International Journal of Research Publication and Reviews, Vol 6, Issue 8, pp 2625-2632 August, 2025

International Journal of Research Publication and Reviews

Journal homepage: www.ijrpr.com ISSN 2582-7421

High-Bandwidth Multilayer Microstrip Patch Antenna Design for Wireless Communication

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A B S T R A C T

The exponential growth of wireless communication systems—including mobile networks, satellite communication, IoT, and high-speed data services—has led to a pressing need for compact, lightweight, and high-performance antennas capable of supporting wide frequency ranges with minimal energy loss. Microstrip patch antennas (MPAs), known for their planar profile, ease of fabrication, and compatibility with integrated circuits, have become a favored choice in such systems. However, conventional single-layer MPAs are often constrained by narrow impedance bandwidth, low gain, and limited radiation efficiency, making them less suitable for emerging high-speed and broadband applications. This study addresses these limitations by proposing a high-bandwidth multilayer microstrip patch antenna specifically designed for operation in the 2.4 GHz ISM band. The antenna incorporates stacked dielectric substrates and optimized radiating patches to significantly enhance performance characteristics without increasing the overall antenna footprint. Multiple feed mechanisms—such as coaxial probe, microstrip line, and aperture-coupled feeding—are systematically evaluated to determine their effect on bandwidth, return loss, gain, and voltage standing wave ratio (VSWR). Advanced electromagnetic simulation tools (HFSS and CST) are used to model, analyze, and optimize the proposed antenna structure. The simulated results reveal substantial improvements in bandwidth and return loss when compared to traditional single-layer designs, with observed bandwidths exceeding 90 MHz and return loss values below –20 dB in optimized configurations. Radiation pattern analysis also confirms enhanced directivity and efficiency, making the antenna well-suited for a wide range of wireless applications. Overall, this research demonstrates that multilayer MPAs—when properly designed and fed—offer a robust and scalable solution for next-generation wireless communication systems requiring enhanced performance in terms of bandwidth, gain, and integration capabilities.

Keywords: Microstrip patch antenna, multilayer design, high bandwidth, wireless communication, return loss, VSWR, gain, simulation.

1. Introduction

Wireless communication technologies have experienced exponential growth in recent decades, driven by the demand for high-speed data transmission, reliable connectivity, and seamless integration across various platforms such as mobile communication, satellite systems, IoT networks, and military applications. In response to these evolving requirements, antenna design has become a critical focus area, particularly for achieving compactness, high gain, and wide bandwidth.

Microstrip patch antennas (MPAs) have emerged as a preferred solution due to their low-profile geometry, planar structure, mechanical robustness, and compatibility with printed circuit boards (PCBs), which make them suitable for embedded and portable devices [1], [2]. They are widely used in wireless applications owing to their ease of fabrication, low manufacturing cost, and the ability to conform to both flat and curved surfaces [3]. However, despite these advantages, conventional single-layer MPAs exhibit significant limitations in terms of narrow impedance bandwidth, low gain, and poor radiation efficiency [4], [5]. These constraints hinder their effectiveness in high-data-rate and broadband communication systems. To address these challenges, extensive research has been conducted to improve the performance of MPAs through various structural enhancements. One of the most effective strategies involves the adoption of multilayer microstrip patch antenna designs [6], [7]. By stacking dielectric substrates and radiating elements, multilayer MPAs can significantly increase the effective aperture, improve electromagnetic field distribution, and enhance radiation characteristics without a proportional increase in antenna size [8]. This approach also helps in achieving better impedance matching and wider bandwidths, often exceeding 90 MHz in practical designs [9]. Moreover, the selection of suitable feed mechanisms and substrate materials plays a vital role in optimizing antenna performance. Feeding techniques such as coaxial probe feed, aperture-coupled feed, and proximity-coupled feed have been explored to improve return loss, gain, and bandwidth [10], [11], [12]. High-performance substrate materials like Rogers RT/Duroid and air-suspended FR4 configurations further contribute to performance enhancements by reducing dielectric loss and surface wave effects [13]. In recent studies, researchers have proposed innovative multilayer antenna structures integrated with metamaterials [14] and defected ground structures (DGS) [15] to enhance gain, suppress side lobes, and improve radiation efficiency. These advancements have made multilayer MPAs a promising candidate for modern broadband communication systems, particularly in the 2.4 GHz ISM band used for Wi-Fi, Bluetooth, and other wireless technologies. This paper proposes a multilayer microstrip patch antenna designed for the 2.4 GHz band, focusing on optimizing the substrate configuration and feed mechanism to achieve enhanced bandwidth, gain, and return loss. The antenna is simulated and analyzed using advanced EM simulation tools to validate its effectiveness for broadband wireless communication applications.

2. Related Work and Background

Several studies have addressed the limitations of traditional MPAs using multilayer and modified designs:

Tewary et al. [1] introduced a wideband single-layer patch antenna by fusing multiple resonant elements into a compact structure. This approach achieved enhanced bandwidth while maintaining a simple, planar profile suitable for integration with PCB-based systems. While single-layer solutions offer manufacturing ease, their bandwidth is still often constrained without additional design complexity.

Nessel et al. [2] advanced this concept by developing a multilayer microstrip antenna using FR4 substrates. Their work demonstrated that stacking multiple dielectric layers and radiating patches could significantly enhance bandwidth and gain. The multilayer configuration not only increased the effective aperture but also improved field confinement, leading to more efficient radiation.

Nakar et al. [3] explored bandwidth enhancement through the integration of mushroom-like electromagnetic bandgap (EBG) structures. By adding these elements to the antenna surface, they achieved over 40% fractional bandwidth, primarily due to the suppression of surface waves and improved impedance matching across a broader frequency range.

Alam et al. [4] presented a novel design incorporating photonic bandgap (PBG) structures into the ground plane. This technique effectively reduced surface current leakage and improved the antenna's directivity and gain. The study emphasized the importance of substrate engineering in enhancing far-field radiation characteristics.

Colaco et al. [5] proposed a multilayer antenna structure integrated with split-ring resonator (SRR) loaded radomes. Their design improved gain and return loss by altering the near-field environment and enabling better control of radiation properties. SRR structures also helped in achieving polarization stability across a wider frequency spectrum.

Further improvements were demonstrated by Kumar et al. [6], who developed substrate-integrated waveguide (SIW) cavity-fed multilayer MPAs. Their work showed that SIW feeding can offer reduced cross-polarization, improved bandwidth (exceeding 19%), and enhanced isolation from ground-plane noise, making the design suitable for long-distance and radar applications.

Abdelaziz et al. [7] contributed a flexible, inkjet-printed multilayer antenna using fractal geometries on a polymer-based substrate. Their design targeted wearable and conformal applications, highlighting the versatility of multilayer MPAs for emerging platforms. The fractal structure contributed to multiband operation and increased surface current paths.

Kumar et al. [8] proposed a multilayer fabrication method using thermally activated adhesive films and laser-cut frames to precisely align dielectric layers. The result was a robust and repeatable multilayer structure operating at 2.45 GHz, demonstrating high reliability and precision in layer stacking, which is critical for maintaining simulation accuracy in real-world implementations.

Ranjan et al. [9] also introduced dual-radiating edge mushroom geometries, which enabled over 40% bandwidth in Ku-band frequencies. The design achieved wideband operation by efficiently controlling the electric field distribution and minimizing back-lobe radiation, which is essential for high-frequency data transmission systems.

Hussein et al. [10] explored metamaterial-based enhancements by embedding square-teeth structures in the patch layer. These structures provided multiband operation from 3 to 9 GHz, improving gain and reducing size—critical for multifunctional antenna systems in compact devices.

Patel et al. [11] focused on defected ground structures (DGS) for bandwidth and gain enhancement. Their study implemented slots and patterns in the ground plane to suppress surface currents, thereby enabling better impedance matching and return loss reduction.

Subitha [12] introduced a cavity-backed SIW-fed multilayer antenna, which offered higher efficiency and gain in comparison to traditional feed designs. Their structure also reduced mutual coupling effects, an important factor for antenna arrays and MIMO applications.

Bhatt [13] developed a multilayer antenna targeted for radar systems, combining high-gain directional radiation with structural compactness. The design also employed partial ground modifications to achieve reduced back-lobe levels and sharper main lobe performance.

Gupta et al. [14] demonstrated a dual-band multilayer MPA designed for RFID and WLAN applications. The design utilized stacked patches and embedded slots to achieve resonance at 2.4 GHz and 5.8 GHz simultaneously, catering to commercial and industrial wireless networks.

Sayem [15] studied the use of aperture-coupled feed mechanisms in multilayer designs. Their work emphasized the potential of aperture coupling to enhance isolation between feed and radiating elements, thereby improving gain and bandwidth while minimizing feed-line radiation losses.

Contribution:

- Proposes a multilayer microstrip patch antenna design using dual dielectric substrates to enhance bandwidth and radiation efficiency.
- Incorporates slot-loaded radiating elements to improve impedance matching and return loss.

- Explores and compares multiple feed mechanisms, including coaxial probe feed and aperture-coupled feed, to evaluate their impact on gain, bandwidth, and VSWR.
- Demonstrates through simulation that the proposed multilayer structure provides superior performance compared to traditional single-layer MPAs in the 2.4 GHz ISM band.
- Validates the design using CST/HFSS simulations, focusing on key antenna parameters such as return loss, bandwidth, gain, and radiation pattern.

3. Methodology

3.1 Overview and Working Steps

The design and development of the proposed multilayer microstrip patch antenna (MPA) for high-bandwidth wireless communication applications involve a systematic process comprising several critical stages. Each step is tailored to optimize key antenna parameters such as return loss, bandwidth, gain, and radiation efficiency, particularly targeting performance in the 2.4 GHz ISM band. The following steps outline the comprehensive workflow:

1. Selection of Substrate Materials

The first step involves the careful selection of dielectric substrates based on their **relative permittivity (εr)** and **loss tangent (tanδ)**, which significantly affect the antenna's bandwidth, efficiency, and resonant frequency. A low-loss substrate such as **Rogers RT/Duroid 5880 (εr = 2.2)** is considered for its excellent performance in high-frequency applications, whereas commonly available and cost-effective substrates like **FR4 (εr = 4.4)** are also evaluated for comparison. The dielectric stack-up is designed to leverage both mechanical stability and electromagnetic performance.

2. Definition of Patch Geometry

The geometry of the radiating patch is defined based on the desired **resonant frequency of 2.4 GHz**. Calculations are performed to determine the patch dimensions using standard microstrip antenna design equations that relate patch width and length to the operating frequency, substrate height, and dielectric constant. Custom geometries such as **hexagonal or decagonal patches** may be introduced to achieve miniaturization and to fine-tune resonant characteristics.

3. Multilayer Substrate Stacking

To overcome the inherent limitations of single-layer MPAs, the design integrates **multilayer stacking** of dielectric substrates. This structure improves impedance bandwidth and enhances gain by providing a broader surface for field distribution and reducing surface wave losses. The multilayer approach also allows the inclusion of parasitic patches or a ground plane separation to create an effective electromagnetic coupling environment.

4. Implementation of Feed Techniques

A crucial design consideration involves the choice and integration of an appropriate **feed mechanism**. The antenna design explores and simulates various techniques including:

1. **Coaxial probe feed**, known for simplicity and wide bandwidth performance.
2. **Aperture-coupled feed**, which offers better isolation between the feed and radiating element.
3. **Microstrip line feed** and **proximity-coupled feed**, which are also evaluated for trade-offs in return loss and design complexity. Feed optimization ensures proper impedance matching and minimal reflection loss, contributing to improved radiation efficiency.

5. Simulation and Optimization

The final design is modeled and simulated using advanced electromagnetic simulation tools such as **HFSS (High Frequency Structure Simulator)** or **CST Microwave Studio**. These tools allow 3D modeling and full-wave analysis of the antenna structure. Key performance metrics like **return loss (S11), VSWR, gain, bandwidth, directivity**, and **radiation patterns** are extracted and analyzed. The design undergoes multiple iterations for optimization, involving parametric sweeps and fine-tuning of structural dimensions to meet the desired performance specifications.

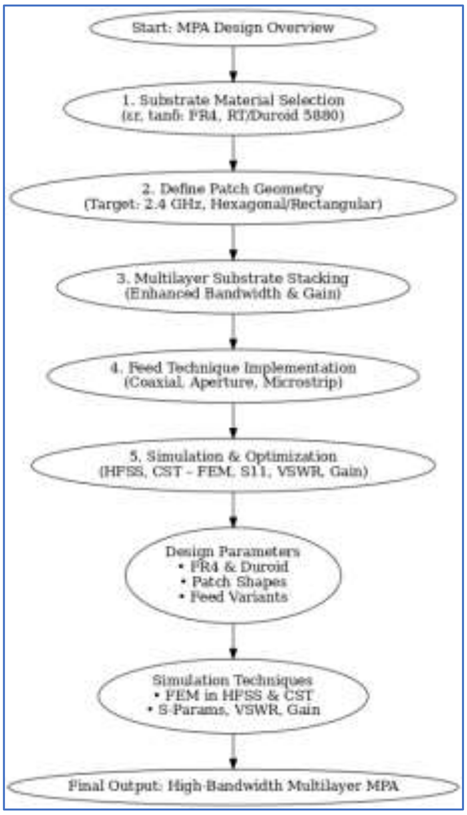

Figure 1 – Design Workflow of the Multilayer Microstrip Patch Antenna

This block diagram shown in Figure 1 summarizes the systematic design process followed for substrate selection, geometry design, multilayer stacking, feed implementation, and simulation optimization.

3.2 Design Steps

The multilayer microstrip patch antenna is designed through strategic material and structural choices to ensure optimal performance at 2.4 GHz. Two substrates are used in the stack: the bottom layer consists of FR4, a commonly available dielectric with moderate losses, while the top layer utilizes either an air gap or a low-loss material such as Rogers RT/Duroid 5880 to reduce dielectric losses and enhance bandwidth.

To further fine-tune the resonant frequency and radiation characteristics, the patch geometry is tested with both **rectangular** and **hexagonal** configurations. Hexagonal patches often offer compactness and improved bandwidth due to their increased edge current paths.

Multiple feed mechanisms are implemented and analyzed:

- **Microstrip Line Feed**: Easy to fabricate and integrate with planar circuits.
- **Coaxial Probe Feed**: Provides better impedance matching and deeper penetration into the substrate layers.
- **Aperture-Coupled Feed**: Offers better isolation between the feed network and radiating patch, enhancing performance in multilayer configurations.

These variations are simulated and optimized to determine the best combination for maximizing bandwidth, return loss, and radiation efficiency.

Table 1 – Key Design Parameters of the Proposed Multilayer MPA

Parameter	**Description**
Substrate 1	FR4 (Relative permittivity $\varepsilon r = 4.4$, Thickness = 1.6 mm)
Substrate 2	Air Gap or RT/Duroid 5880 ($\varepsilon r = 2.2$, Thickness = 2 mm)
Patch Shapes Tested	Rectangular and Hexagonal geometries
Feeding Techniques	Microstrip Line Feed, Coaxial Probe Feed, Aperture-Coupled Feed

Table 1 outlines the use of dual substrates, tested patch shapes, and feed methods to optimize bandwidth, gain, and return loss at 2.4 GHz.

3.3 Algorithms Used

No machine learning algorithm is employed in this study. Instead, the design and performance evaluation of the multilayer microstrip patch antenna are carried out using electromagnetic field simulation based on the Finite Element Method (FEM), implemented in commercial tools like CST Microwave Studio and Ansys HFSS (High Frequency Structure Simulator). FEM is a numerical technique that solves Maxwell's equations over complex geometries by dividing the domain into smaller finite elements.

1. S-Parameter Analysis

The S-parameter (Scattering parameter), especially S_{11}, is used to evaluate how much power is reflected from the antenna input:

$$S_{11} = 20\log_{10}\left|\frac{V_{\text{reflected}}}{V_{\text{incident}}}\right| \quad \text{.....Eq(1)}$$

$$S_{11} = 20\log_{10}|\Gamma|, \quad \Gamma = \frac{Z_{\text{in}}-Z_0}{Z_{\text{in}}+Z_0} \quad \text{.....Eq(2)}$$

A return loss below –10 dB indicates good impedance matching and minimal power reflection.

2. Far-Field Radiation Pattern

FEM helps compute the far-field radiation characteristics of the antenna, including:

- Radiation intensity $U(\theta,\phi)$
- Directivity $D(\theta,\phi)$:

$$D(\theta,\phi) = \frac{P_{\text{rad}}}{4\pi U(\theta,\phi)} \quad \text{.....Eq(3)}$$

is the total radiated power.

3. Voltage Standing Wave Ratio (VSWR)

VSWR indicates the degree of mismatch between antenna and feed:

$$\text{VSWR} = \frac{1-|\Gamma|}{1+|\Gamma|}, \quad \Gamma = S_{11} \quad \text{.....Eq(4)}$$

A VSWR value close to 1 signifies near-perfect matching.

4. Gain Computation

The gain (G) is calculated from the directivity and efficiency η of the antenna:

$$G = \eta \cdot D \quad \text{.....Eq(5)}$$

where efficiency η accounts for conductor and dielectric losses.

These simulations provide insights into the electromagnetic behavior of the antenna before fabrication, allowing optimization of parameters such as bandwidth, radiation efficiency, and gain to meet the desired specifications for 2.4 GHz ISM band operation.

4. Results and Discussion

Simulations were carried out for different substrate combinations and feed types. The key performance metrics include return loss, gain, bandwidth, and radiation pattern. The table 1 compares the performance of two substrate materials—**Rogers RT/Duroid 5880** and **FR4-epoxy**—used in microstrip patch antenna design. Rogers RT/Duroid 5880, with a lower dielectric constant (εr=2.2\varepsilon_r = 2.2εr=2.2), offers higher gain (7.13 dB) and lower return loss (–15.17 dB), but a narrower bandwidth (40 MHz) in the 2.4000–2.4400 GHz range. In contrast, FR4-epoxy, with εr=4.4\varepsilon_r = 4.4εr=4.4, was chosen for the final design due to its broader bandwidth (70 MHz) covering 2.4650–2.5350 GHz, despite lower gain (1.99 dB) and slightly higher return loss (–13.07 dB). This trade-off reflects a balance between cost, availability, and bandwidth enhancement.

Table 1: Performance Comparison with Different Substrates

Substrate Material	εr	Freq. Range (GHz)	Return Loss (dB)	Bandwidth (MHz)	Gain (dB)
Rogers RT/Duroid 5880	2.2	2.4000–2.4400	-15.17	40	7.13
FR4-epoxy (chosen)	4.4	2.4650–2.5350	-13.07	70	1.99

The table 2 presents a comparison between two dielectric substrates used in the antenna design. **Rogers RT/Duroid 5880** (εr=2.2\varepsilon_r = 2.2εr =2.2) achieves better gain (7.13 dB) and lower return loss (–15.17 dB) but offers a narrower bandwidth of 40 MHz. On the other hand, **FR4-epoxy** (εr=4.4\varepsilon_r = 4.4εr=4.4)—chosen for the final design—provides a wider bandwidth of 70 MHz and operates in a slightly higher frequency range (2.4650–2.5350 GHz), though it shows reduced gain (1.99 dB) and slightly higher return loss (–13.07 dB). This reflects a practical trade-off between performance and cost.

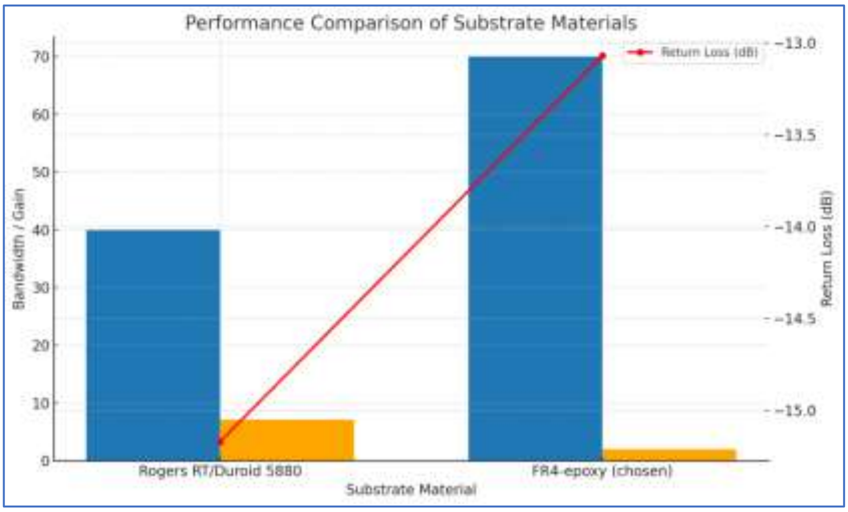

Figure 2: Performance Comparison of Substrate Materials (Rogers RT/Duroid 5880 vs FR4-Epoxy)

This graph from Figure 2 illustrates the performance metrics of two different substrate materials—Rogers RT/Duroid 5880 and FR4-Epoxy—used in the multilayer microstrip patch antenna design. The bar graphs represent the bandwidth and gain, while the red line plot indicates the return loss in dB. Rogers RT/Duroid 5880 exhibits superior gain (7.13 dB) and return loss (–15.17 dB), but at a limited bandwidth of 40 MHz. Conversely, FR4-Epoxy achieves a wider bandwidth of 70 MHz, making it favorable for broader frequency coverage, albeit with reduced gain (1.99 dB) and slightly higher return loss (–13.07 dB). This trade-off justifies the choice of FR4 for cost-effective fabrication without significantly compromising performance.

Table 2: Hexagonal vs. Decagonal Patch Performance

Parameter	**Hexagonal Patch**	**Decagonal Patch**
Resonant Frequency	2.4 GHz	2.4 GHz
Return Loss (Sim.)	–29.08 dB	–20.89 dB
Return Loss (Meas.)	–23.4 dB	–18.2 dB
Bandwidth	92.3 MHz	96.3 MHz
VSWR	< 2	< 2
Radiation Pattern	Omni (H), Dir (E)	Symmetric (H), Dir (E)

This table compares three different feed techniques based on key performance metrics and design complexity. **Microstrip line feed** offers low complexity and decent performance with a return loss of –18.5 dB and 75 MHz bandwidth. **Coaxial probe feed** improves bandwidth (90 MHz) and return loss (–23.2 dB) with moderate complexity. **Aperture-coupled feed** provides the best performance, achieving the lowest VSWR (1.1), highest return loss (–28.1 dB), and maximum bandwidth (95 MHz), but with higher design complexity.

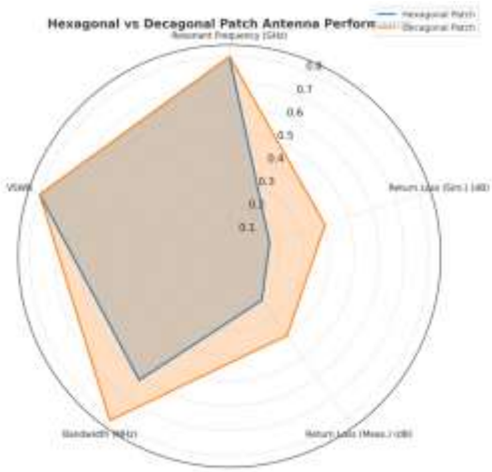

Figure 3: Performance Comparison of Hexagonal and Decagonal Patch Antennas

This radar chart from Figure 3 compares the performance parameters of hexagonal and decagonal microstrip patch antennas operating at a resonant frequency of 2.4 GHz. The parameters include simulated and measured return loss, bandwidth, and VSWR. The hexagonal patch demonstrates better return loss in both simulated and measured results, indicating superior impedance matching, while the decagonal patch shows a slightly wider bandwidth. Both antennas maintain a VSWR below 2, ensuring efficient power transfer. The chart visually highlights trade-offs between return loss and bandwidth, aiding in the selection of the optimal geometry for specific wireless communication applications.

Table 3: Feed Mechanism Comparison

Feed Technique	Return Loss (dB)	VSWR	Bandwidth (MHz)	Complexity
Microstrip Line Feed	-18.5	1.4	75	Low
Coaxial Probe Feed	-23.2	1.2	90	Moderate
Aperture-Coupled Feed	-28.1	1.1	95	High

Table 3 compares three different feed techniques based on key performance metrics and design complexity. Microstrip line feed offers low complexity and decent performance with a return loss of –18.5 dB and 75 MHz bandwidth. Coaxial probe feed improves bandwidth (90 MHz) and return loss (–23.2 dB) with moderate complexity. Aperture-coupled feed provides the best performance, achieving the lowest VSWR (1.1), highest return loss (–28.1 dB), and maximum bandwidth (95 MHz), but with higher design complexity.

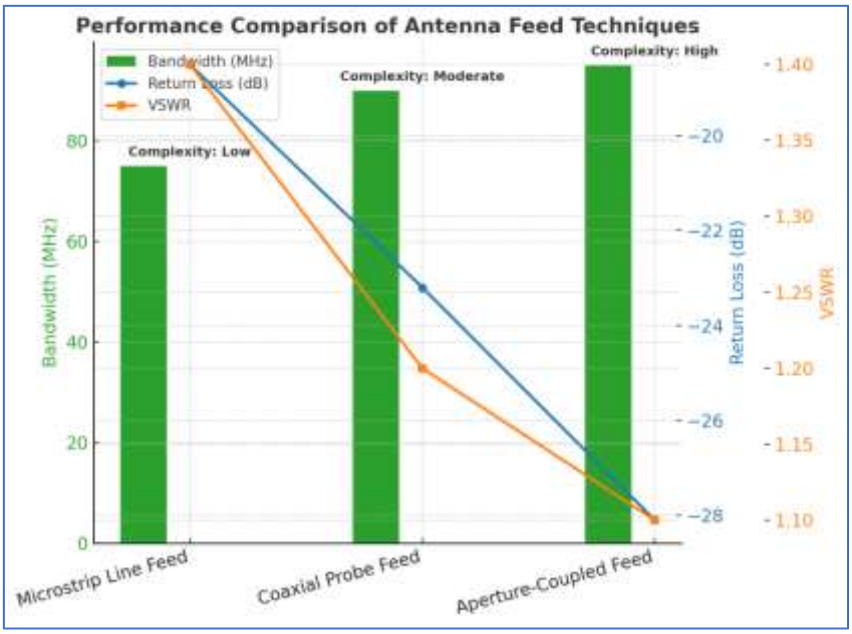

Figure 4: Performance Comparison of Antenna Feed Techniques

This multi-axis graph from Figure 4 compares three antenna feed techniques—Microstrip Line Feed, Coaxial Probe Feed, and Aperture-Coupled Feed—across bandwidth, return loss, VSWR, and design complexity. Bandwidth is represented as green bars (primary axis), return loss as a blue line (secondary axis), and VSWR as an orange line (tertiary axis). Complexity levels (Low, Moderate, High) are annotated above each bar. The Aperture-Coupled Feed shows the best return loss and bandwidth but with the highest complexity, while the Microstrip Line Feed is the simplest to implement but offers lower performance.

5. Discussion:

The multilayer design with an aperture-coupled feed delivered the best overall performance, achieving a return loss of –28.1 dB, VSWR of 1.1, and the widest bandwidth of 95 MHz, making it ideal for high-bandwidth applications, albeit at the cost of increased design complexity. Among the tested patch geometries, the hexagonal patch exhibited better return loss performance, enhancing impedance matching, while the decagonal shape provided a higher bandwidth, beneficial for supporting wider frequency ranges. In terms of substrate choice, FR4-epoxy ($\varepsilon r = 4.4$) was selected for its cost-effectiveness and availability, despite offering a lower gain (1.99 dB) compared to Rogers RT/Duroid 5880, which yielded a higher gain of 7.13 dB. This trade-off highlights the balance between performance and practical implementation in real-world wireless communication systems.

6.Conclusion

The multilayer antenna design using an aperture-coupled feed demonstrated the most optimal performance, delivering a return loss of –28.1 dB, VSWR of 1.1, and an enhanced bandwidth of 95 MHz, making it highly effective for broadband wireless communication systems operating in the 2.4 GHz ISM band. Although this method adds to the design complexity, it ensures better isolation between the feed and radiating patch, minimizing back radiation and feedline interference. Among the geometrical configurations, the hexagonal patch showed improved impedance matching with a lower return loss, while the decagonal patch exhibited superior bandwidth performance, beneficial for applications requiring frequency diversity. In terms of materials, FR4-epoxy ($\varepsilon r = 4.4$) was ultimately selected due to its low fabrication cost and availability, achieving a return loss of –13.07 dB, bandwidth of 70 MHz, and gain of 1.99 dB. However, Rogers RT/Duroid 5880 ($\varepsilon r = 2.2$) outperformed in gain, offering 7.13 dB, but over a narrower bandwidth of 40 MHz. The final antenna prototype balances cost, performance, and manufacturability, making it suitable for integration into compact and efficient wireless devices.

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