

Development of a Folded Dipole Antenna for IoT Networks

Mia Shazrena Sha'ari¹, Huda A Majid^{1*}, Najib Mohammed Ahmed Al-Fadhali¹

¹ Department of Electrical Engineering Technology, Faculty of Engineering Technology, University Tun Hussein Onn Malaysia, Education Hub Pagoh, 84600, MALAYSIA

*Corresponding Author: mhuda@uthm.edu.my

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Abstract

The development of optimized antenna designs is necessitated by the increasing demand for efficient and cost-effective communication solutions in IoT networks. In this study, a folded dipole antenna tailored for IoT applications is designed, with precise simulation and analysis conducted using CST Studio Suite software. The folded dipole antenna offers numerous advantages, including enhanced impedance matching, wide bandwidth, and compact size, making it a suitable candidate for IoT devices that require reliable and low-power communication. A systematic design approach was employed, incorporating both theoretical analysis and simulation tools within CST Studio Suite to optimize the antenna's performance. The design parameters were meticulously adjusted to achieve the desired frequency response, impedance matching, and radiation pattern, ensuring compatibility with the operational frequency of 5.11GHz and two resonance frequency which are 6.1GHz and 6.87GHz, which is commonly used in IoT networks, such as Wi-Fi. The antenna is designed with an FR-4 substrate, known for its suitable electrical properties and cost-effectiveness in mass production. The results of this study indicate that the folded dipole antenna, designed using CST Studio Suite and an FR-4 substrate, is a viable solution for enhancing IoT network performance. Its design simplicity, combined with robust performance characteristics, makes it an ideal choice for widespread deployment in the growing IoT landscape.

1. Introduction

Designing a folded dipole antenna for IoT networks focuses on achieving optimal performance through broad bandwidth, improved impedance, and compact size, making it ideal for constrained IoT environments. The process starts with defining network requirements such as operating frequencies (5.11GHz, 6.1GHz, and 6.87GHz), bandwidth, and device constraints. An antenna is designed and simulated using CST Studio Suite [1], which provides detailed analyses of parameters like radiation patterns, impedance, and gain. The design incorporates an FR-4 substrate, widely used in PCB manufacturing, to simulate real-world conditions accurately. This ensures the antenna design is both reliable and efficient before proceeding to the fabrication phase. The folding technique used in the dipole antenna enhances its adaptability across various IoT applications. After optimization, the antenna is fabricated and tested to evaluate its linear characteristics and verify its performance under operational conditions, ensuring its suitability for deployment in IoT networks.

1.1 Design Consideration for IoT Devices

In IoT networks, devices often operate in environments with limited space and power. The compact size and low power consumption of the folded dipole antenna make it well-suited for these conditions. The design focuses not only on performance but also on ensuring the antenna's scalability and integration into a variety of IoT devices, from simple sensors to complex communication modules.

1.2 Operating Frequency and Multi-band Performance

Given the diverse communication needs in IoT, antennas need to operate efficiently across various frequency bands. For this project, the antenna is designed to operate at specific frequencies, including 5.11GHz, 6.1GHz, and 6.87GHz, which are suitable for ISM band applications. This multi-band operation enables the antenna to support a wide range of IoT communication protocols such as Wi-Fi, Bluetooth, and other low-power wireless systems, ensuring its versatility for IoT networks.

1.3 Benefits of the Folded Dipole Antenna Design

The folded dipole antenna is a proven choice for IoT applications due to its superior impedance matching, broad bandwidth, and compact size. The folded design significantly improves impedance matching compared to a simple dipole antenna, making it more efficient for a wide range of IoT frequencies [2]. Additionally, the antenna's compact design allows it to be integrated into small IoT devices, where space and power constraints are critical. These advantages make the folded dipole antenna an excellent choice for IoT networks, where both performance and size are essential.

1.4 Antenna Material and Substrate

For this project, FR-4 was selected as the substrate material due to its cost-effectiveness and favorable electrical properties for mass production [3]. The choice of substrate plays a vital role in determining the antenna's performance, particularly in terms of signal integrity and efficiency.

1.5 Simulation and Optimization

CST Studio Suite is used to model and optimize the antenna design before fabrication. This simulation ensures that the antenna meets specific performance requirements, such as bandwidth, radiation pattern, and impedance matching, which are essential for IoT applications. The ability to simulate real-world conditions significantly reduces the need for multiple physical prototypes and speeds up the development process.

2. Methodology

2.1 Project Flowchart

The proposed methodology for designing a folded dipole antenna is divided into three phases. In Phase 1, the operating frequency of 5.11GHz is chosen for ISM band applications, and a literature review is conducted to select the antenna type [4] and suitable substrate material, with FR-4 being chosen for its cost-effectiveness and performance [5], [6], [7], [8]. The folded dipole antenna is selected for its wideband characteristics, high input impedance, and improved matching capabilities, with additional resonant frequencies at 6.1GHz and 6.87GHz. In Phase 2, the antenna is designed and simulated using CST Studio Suite, which helps optimize parameters like radiation pattern, gain, bandwidth, and impedance matching. Phase 3 involves the fabrication and testing of the antenna using FR-4 as the substrate, with the performance evaluated through linear measurements using a Vector Network Analyzer (VNA). **Fig.1** shows the flowchart of work performed for this project until its completion.

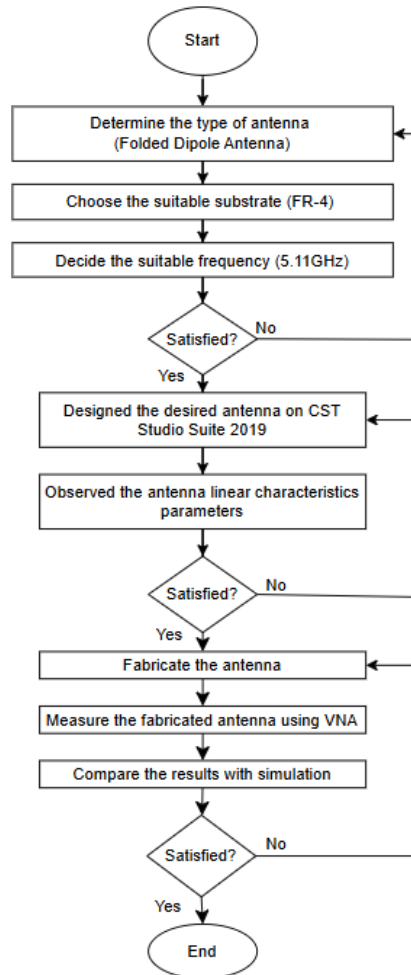


Fig. 1: Flowchart of the project

2.2 Antenna Design and Configuration

The antenna is designed and simulated by using CST Studio Suite software. The chosen antenna is single-band folded dipole antenna that are proposed at 5.11GHz, ISM Band. The design, as shown in Fig.2, for the single-band folded dipole antenna that operate at 5.11GHz make use of FR-4 as its substrate. The material dielectrics constant (ϵ_r) of 4.4, a loss tangent ($\tan \delta$) of 0.02 and thickness (h) of 1.5mm. The dimension of the antenna is shown in Table 1.

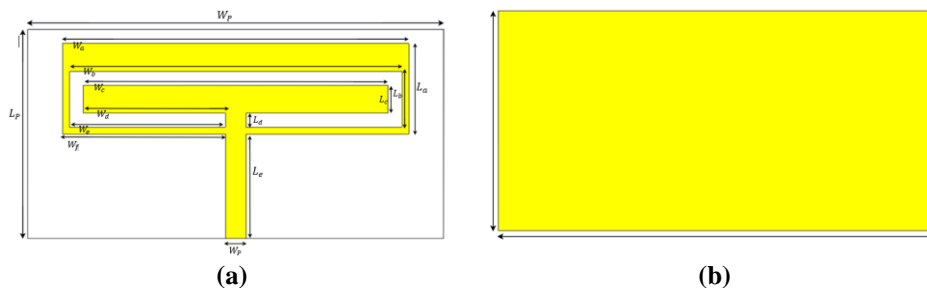


Fig. 2: The proposed single-band folded dipole antenna with FR-4 at 5.11GHz (a) Top View; (b) Bottom View

Table 1: Dimension of the single-band folded dipole antenna with FR-4 at 5.11GHz

Parameter	Values (mm)
W_p	60
L_p	30

W_a	50
L_a	13
W_b	48
L_b	8
W_c	44
L_c	4
W_d	20.5
L_d	2
W_e	22.5
L_e	15
W_f	23.5
W_P	3
W_G	60
L_G	30

2.3 Flowchart of Fabrication Process

As shown in **Fig.3**, the PCB layout for the folded dipole antenna design is first created in CST Studio Suite and exported in DFX format to ensure compatibility with fabrication tools. The antenna’s AutoCAD drawing is printed onto a transparent film, which serves as a mask during the fabrication process. The FR-4 substrate is then laminated using a Photoniex laminating machine, where a photoresist film is applied to ensure a smooth surface for UV exposure. The substrate is exposed to UV light, transferring the antenna design onto the photoresist film. After exposure, the film is removed, and the substrate is ready for etching, where unwanted copper is removed using a ferric chloride etching solution. The etched substrate is rinsed to stop the chemical reaction, revealing the circuit pattern.

In the final steps, an SMA connector is soldered to the antenna port, ensuring proper impedance matching at 50Ω for optimal performance in communication systems. This step is critical to maintain signal integrity, minimize reflection, and ensure consistent performance. Once the SMA connector is attached, the antenna is ready for further testing and integration into the IoT network. The entire process involves careful handling of each stage to ensure the antenna meets the required specifications and performs reliably.

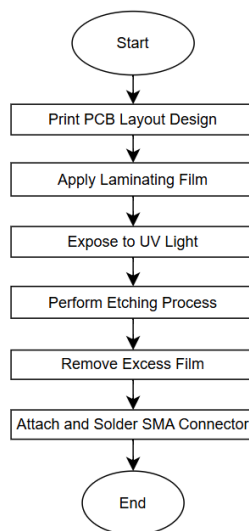


Fig. 3: Flowchart of the fabrication process of the single-band folded dipole antenna with FR-4 at 5.11GHz

3. Result and Discussion

The simulations were done using CST Studio Suite to check the antenna's reflection coefficient, VSWR, and radiation patterns. Real measurements were also taken to see how the antenna performs in practice. The simulated and measured results are compared, and any differences are discussed to understand what might have caused them.

3.1 Reflection Coefficient and Bandwidth

Fig.4 shown the reflection coefficient (S_{11}) of the single-band folded dipole antenna at 5.11GHz shows efficient operation with a value of -18.57dB, indicating good impedance matching at the operating frequency. Additionally, two resonant frequencies at 6.0953GHz and 6.8699GHz were observed with corresponding S_{11} values of -11.271dB and -10.314dB, respectively, suggesting the antenna's potential for multi-band operation. However, further investigation is required to assess the antenna's performance at these frequencies, as the relatively low S_{11} values imply reasonable impedance matching. The -10dB impedance bandwidth for 5.11GHz is calculated to be 84MHz, ensuring effective performance over this frequency range.

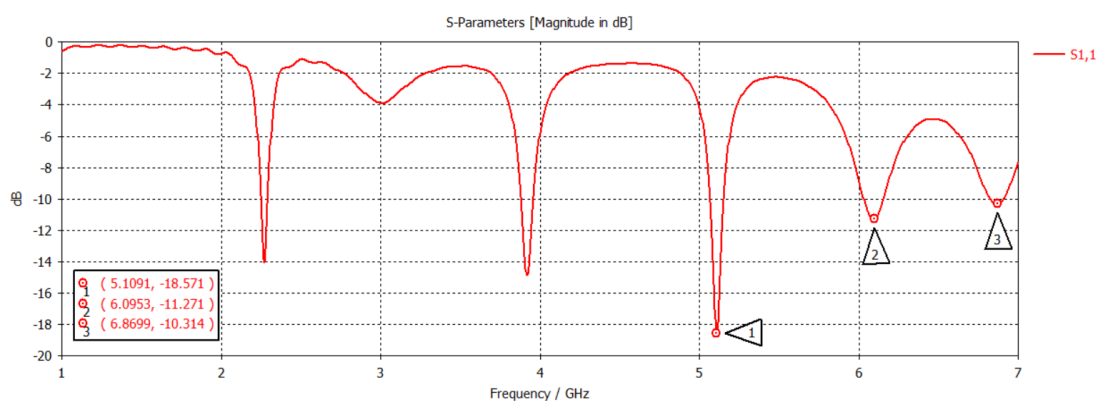


Fig. 4: Reflection coefficient of the single-band folded dipole antenna with FR-4 at 5.11GHz

3.2 Measured Reflection Coefficient

The comparison between the simulated and measured reflection coefficients (S_{11}) of the single-band folded dipole antenna with an FR-4 substrate at 5.11GHz, as shown in **Fig.5**, reveals differences that can be attributed to several factors. Variations in the fabrication process, such as inaccuracies in cutting or soldering the SMA connectors, can shift the resonance frequency and affect impedance matching, leading to discrepancies between the simulated and measured results. Environmental factors, including temperature, humidity, and nearby objects, can also influence antenna performance during measurement. Additionally, variations in the measurement setup, such as equipment calibration and antenna placement, can contribute to the differences, as simulations assume ideal conditions, while real-world factors like material losses and imperfect soldering are not accounted for.

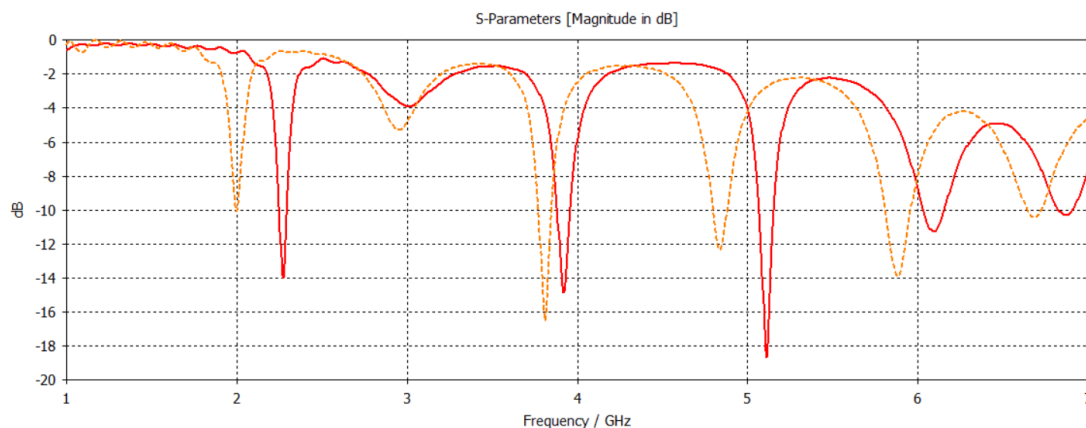


Fig. 5: Comparison between simulated and measured reflection coefficients of the single-band folded dipole antenna with FR-4 at 5.11GHz

3.3 Voltage Standing Wave Ratio

Fig.6 shows the VSWR at 5.11GHz is 1.2966 that shows that the antenna is very well-matched to the 50Ω systems impedance. With this value, only about 1.27% of the transmitted power is reflected, while the rest is effectively radiated or received. This indicated that the antenna is efficient and overall performance.

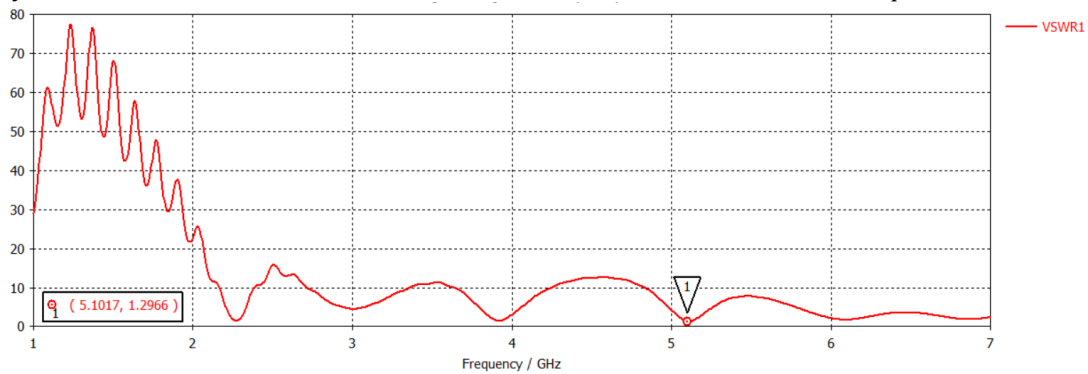


Fig. 6: Voltage Standing Ratio Wave for single-band folded dipole antenna with FR-4 at 5.11GHz

3.4 Radiation Pattern

3.4.1 Simulated Radiation Pattern at 6.87GHz

The main lobe direction shifted to 29.0°, with the E-field showing a magnitude of 10.9dB (V/m) and an angular width of 59.9°, as shown in Fig.7 (a). The side lobe level was -4.8dB, indicating a broader main lobe and higher side lobes compared to the previous two frequencies. Fig.7 (b) shows the H-field at this frequency had a main lobe magnitude of -40.6dB (A/m), with the same main lobe direction and angular width as the E-field, and a side lobe level of -4.8dB. This suggests that the antenna has a broader radiation pattern at this frequency, with slightly higher side lobe levels.

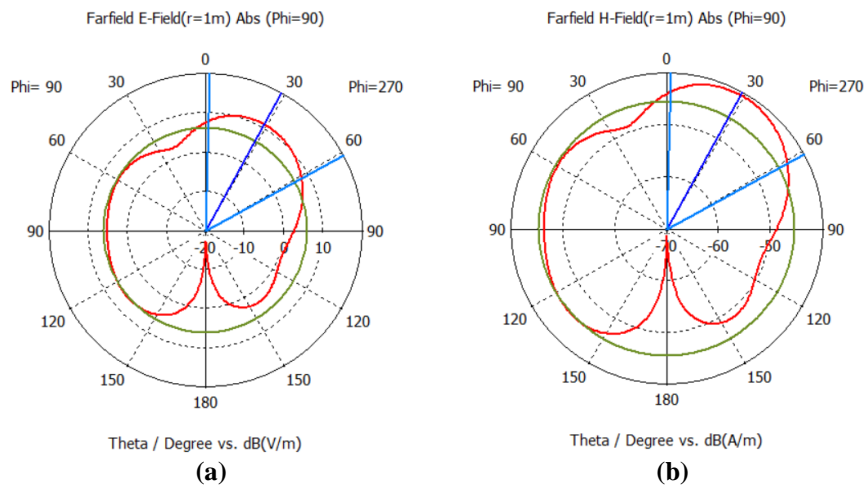


Fig. 7: Radiation pattern of the simulated single-band folded dipole antenna with FR-4 at 6.87GHz in the (a) E-plane; (b) H-plane

3.4.2 Simulated Radiation Pattern at 6.1GHz

The E-field showed an improvement in the main lobe magnitude, reaching 12.1dB (V/m), and the main lobe direction remained at 1.0°. Fig.8 (a) shows the angular width (3dB) was 92.8°, and the side lobe level dropped to -15.6dB, indicating better performance in reducing unwanted radiation. The H-field showed similar results with a -39dB (A/m) as shown in Fig.8 (b), with the same main lobe direction and angular width as the E-field, and a side lobe level of -15.6dB. This shows that the antenna's efficiency and radiation focus improve slightly at this resonant frequency.

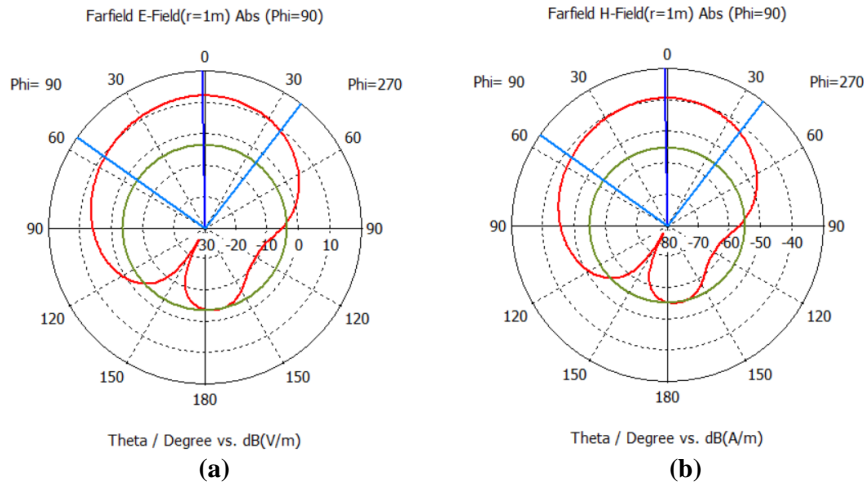


Fig. 8: Radiation pattern of the simulated single-band folded dipole antenna with FR-4 at 6.1GHz in the (a) E-plane; (b) H-plane

3.4.3 Simulated Radiation Pattern at 5.11GHz

Fig.9 shows that at operating frequency, the antenna exhibited good performance, with the E-field showing a main lobe magnitude of 9.94dB (V/m) and a main lobe direction at 1.0° . The angular width (3dB) was 92.9° , and the side lobe level was -9.3dB. The H-field at this frequency had a main lobe magnitude of -41.6dB (A/m), with the same main lobe direction and angular width as the E-field. The side lobe level for the H-field was also -9.3dB. The antenna radiates efficiently in the desired direction, with low side lobes, indicating minimal unwanted radiation.

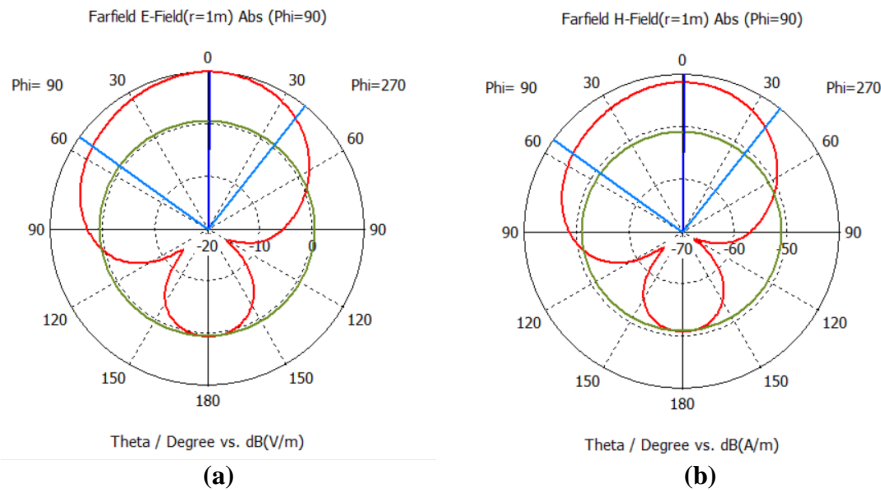


Fig. 9: Radiation pattern of the simulated single-band folded dipole antenna with FR-4 at 5.11GHz in the (a) E-plane; (b) H-plane

3.4.4 Measured Radiation Pattern at 5.11GHz

The measured radiation patterns of the single-band folded dipole antenna were obtained at a frequency of 10GHz in both E-plane and H-plane, as shown in **Fig.10**. In the E-plane, the main lobe was observed at 32° with a half-power beamwidth of 81.07° , while in the H-plane, the main lobe was at 49° with a wider half-power beamwidth of 117.95° . The measured side lobe levels were -10.02dB in the E-plane and -12.38dB in the H-plane, suggesting that antenna radiates most of its energy in the desired direction with minimal radiation in undesired directions. Due to limitations in available equipment, the measurements were conducted at 10GHz instead of the resonant frequency of the antenna.

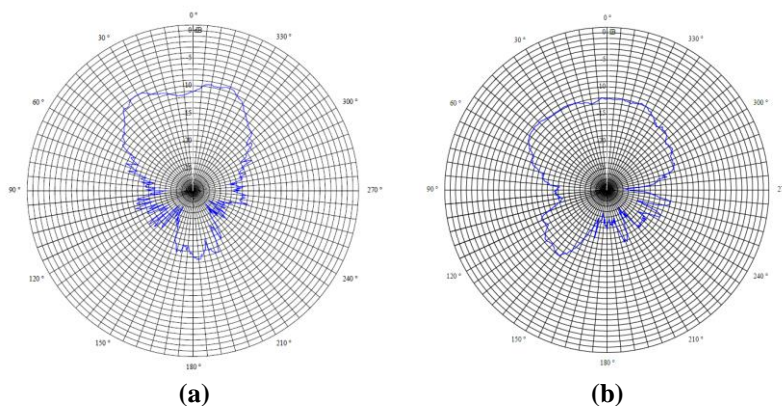


Fig. 10: Radiation pattern of the measured single-band folded dipole antenna with FR-4 at 5.11GHz in the (a) E-plane; (b) H-plane

3.4.5 Comparison between Measured and Simulated Radiation Pattern

Due to equipment limitations, the measured radiation pattern was captured at 10GHz, while the simulated radiation patterns were taken at the designed frequencies of 5.11GHz, 6.1GHz, and 6.87GHz. This variation in frequency accounts for the differences between the measured and simulated results. In the E-plane, the measured main lobe occurred at 32° with a half-power beamwidth (HPBW) of 81.07° and a side lobe level of -10.02dB . In comparison, the simulated HPBWs were between 92.8° and 92.9° with side lobe levels ranging from -9.3dB to -15.6dB . The measured HPBW is narrower, which is likely due to the higher frequencies making the antenna more focused and concentrating more energy in one direction.

In the H-plane, the measured main lobe was at 49° with an HPBW of 117.95° and a side lobe level of -12.38dB . Simulated HPBWs ranged from 59.9° to 92.9° with side lobe levels between -9.3dB and -15.6dB . The measured HPBW is wider, which may be attributed to the current distribution at higher frequencies, causing broader energy dispersion in this plane. The discrepancies between the measured and simulated results stem from the use of a higher frequency (10GHz) for measurement, which alters the radiation pattern compared to the designed frequencies.

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