

# Design and Substrate Analysis of Pentagonal Microstrip Patch Antenna

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**Abstract**— The design and substrate analysis of a pentagonal microstrip patch antenna for wireless communication and multi-band Internet of Things applications are presented in this work. In order to examine the impact of substrate permittivity on resonant frequency, return loss, VSWR, and gain, the proposed antenna is constructed and simulated using CST Studio Suite and assessed across three dielectric substrate materials: FR4 ( $\epsilon_r = 4.3$ ), RT Duroid ( $\epsilon_r = 2.2$ ), and PTFE ( $\epsilon_r = 2.1$ ). With a gain of 4.130 dBi, a VSWR of 1.351, and a return loss of  $-16.518$  dB, the FR4 substrate generates a resonant frequency of 5.00 GHz. With a gain of 7.957 dBi, a VSWR of 1.506, and a return loss of  $-13.886$  dB, the RT Duroid substrate resonates at 6.859 GHz. With return losses of  $-13.844$  dB and  $-16.395$  dB, VSWRs of 1.356 and 1.509, and gains of 8.122 dBi and 6.926 dBi, respectively, the PTFE substrate displays dual-band behavior at 7.005 GHz and 10.305 GHz. The findings show that while PTFE specifically permits dual-band operation, lower permittivity substrates raise the resonance frequency and enhance gain performance. The suggested pentagonal patch antenna shows potential for C-band and X-band wireless and Internet of Things applications and achieves high impedance matching across all substrates.

**Index Terms**— Pentagonal microstrip patch antenna, FR4, RT Duroid, PTFE, Internet of Things, CST Studio Suite, return loss, and VSWR are among the index terms.

## I. INTRODUCTION

As the link between electronic circuitry and the propagation of electromagnetic waves in free space, antennas are essential parts of contemporary wireless communication systems. By transforming electrical energy into electromagnetic radiation and vice versa, they allow radio frequency signals can be transmitted and received. Antennas are extensively used in a variety of technologies, such as satellite communication, radar systems, wireless sensor networks, IoT infrastructure, and mobile communication networks, due to this crucial function. The electrical properties of an antenna, including resonant frequency, bandwidth, gain, radiation pattern, and impedance matching, have a significant impact on the performance of any wireless system. Compact, lightweight, multi-band antennas that can stably operate across many frequency ranges simultaneously are in high demand due to the increasing growth of Internet of Things (IoT) devices and next-generation wireless systems. Antennas for these systems must be able to handle a variety of wireless protocols, take up little physical area, and have consistent radiation properties. Researchers have been actively exploring new antenna shapes and substrate compositions that can offer enhanced multi-band performance while preserving design simplicity and fabrication viability in order to satisfy this demand.

Due to their well-known benefits of low profile, light weight, ease of fabrication, and direct compatibility with printed circuit board technology, microstrip patch antennas have become one of the most popular solutions among the different antenna configurations examined in the literature. These antennas are very appealing for Internet of Things devices, wireless communication systems, and portable electronic applications since they are easily integrated with wireless modules and microwave circuits. Conventional rectangular microstrip patch antennas are limited to single-frequency operation and are intrinsically narrowband, notwithstanding their benefits. Researchers have suggested a number of methods to get around these restrictions, such as using slots, fractal structures, modified patch geometry, and different substrate materials. When

developing microstrip patch antennas, substrate material selection is a crucial design factor. The resonant frequency, radiation bandwidth, gain, and total antenna efficiency are all directly impacted by the substrate's dielectric constant and loss tangent. Higher permittivity substrates typically result in narrower bandwidth and lower gain, but they also tend to minimize the antenna's physical dimensions. On the other hand, low-permittivity substrates provide increased gain, improved radiation efficiency, and multi-band functioning in specific geometries. The published literature still lacks a thorough comparative analysis specifically for pentagonal microstrip patch designs targeting multi-band IoT frequencies, despite the availability of many substrate materials.

In order to close that gap, the design and thorough substrate analysis of a pentagonal microstrip patch antenna simulated in CST Studio Suite are presented in this study. Three substrate materials are assessed: PTFE ( $\epsilon_r = 2.1$ ), RT Duroid ( $\epsilon_r = 2.2$ ), and FR4 ( $\epsilon_r = 4.3$ ). Return loss (S11), VSWR, resonance frequency, and gain are used to compare performance. One important discovery is that the PTFE substrate is a good option for C-band and X-band multi-band wireless systems because it allows dual-band resonance at 7.005 GHz and 10.305 GHz. The findings offer useful design recommendations for choosing a substrate for developing pentagonal patch antennas for Internet of Things and contemporary wireless applications. This is how the rest of the paper is structured. The antenna design process and geometry are covered in Section II. The simulation results and comparative substrate analysis are shown in Section III. The paper's main conclusions and recommendations for future research are presented in Section IV.

## II. ANTENNA DESIGN METHODOLOGY

### A. Design Equations

Standard transmission line model equations are used in the design of the pentagonal microstrip patch antenna. Equation (1) is used to determine the radiating patch's width:

$$W = \frac{c}{2f_r} \sqrt{\frac{2}{\epsilon_r + 1}}$$

where  $W$  is the patch width,  $c$  is the free-space velocity of light ( $3 \times 10^8$  m/s),  $f_r$  is the resonant frequency, and  $\epsilon_r$  is the substrate dielectric constant.

Equation (2) provides the effective dielectric constant:

$$\epsilon_{r_{eff}} = \frac{\epsilon_r + 1}{2} + \frac{\epsilon_r - 1}{2} \left(1 + \frac{12h}{W}\right)^{-1/2}$$

where  $h$  is the substrate thickness.

Equation (3) provides the longer length caused by fringing fields:

$$\Delta L = 0.412h \frac{(\epsilon_{r_{eff}} + 0.3) \left(\frac{W}{h} + 0.264\right)}{(\epsilon_{r_{eff}} - 0.258) \left(\frac{W}{h} + 0.8\right)}$$

Equation (4) is used to determine the effective patch length:

$$L_{eff} = \frac{c}{2f_r \sqrt{\epsilon_{r_{eff}}}}$$

Equation (5) is then used to determine the actual patch length:

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

### B. Antenna Geometry and Structure

CST Studio Suite electromagnetic simulation software is used to develop and simulate the suggested pentagonal microstrip patch antenna. The antenna is made up of a full ground plane on one face and a pentagonal radiating patch printed on a dielectric substrate. RF power is sent directly to the radiating patch via a conducting strip attached at the base of the pentagonal structure using the microstrip line feed technique. Because of its simplicity, compatibility with planar production techniques, and ease of impedance matching with the typical  $50 \Omega$  feed line, this feeding approach was selected.

The dimensions of the substrate and ground plane are 25.48 mm by 21.48 mm. For comparison investigation, three

substrate materials with uniform thicknesses of 1.6 mm are used separately: FR4 with a dielectric constant of 4.3, RT Duroid with a dielectric constant of 2.2, and PTFE with a dielectric constant of 2.1.

To guarantee excellent electrical conductivity and effective radiation performance, the radiating patch and ground plane are composed of annealed copper with a thickness of 0.035 mm. Compared to traditional rectangular patches, the radiating element's regular pentagonal form lengthens the effective surface current path.

This geometric alteration facilitates multi-band resonance behavior and enhances impedance matching, especially when low-permittivity substrates are employed.

The main radiating dimensions of the structure are defined by the pentagonal patch's top side measuring 11.18 mm and its left side height measuring 11.40 mm.

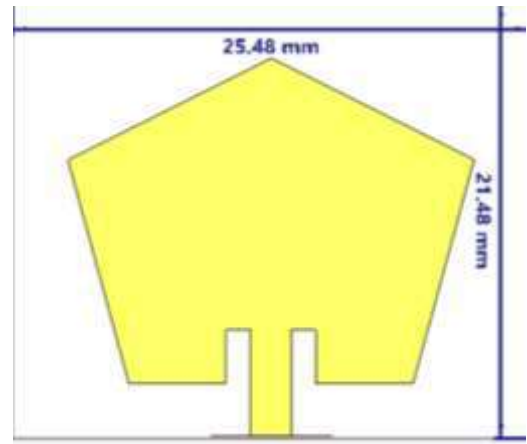


Fig. 2.1. Proposed pentagonal microstrip patch antenna structure in CST Studio Suite

The pentagonal patch's bottom center is where the microstrip feed line is linked. The feed line's 1.95 mm width is intended to provide  $50 \Omega$  characteristic impedance matching. To provide room for the feed line transition, a notch of 1.20 mm in width and 2.60 mm in depth is added at the patch's base. The base offset from the left edge to the notch is 4.80 mm, and the feed line length that extends below the patch is 5.15 mm. Fig. 2.1 depicts the entire antenna structure, whereas Fig. 2.2 shows the annotated geometry with all dimensions.

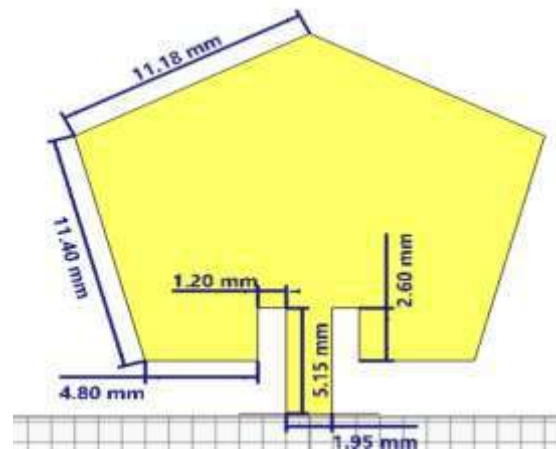


Fig. 2.2 Annotated dimensions of the proposed pentagonal microstrip patch antenna

### C. Parameter Table

TABLE I: Antenna Dimensions

Parameter	Description	Value (mm)
Ws	Substrate width	25.48
Ls	Substrate length	21.48
Pt	Pentagon top side	11.18
Pl	Pentagon left side height	11.40
Wf	Feed line width	1.95
Lf	Feed line length	5.15
Wn	Notch width	1.20
Dn	Notch depth	2.60
h	Substrate thickness	1.6

### III. PERFORMANCE ANALYSIS ON VARIOUS SUBSTRATES

The pentagonal patch's bottom center is where the microstrip feed line is linked. The feed line's 1.95 mm width is intended to provide  $50 \Omega$  characteristic impedance matching. To provide room for the feed line transition, a notch of 1.20 mm in width and 2.60 mm in depth is added at the patch's base. The base offset from the left edge to the notch is 4.80 mm, and the feed line

length that extends below the patch is 5.15 mm. Fig. 2.1 depicts the entire antenna structure, whereas Fig. 2.2 shows the annotated geometry with all dimensions.

**A. Effect on Resonant Frequency**

According to the transmission line model, the square root of the substrate's effective dielectric constant has an inverse relationship with the resonance frequency of a microstrip patch antenna. The resonant frequency gradually rises when the dielectric constant drops from FR4 ( $\epsilon_r = 4.3$ ) to RT Duroid ( $\epsilon_r = 2.2$ ) and then to PTFE ( $\epsilon_r = 2.1$ ). For C-band wireless communication, the FR4 substrate generates a single resonance at 5.00 GHz. The PTFE substrate produces dual-band resonances at 7.005 GHz and 10.305 GHz due to its lowest permittivity, but the RT Duroid substrate pushes the resonance to 6.859 GHz. One unique benefit of the PTFE arrangement is its dual-band behavior, which allows the antenna to function concurrently in the C-band and X-band frequency bands within a single compact construction.

**B. Effect on Return Loss (S11)**

The impedance matching between the antenna and the feed line is measured by the return loss. For practical antenna operation, a return loss value of less than  $-10$  dB is deemed acceptable, meaning that the antenna radiates more than 90% of the input power. All three substrates reach return loss values that meet this requirement, as seen in Table III. Excellent impedance matching is demonstrated by the FR4 substrate's deepest single-band return loss of  $-16.518$  dB at 5.00 GHz. At 6.859 GHz, the RT Duroid substrate registers a return loss of  $-13.886$  dB. The PTFE substrate exhibits consistent impedance matching throughout both bands, achieving return losses of  $-13.844$  dB and  $-16.395$  dB at its two resonance frequencies of 7.005 GHz and 10.305 GHz, respectively.

**C. Effect on VSWR**

The efficiency of power transfer between the transmission line and the antenna is measured by the Voltage Standing Wave Ratio (VSWR), which is directly correlated with the reflection coefficient. The usual criterion for satisfactory antenna performance is a VSWR value less than 2. This criterion is met by the proposed pentagonal antenna's three substrate variants. The FR4 substrate has the best impedance matching of the three, achieving the lowest VSWR of 1.351 at 5.00 GHz. At 6.859 GHz, the RT duroid substrate records a VSWR of 1.507. At its two operational frequencies, the PTFE substrate yields VSWR values of 1.357 and 1.510.

**D. Effect on Gain**

The ability of the antenna to focus radiated power in a particular direction is reflected in antenna gain, a crucial performance metric. The permittivity of the substrate has a major impact on the gain of a microstrip patch antenna; materials with lower permittivity typically support higher gain because of less dielectric losses and increased radiation efficiency. The simulation findings show that the RT Duroid substrate achieves a significantly higher gain of 7.957 dBi at 6.859 GHz, while the FR4 substrate provides the lowest gain of 4.130 dBi at 5.00 GHz. The maximum gain, 8.122 dBi at 7.005 GHz and 6.926 dBi at 10.305 GHz, is produced by the PTFE substrate. The value of employing low-permittivity substrates for high-gain antenna applications is amply demonstrated by the steady increase in gain from FR4 to RT Duroid to PTFE.

**E. Consolidated Parametric Comparison**

The complete performance comparison of the three substrate materials is presented in Table III. The table consolidates all key parameters including resonant frequency, return loss, VSWR, and gain for a direct side-by-side evaluation.

**TABLE III: Performance Comparison of Substrate Materials**

Substrate	$\epsilon_r$	Frequency (GHz)	S11 (dB)	VSWR	Gain (dBi)
FR4	4.3	5.000	-16.518	1.351	4.130
RT Duroid	2.2	6.859	-13.886	1.507	7.957
PTFE	2.1, 2.1	7.005, 10.305	-13.844, -16.395	1.357, 1.510	8.122, 6.926

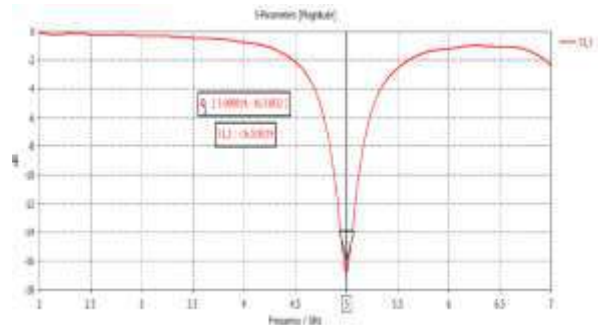
The following important conclusions are derived from the comparison analysis. First, the resonant frequency rises by around 40%, from 5.00 GHz to 7.005 GHz, when the substrate permittivity is reduced from 4.3 to 2.1. Second, the gain improves by around 97%, almost doubling from 4.130 dBi on FR4 to 8.122 dBi on PTFE. Third, the pentagonal patch shape offers strong impedance matching across a variety of dielectric materials, as all substrates retain VSWR values well below 2 and return losses greater than  $-10$  dB. Fourth, and perhaps most importantly, of the three alternatives assessed, the PTFE substrate is the best appropriate for multi-band Internet of Things and wireless communication applications because it allows dual-band operation at 7.005 GHz and 10.305 GHz.

**IV. RESULTS AND DISCUSSION**

For three distinct substrate materials—FR4 ( $\epsilon_r = 4.3$ ), RT Duroid ( $\epsilon_r = 2.2$ ), and PTFE ( $\epsilon_r = 2.1$ )—the simulation results of the suggested pentagonal microstrip patch antenna are shown and examined. The electromagnetic simulation program CST Studio Suite was used for all of the simulations. Return loss (S11), gain, radiation pattern, and voltage standing wave ratio (VSWR) are used to assess the antenna's performance. There is a thorough discussion of how substrate permittivity affects each performance metric.

**A. FR4 Substrate ( $\epsilon_r = 4.3$ )**

**Return Loss (S11):** Fig. 4.1 displays the pentagonal patch antenna's return loss response on the FR4 substrate. The antenna confirms adequate impedance matching between the feed line and the radiating patch by resonating at a frequency of 5.00 GHz with a return loss of  $-16.518$  dB, far below the typical  $-10$  dB threshold. At this frequency, efficient power transfer is shown by the deep and strong resonance.



**Fig.4.1. Simulated S11 response of pentagonal antenna on FR4 substrate (5.00 GHz)**

**VSWR:** Fig. 4.2 illustrates the FR4 substrate antenna's VSWR characteristic. The VSWR is 1.351 at the resonance frequency of 5.00 GHz, which is significantly less than the permissible limit of 2. This low VSWR value attests to effective power

radiation and little reflection at the antenna port. As a result, the antenna meets the impedance matching specifications needed for realistic wireless system integration.

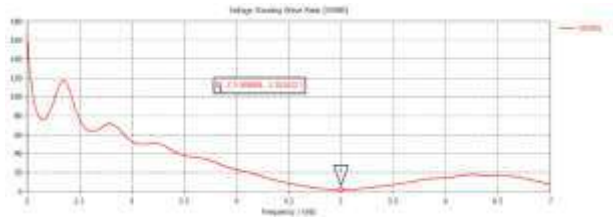


Fig.4.2. Simulated VSZR of pentagonal antenna on FR4 substrate (5.00 GHz)

**Radiation Pattern and Gain:** Fig. 4.3 displays the FR4 antenna's three-dimensional far-field gain pattern at 5.00 GHz. With the highest gain oriented along the positive z-axis, the radiation pattern displays a broadside radiation feature. With a radiation efficiency of  $-2.057$  dB and a total efficiency of  $-2.155$  dB, the antenna attains a peak gain of 4.130 dBi. The greatest radiation direction is represented by the red area in the 3D pattern, indicating stable and acceptable radiation performance for wireless and Internet of Things applications.

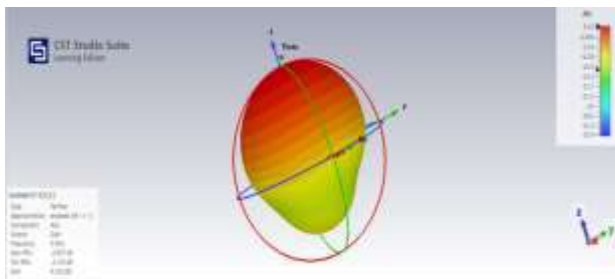


Fig.4.3 3D far-field gain pattern on FR4 substrate at 5.00 GHz (Gain = 4.130 dBi)

**B. RT Duroid Substrate ( $\epsilon_r = 2.2$ )**

**Return Loss (S11):** Fig.4.4 displays the antenna's S11 response on the RT Duroid substrate. The resonant frequency shifts upward to 6.859 GHz due to the lower dielectric constant of 2.2 compared to FR4, which is in keeping with the transmission line theory's prediction of an inverse relationship between permittivity and resonant frequency. At this frequency, the antenna achieves a return loss of  $-13.886$  dB, confirming sufficient impedance matching and meeting the  $-10$  dB criteria.

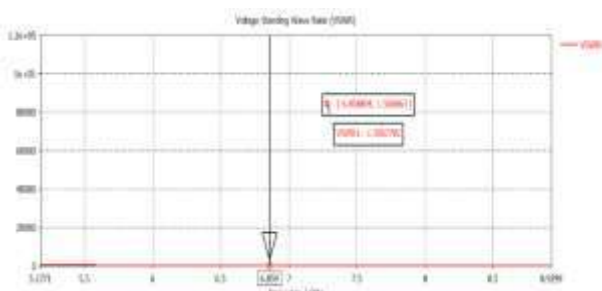


Fig.4.4 Simulated S11 response of pentagonal antenna on RT Duroid substrate (6.859 GHz)

**VSWR:** As seen in Fig. 4.5, the RT Duroid antenna's VSWR at 6.859 GHz is 1.507, which is still below the permissible limit of 2. This figure verifies adequate impedance matching and effective energy transmission from the feed line to the radiating patch at the operational frequency, while being marginally higher than the FR4 VSWR.

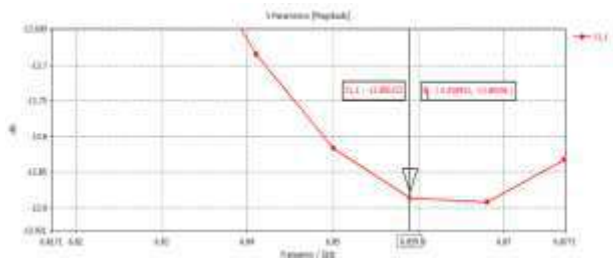


Fig.4.5 Simulated VSZR of pentagonal antenna on RT Duroid substrate (6.859 GHz)

**Radiation Pattern and Gain:** Figure 4.6 displays the RT Duroid antenna's 3D far-field gain pattern at 6.859 GHz. With a peak gain of 7.957 dBi, a radiation efficiency of 0.3312 dB, and a total efficiency of 0.1487 dB, the antenna generates a clearly defined broadside radiation lobe. The lower dielectric constant of RT Duroid, which lowers dielectric losses and improves radiation efficiency, is responsible for the noticeably higher gain as compared to FR4. Because of this, the RT Duroid arrangement is a great option for IoT and high-gain C-band applications.

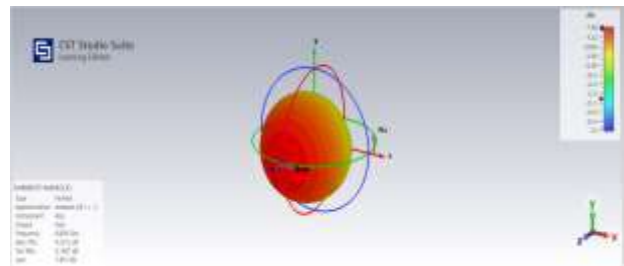


Fig. 4.6 3D far-field gain pattern on RT Duroid substrate at 6.859 GHz (Gain = 7.957 dBi)

**C. PTFE Substrate ( $\epsilon_r = 2.1$ )**

**Return Loss (S11):** Figure 4.7 displays the PTFE substrate antenna's S11 response. Among the three materials tested, the PTFE substrate has the lowest dielectric constant of 2.1, which results in a distinct dual-band resonance behavior. There are two different resonance frequencies found: 10.305 GHz with a return loss of  $-16.395$  dB and 7.005 GHz with a return loss of  $-13.844$  dB. Good impedance matching at both working frequencies is shown by both resonances meeting the  $-10$  dB return loss requirement. Because it allows the antenna to concurrently support C-band and X-band wireless communication systems inside a single compact structure, the dual-band behavior is especially important.

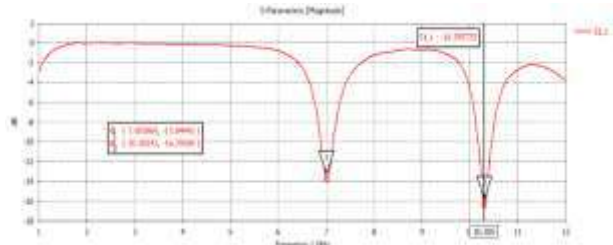


Fig.4.7 Simulated S11 response of pentagonal antenna on PTFE substrate (7.005 GHz & 10.305 GHz)

**VSWR:** Figures 4.8 and 4.9 display the VSWR charts for the PTFE antenna's two resonant frequencies. The VSWR is 1.357 at 7.005 GHz and 1.510 at 10.305 GHz. Effective impedance matching and little reflection at both working bands are confirmed by the fact that both values are well under the permissible limit of 2. The PTFE substrate's adaptability in permitting multi-band antenna operation with a single pentagonal patch geometry is demonstrated by the dual-band VSWR values.

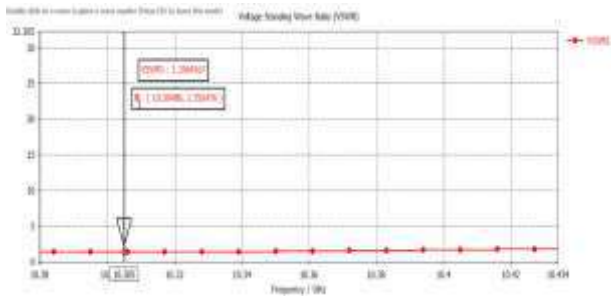


Fig.4.8 Simulated VSWR of pentagonal antenna on PTFE substrate at 7.005 GHz (VSWR = 1.357)

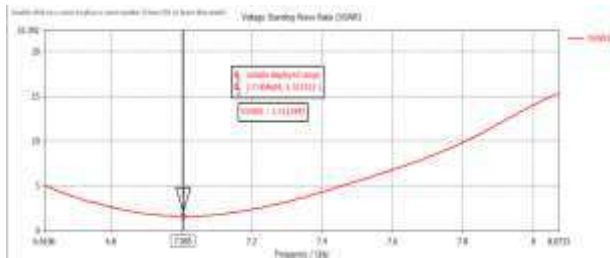


Fig.4.9 Simulated VSWR of pentagonal antenna on PTFE substrate at 10.305 GHz (VSWR = 1.510)

**Radiation Pattern and Gain:** Figures 4.10 and 4.11 display the PTFE antenna's 3D far-field gain patterns at both resonant frequencies. The antenna exhibits a clean broadside radiation pattern at 7.005 GHz, achieving a peak gain of 8.122 dBi with a radiation efficiency of 0.3829 dB and a total efficiency of 0.1987 dB. With a radiation efficiency of -0.03509 dB and a total efficiency of -0.1358 dB at 10.305 GHz, the gain is 6.926 dBi. Higher-order mode excitation at X-band frequencies introduces extra radiation lobes, resulting in a slightly more complex radiation pattern at 10.305 GHz. However, strong radiation performance across the dual band is confirmed by the gain values at both frequencies.

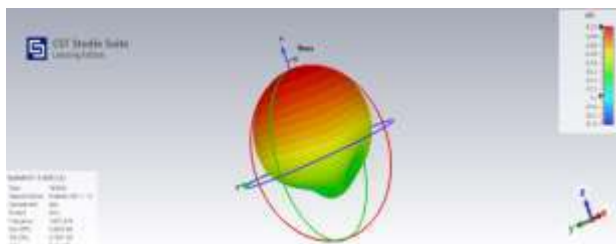


Fig.4.10 3D far-field gain pattern on PTFE substrate at 7.005 GHz (Gain = 8.122 dBi)

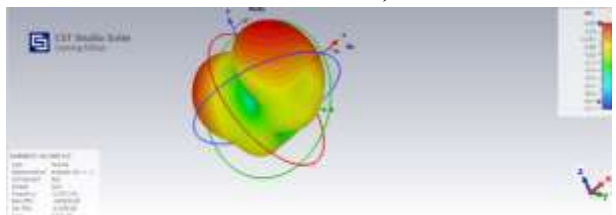


Fig.4.11 3D far-field gain pattern on PTFE substrate at 10.305 GHz (Gain = 6.926 dBi)

**D. Comparative Analysis**

Table II provides a detailed comparison of all three substrate designs. The findings unequivocally show that, in accordance with transmission line theory, lowering the substrate permittivity from 4.3 (FR4) to 2.1 (PTFE) gradually raises the resonance frequency from 5.00 GHz to 7.005 GHz and 10.305 GHz. Because lower permittivity materials have lower dielectric losses, the gain increases significantly from 4.130 dBi on FR4 to a maximum of 8.122 dBi on PTFE at 7.005 GHz. The PTFE substrate is particularly well-suited for multi-band IoT and wireless communication applications that require simultaneous C-band and X-band operation since only it generates dual-band resonance.

**TABLE II: COMPARATIVE PERFORMANCE OF SUBSTRATE MATERIALS**

Substrate	$\epsilon_r$	Frequency (GHz)	S11 (dB)	VSWR	Gain (dBi)
FR4	4.3	5.000	-16.518	1.351	4.130
RT Duroid	2.2	6.859	-13.886	1.507	7.957
PTFE	2.1	7.005, 10.305	-13.844, -16.395	1.357, 1.510	8.1, 6.926

The findings verify that all three substrate topologies meet the essential criteria for realistic antenna deployment by achieving VSWR values below 2 and return losses better than -10 dB. Because of its strong radiation efficiency across both resonant frequencies, highest gain, and dual-band functioning, the PTFE substrate is found to be the best overall performer.

**V. CONCLUSION**

This work presents the design and substrate analysis of a pentagonal microstrip patch antenna for wireless communication and multi-band Internet of Things applications. The suggested antenna was developed using a microstrip line feed technique on a small substrate measuring 25.48 mm by 21.48 mm, and it was simulated using electromagnetic modeling software called CST Studio Suite. To comprehensively examine the impact of substrate permittivity on antenna performance, three dielectric substrate materials were applied to the identical pentagonal patch geometry: FR4 ( $\epsilon_r = 4.3$ ), RT Duroid ( $\epsilon_r = 2.2$ ), and PTFE ( $\epsilon_r = 2.1$ ).

The simulation results show that all three substrate topologies achieve VSWR values below 2 and return loss values below -10 dB, indicating effective power radiation and good impedance matching in every scenario. For C-band wireless applications, the FR4 substrate generates a single-band resonance at 5.00 GHz with a gain of 4.130 dBi, a VSWR of 1.351, and a return loss of -16.518 dB. Because of its lower dielectric constant and lower material losses, the RT Duroid substrate greatly increases the gain to 7.957 dBi while shifting the resonance frequency to 6.859 GHz. The PTFE substrate is the most adaptable of the three substrates for multi-band IoT, C-band, and X-band wireless communication systems because it allows dual-band operation at 7.005 GHz and 10.305 GHz with gains of 8.122 dBi and 6.926 dBi, respectively.

While the pentagonal patch geometry consistently maintains stable impedance matching regardless of the substrate material used, the comparative substrate analysis verifies that lower permittivity materials gradually shift the resonant frequency upward, improve gain, and enhance radiation efficiency. For applications needing dual-band operation and high gain in a small planar construction, the PTFE substrate is determined to be the best option.

In order to further improve bandwidth and multi-band performance, future work will concentrate on fabricating and experimentally validating the suggested antenna as well as investigating other low-permittivity substrate materials and modified pentagonal geometries with slots or fractal boundaries.

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