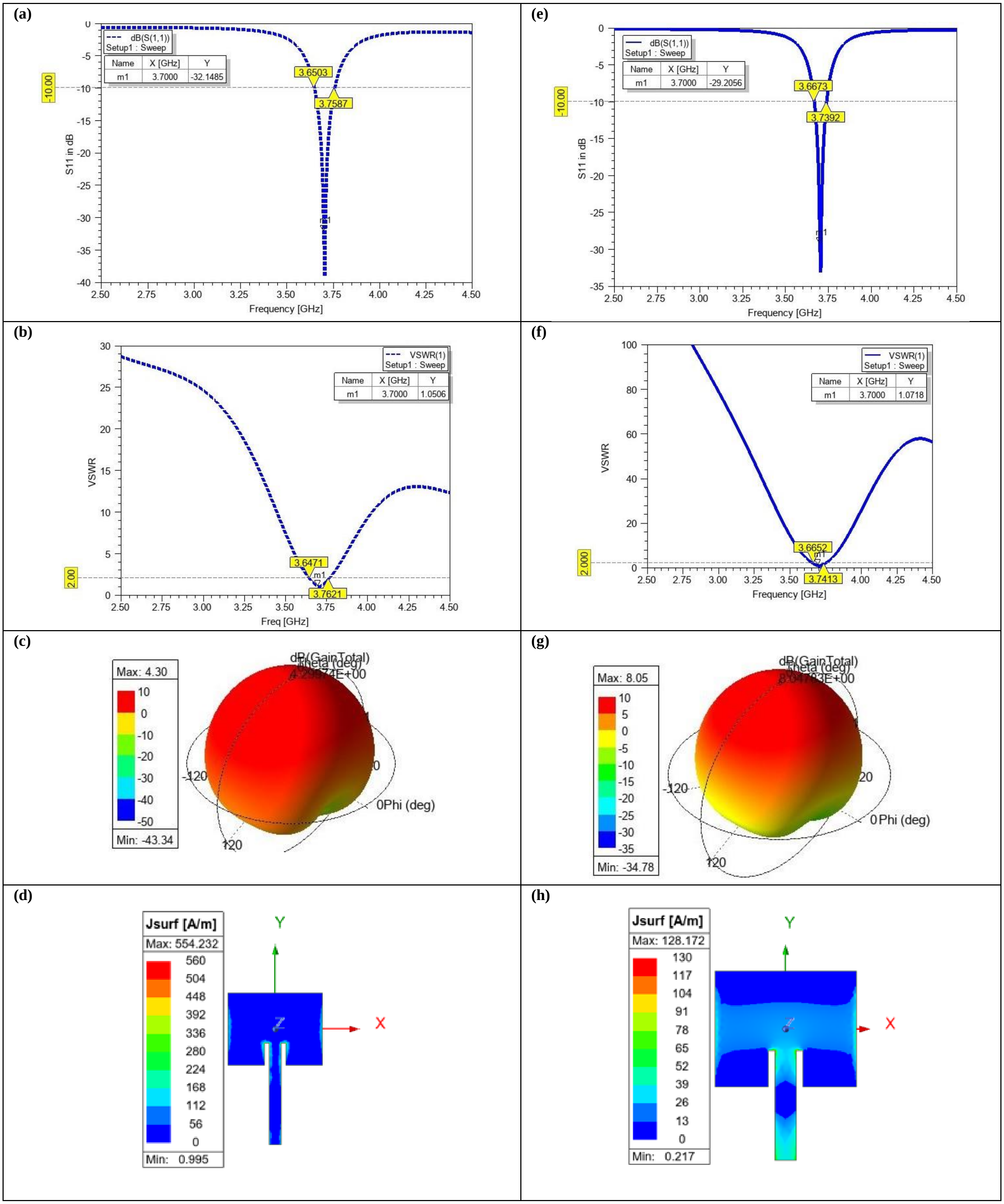


Fig. 5 Simulated results of the antenna designed on FR4 (left column) and RT Duroid (right Column) Substrates with Inset Feed.
(Fig. 5a,5e- Plot of S11 versus frequency, Fig. 5b,5f- Plot of VSWR versus frequency, Fig. 5c,5g – 3D plot of Gain, Fig. 5d,5h- Surface Current Distribution)

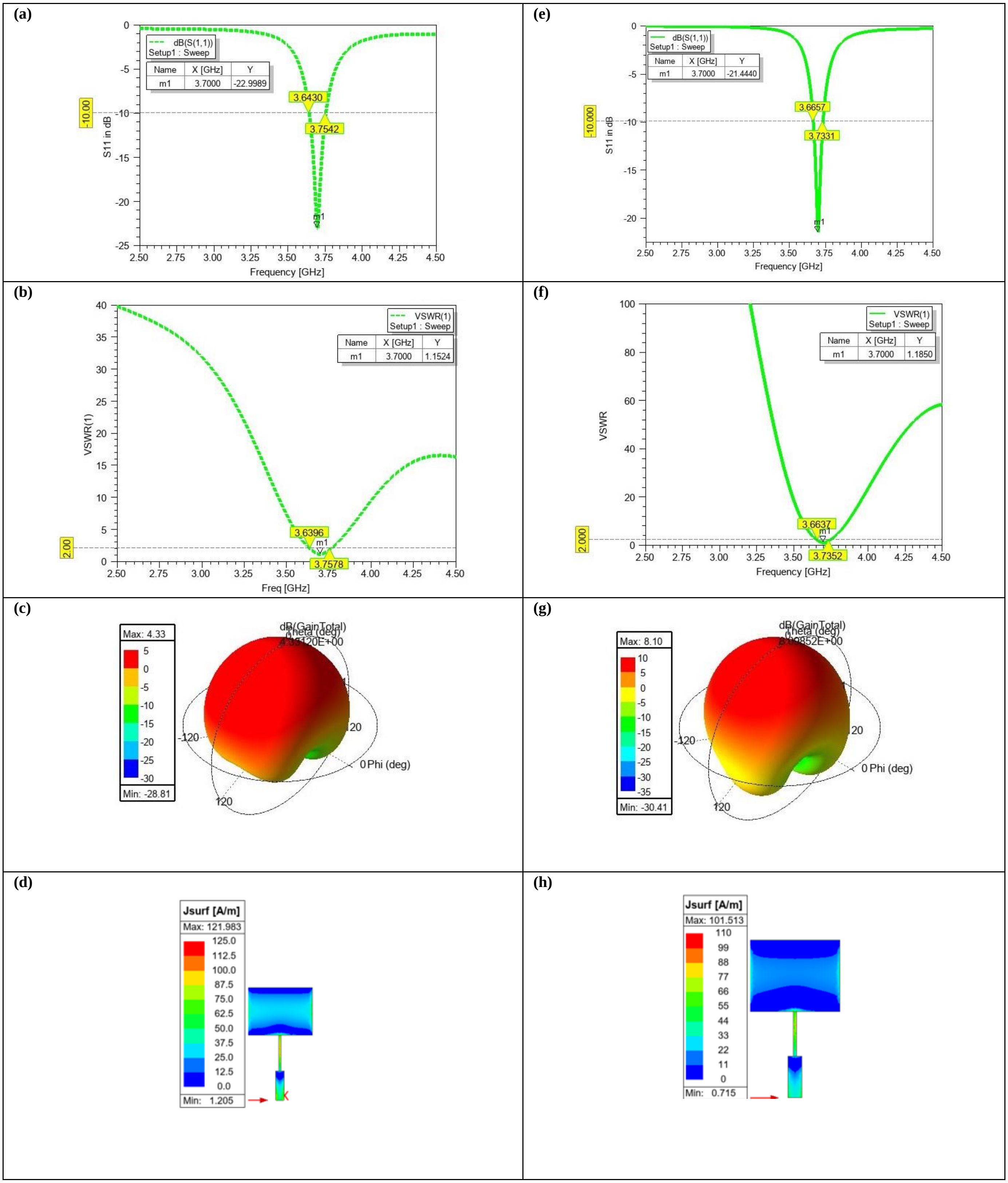


Fig. 6 Simulated results of the antenna designed on FR4 (left column) and RT Duroid (right Column) Substrates with Quarter wave Feed. (Fig.6a,6e- Plot of S11 versus frequency, Fig.6b,6f- Plot of VSWR versus frequency, Fig.6c,6g – 3D plot of Gain, Fig.6d,6h- Surface Current Distribution).

5. Conclusion

In this paper, microstrip patch antennas were designed with a constant length, substrate width, and ground plane on FR4, RT-Duroid substrates using Direct, Inset and Quarter wave feeding techniques at a frequency of 3.7 GHz. The structure of the antennas was analysed using an HFSS simulator. The study reveals that the antennas designed with a low loss RT-Duroid substrate provide better gain and efficiency than the FR4 substrate with a narrow bandwidth. It was also found that a high dielectric constant substrate is preferred for a bandwidth-critical application. In contrast, low loss substrates must be preferred for applications concentrating on Gain and Efficiency. A minimum of 35 MHz more bandwidth has been obtained for the antennas designed over a FR4 substrate with gains of 4.72 dBi,4.3 dBi, and 4.33 dBi. The better Gains of 8.08 dBi, 8.05 dBi, 8.10 dBi and Radiation efficiencies of 98.62%, 98.31%, and 98.33% were achieved on a low loss RT-Duroid substrate. The S11 values of -21.2316 dB, -32.1585 dB, -22.9989 dB and, -22.27 dB, -29.2056 dB, -21.45 dB were obtained, respectively, for the Direct, Inset, Quarter wave feeds on FR4 and RT-Duroid substrates. The VSWR values 1.0506 and 1.0718 obtained for the inset feed antennas signify that inset feed is a better choice for excellent impedance matching than the direct, quarter wave feeds over a constant length, substrate width, and ground plane. The designed MSPAs that provide better gain, efficiencies and moderate bandwidth can be used in 5G applications such as Industrial IoT, Remote Surveillance, Tracking and Navigation, Fleet management, etc. The MSPAs with moderate gain, efficiency, and good bandwidth can be accommodated in live streaming, industrial automation, augmented and virtual reality, remote surgery, etc.

Future Scope

The proposed methodology can be extended to the design of 2*2 and 4*4 MIMO antennas to improve the performance parameters further to meet the demand of users in terms of high data rate, low latency, wide bandwidth, etc, in 5G applications. Also, the proposed implementations can be experimented with by employing slots/slits, defects in the ground, meta surface, etc., to obtain the multi-band and wide-band characteristics and better gain that leads to accommodating multiple 5G applications in a single structure. The researchers can also work on incorporating machine learning algorithms to analyse the characteristics of MSPAs with the feed and substrate variations over a constant length and width of a ground substrate.

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