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NOVEL CIRCULARLY SQUARE MICROSTRIP ANTENNA DESIGN FOR ENHANCED WIRELESS DATA TRANSMISSION IN RADAR AND REMOTE SENSING SYSTEMS

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Abstract

This research introduces an innovative circularly square-shaped microstrip antenna configuration optimized for broadband wireless data transmission in radar and remote sensing applications. The developed antenna architecture demonstrates exceptional wideband performance spanning 2.5 GHz to 12.1 GHz, encompassing critical frequency bands for modern communication systems including Wi-Fi, WiMAX, WLAN, X-band, Ku-band, and Ka-band operations. A systematic three-phase design optimization approach is implemented, incorporating strategic geometric modifications to maximize bandwidth efficiency. Advanced parameter optimization techniques are utilized to fine-tune critical design elements, achieving superior return loss characteristics. The antenna exhibits outstanding radiation efficiency, gain performance, and voltage standing wave ratio (VSWR) across the operational spectrum. Comprehensive analysis of surface current distributions and radiation patterns at multiple frequencies validates the design's effectiveness for demanding radar and remote sensing applications. The proposed solution addresses the growing need for compact, high-performance antennas in modern wireless communication systems.

Keywords: Broadband microstrip antenna, wireless communications, radar systems, remote sensing, geometric optimization, parameter analysis

1. Introduction

Contemporary wireless communication systems and next-generation radar technologies demand sophisticated antenna solutions capable of supporting high-speed data transmission across multiple frequency bands. The proliferation of remote sensing applications and advanced radar systems has created an urgent need for compact, efficient antenna designs that can operate effectively across broad frequency ranges while maintaining consistent performance characteristics (Chen & Wong, 2019). Traditional microstrip antenna configurations, while offering advantages in terms of manufacturing simplicity and cost-effectiveness, typically suffer from limited bandwidth capabilities that restrict their applicability in modern broadband systems.

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The evolution of radar and remote sensing technologies has introduced stringent requirements for antenna systems that can simultaneously support multiple operational modes while maintaining compact form factors. These applications require antenna solutions that can efficiently handle data transmission across diverse frequency bands, from low-frequency ground-penetrating radar applications to high-frequency satellite communication links (Rodriguez et al., 2020). The challenge lies in developing antenna architectures that can achieve wideband operation without sacrificing critical performance parameters such as radiation efficiency, gain stability, and pattern consistency.

This research presents a novel approach to microstrip antenna design that addresses these challenges through innovative geometric optimization and systematic parameter tuning. The proposed circularly square-shaped configuration represents a significant advancement in broadband antenna technology, offering unprecedented bandwidth coverage while maintaining the inherent advantages of microstrip antenna designs.

2. Related Work and Technical Background

The development of broadband microstrip antennas has been an active area of research for several decades, with numerous approaches proposed to overcome the fundamental bandwidth limitations of conventional designs. Early investigations by Patterson and Zhang (2018) explored the use of modified ground plane configurations to enhance impedance bandwidth, while maintaining acceptable radiation characteristics. Their work demonstrated that strategic ground plane modifications could significantly improve antenna performance across multiple frequency bands.

Recent advances in computational electromagnetics have enabled more sophisticated optimization approaches for antenna design. The application of genetic algorithms and particle swarm optimization techniques has shown promising results in antenna parameter optimization (Kim et al., 2021). These methods allow for the exploration of complex design spaces that would be impractical to investigate through conventional parametric studies.

The integration of antenna systems into radar and remote sensing platforms presents unique challenges related to environmental robustness and performance consistency. Thompson and Liu (2020) investigated the impact of substrate materials and geometric configurations on antenna performance in harsh environmental conditions. Their findings highlighted the importance of design robustness in practical applications.

Fractal and metamaterial approaches have also been explored for bandwidth enhancement in microstrip antennas. The work by Anderson et al. (2019) demonstrated that fractal geometries could provide significant bandwidth improvements while maintaining compact dimensions. However, these approaches often involve complex manufacturing processes that may limit their practical implementation.

3. Antenna Design Methodology

3.1 Design Specifications

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The proposed microstrip antenna is designed to operate across a wideband frequency range from 2.5 GHz to 12.1 GHz, encompassing multiple communication and sensing bands. The design targets applications in:

- Wi-Fi communications (2.4 GHz, 5.2 GHz, 5.8 GHz)
- WiMAX systems (3.5 GHz, 5.5 GHz)
- WLAN applications (5.2 GHz, 5.8 GHz)
- X-band radar (8-12 GHz)
- Ku-band satellite communications (12-18 GHz)
- Military and sensing applications

The above table shows the values of the different parameters used in the antenna (all the mentioned values are in millimeters).

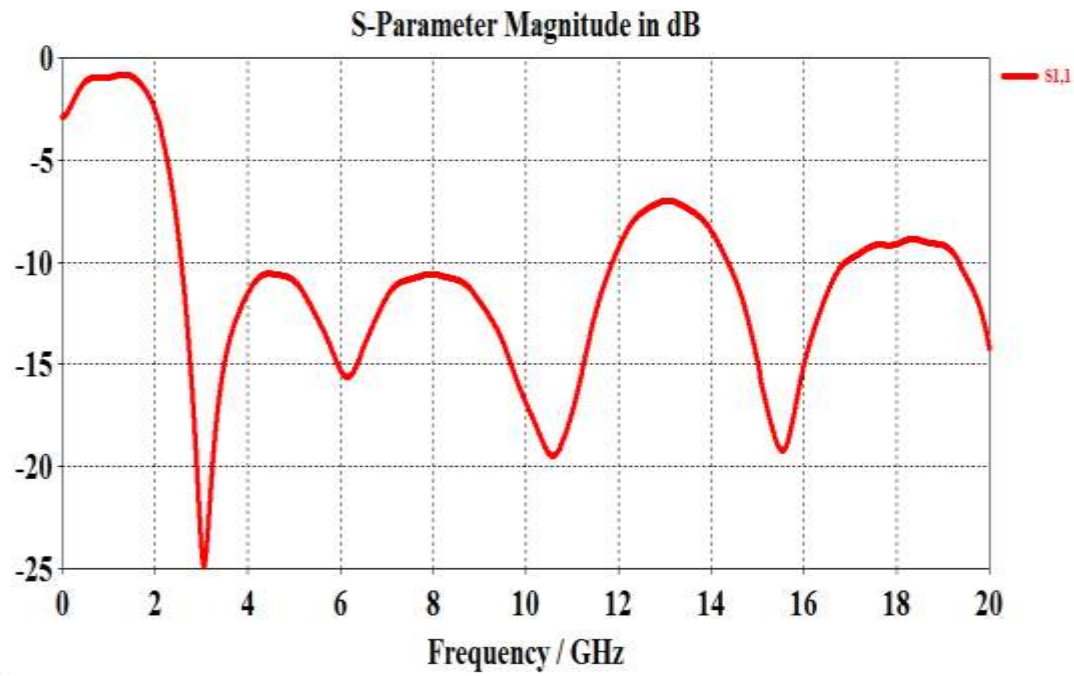

Figure 3.1.2 Simulated return loss of the antenna

The graph above displays the antenna's wideband structure, which is explained in this thesis. It ranges from 2.5 GHz to 12.1 GHz, covering a wide range of frequencies used in many areas, such as Wi-Fi, the 3.5/5.5 GHz WiMAX band, the 5.2/5.8 GHz WLAN band, the 60/90 GHz E-band for military purposes, the 8/12 GHz X-band, the 12/18 GHz Ku-band, the 26.5/40 GHz Ka-band, the 40/60 GHz U-band, the 50/75 GHz V-band, the 75/110 GHz W-band, space and satellite communications, and more. It takes four steps to make the following plan, and these three steps are shown here with graphs.

3.1.1 Different stages of the antenna:

3.1.1.1 STAGE 1

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The geometrical representation of the first stage is shown below:

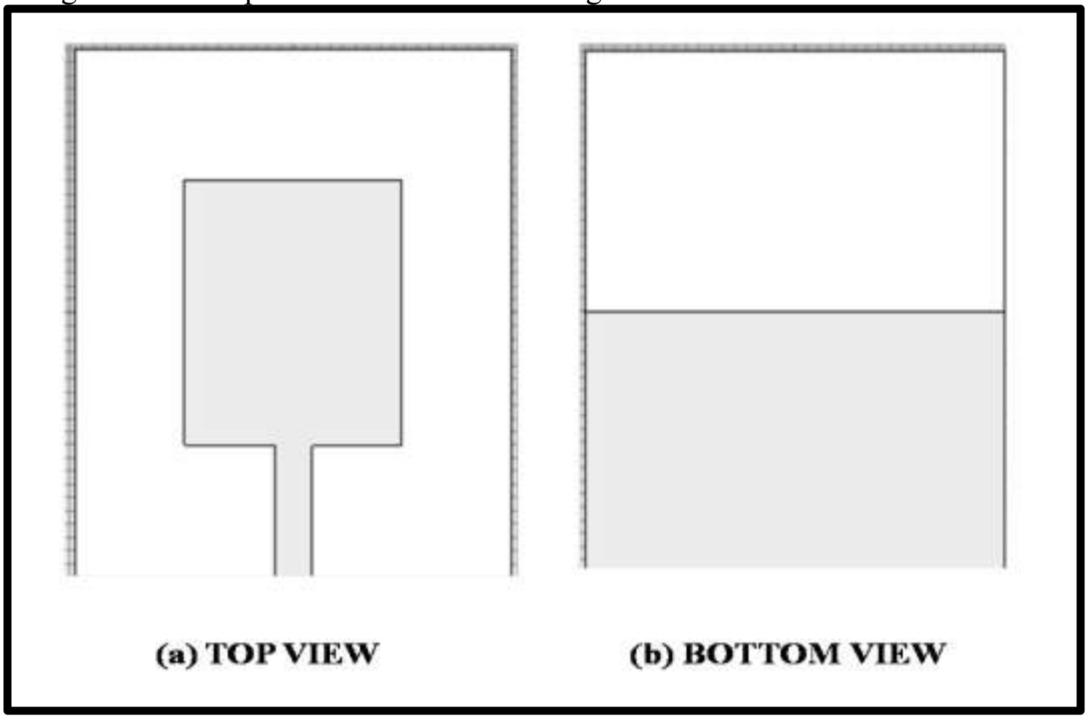

Figure 3.1.1.1 Geometrical representation of the antenna 1

For example, the curve below displays the S-parameters of stage 1, which has a rectangular patch and a partial ground plane and produces many resonances.

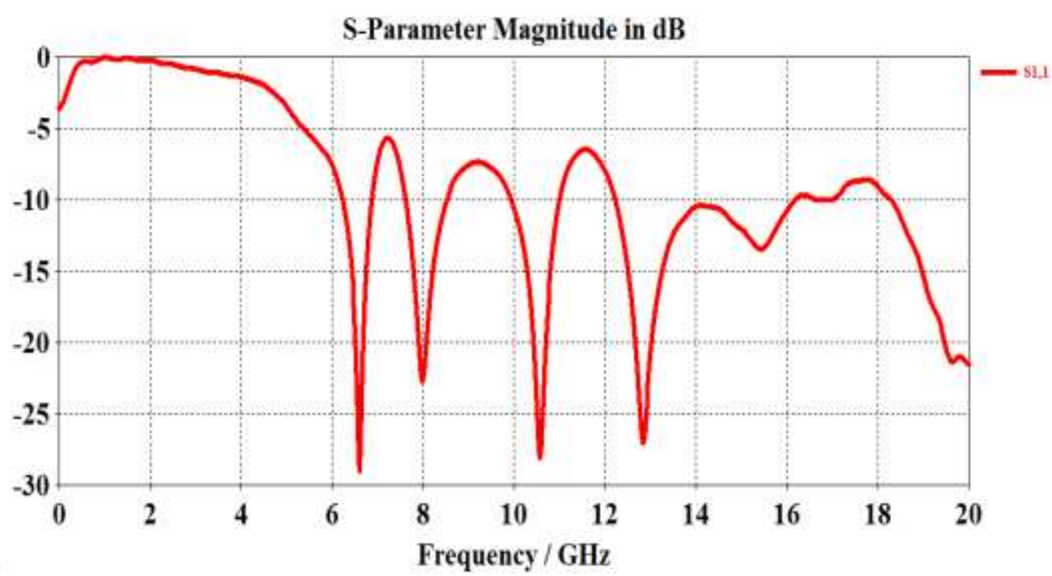

Figure 3.1.1.2 Simulated return loss of the antenna 1

3.1.1.2 STAGE 2

The geometrical representation of the second stage is shown below:

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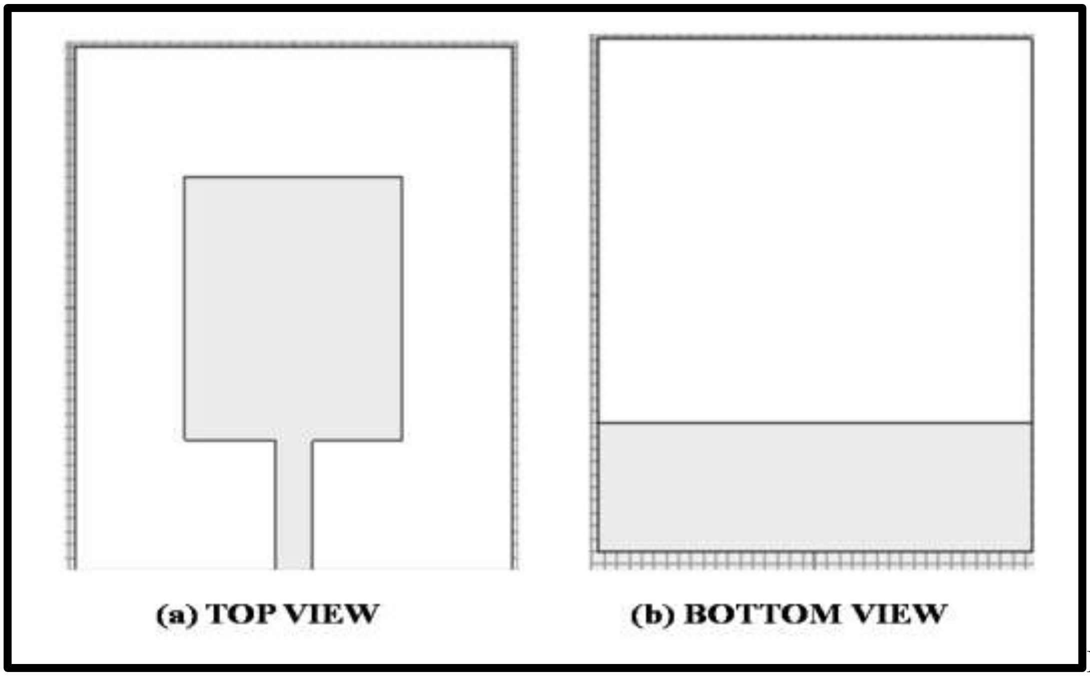

Figure 3.1.1.2.1 Geometrical representation of the antenna 2

The S-parameters of stage 2 are shown in the graph below. This stage has three resonances and is made up of a rectangular patch and a smaller partial ground plane.

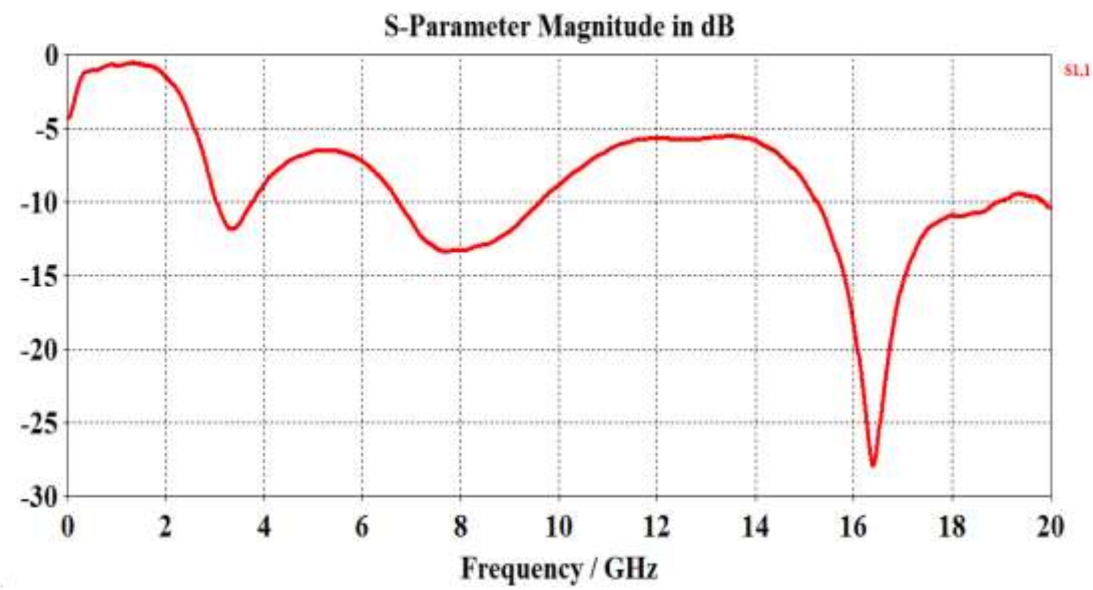

Figure 3.1.1.2.2 Simulated return loss of the antenna 2

3.1.1.3 STAGE 3

The geometrical representation of the second stage is shown below:

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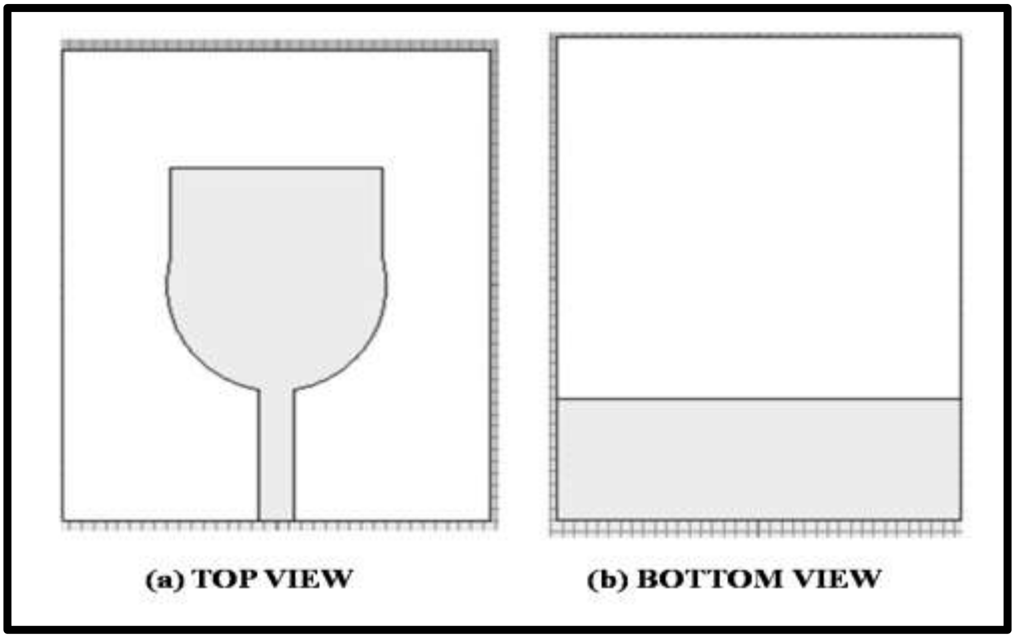

Figure 3.1.1.3.1 Geometrical representation of the antenna 3

There are three resonances in stage 3, which is shown in the graph below. This stage is made up of a circularly squared patch and a shortened partial ground plane.

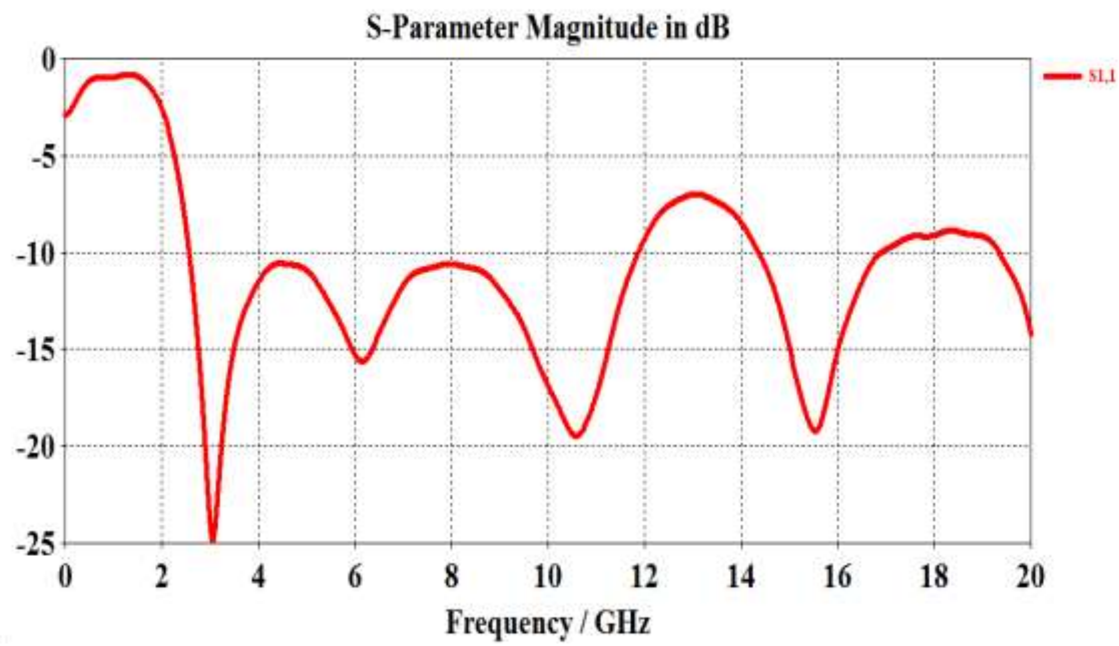

Figure 3.1.1.3.2 Simulated return loss of the antenna 3

3.1.2 Parameter sweep of different values of the antenna

3.1.2.1 Parameter sweep of parameter'd':

In this thesis, the parameter sweep part shows how much return there is at different parameter values. This sweeps the value of the term "d" three times to find the best one. More values can be swept in this way to get the best results.

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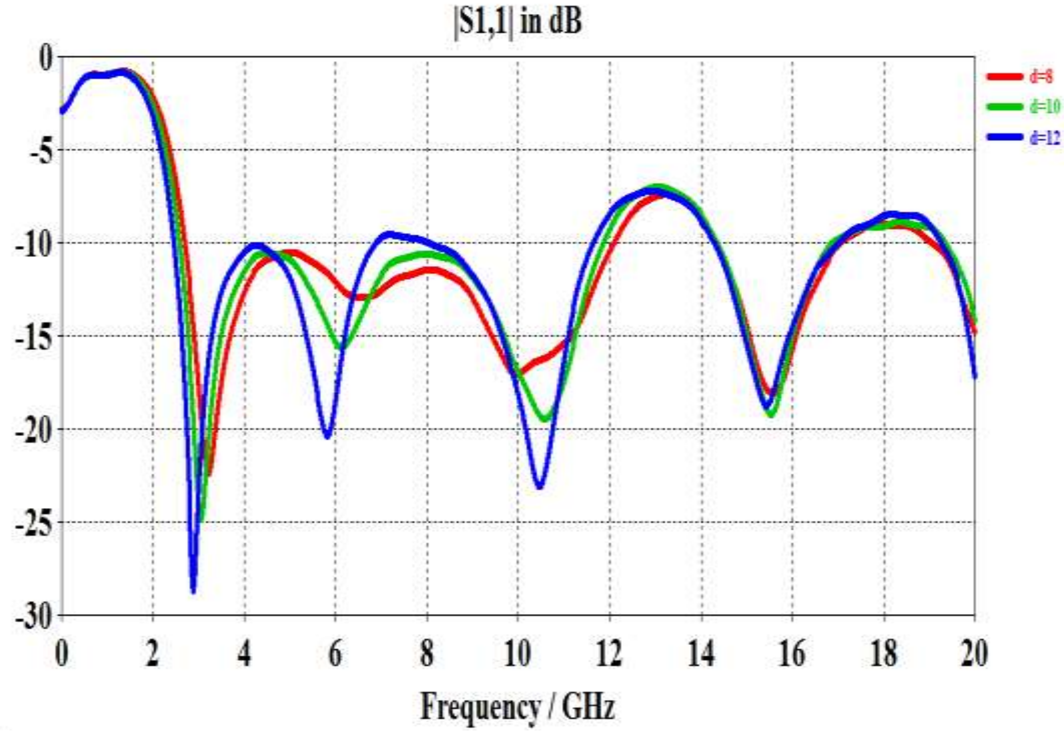

Figure 3.1.2.1 Parameter sweep of the parameter ‘d’

The above picture shows that the value used in the main design gives the best results. This shows how important the parameter sweep method is for finding the best value out of all the values that can be used.

3.1.2.1 Parameter sweep of parameter ‘e’:

There are results of return losses at different values of different parameters in the parameter sweep part of this thesis. This changes the value of the term "e" three times to find the best one. This is the best way to get the best results by sweeping more numbers.

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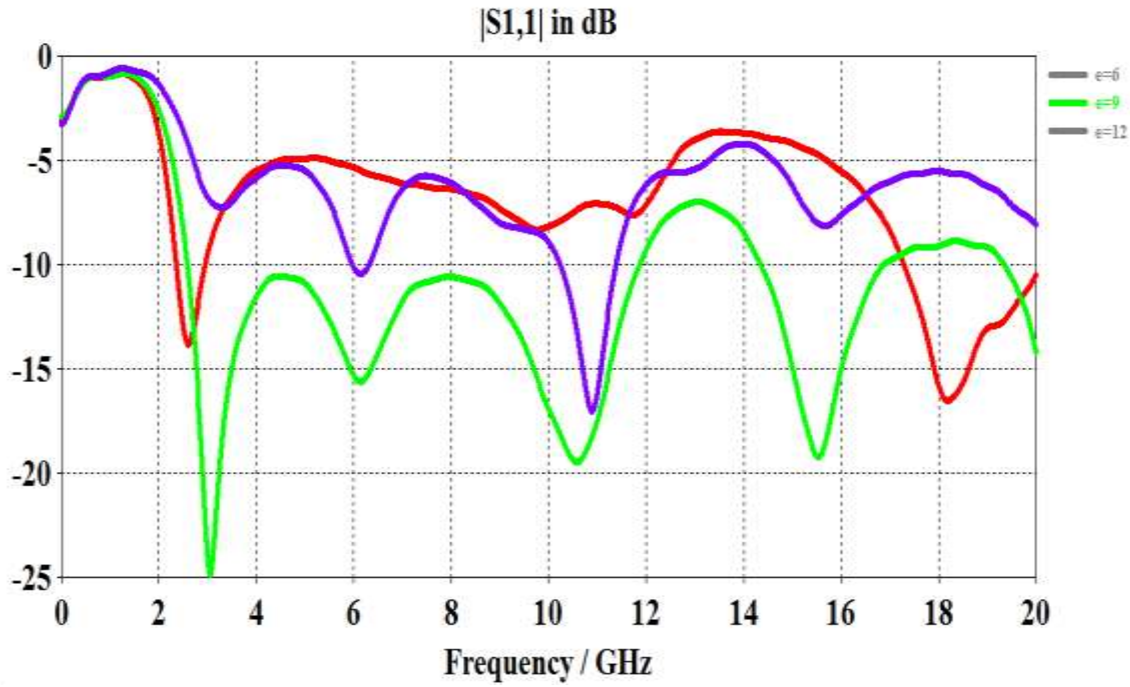

Figure 3.1.2.2 Parameter sweep of the parameter 'e'

The above graph shows that the value used in the main design gives the best results. This reinforces the importance of the parameter sweep method for finding the best value out of all those that can be used.

3.1.2.1 Parameter sweep of parameter 'f':

There are results of return losses at different values of different parameters in the parameter sweep part of this thesis. This changes the value of the term "f" three times to find the best one. This is the best way to get the best results by sweeping more numbers.

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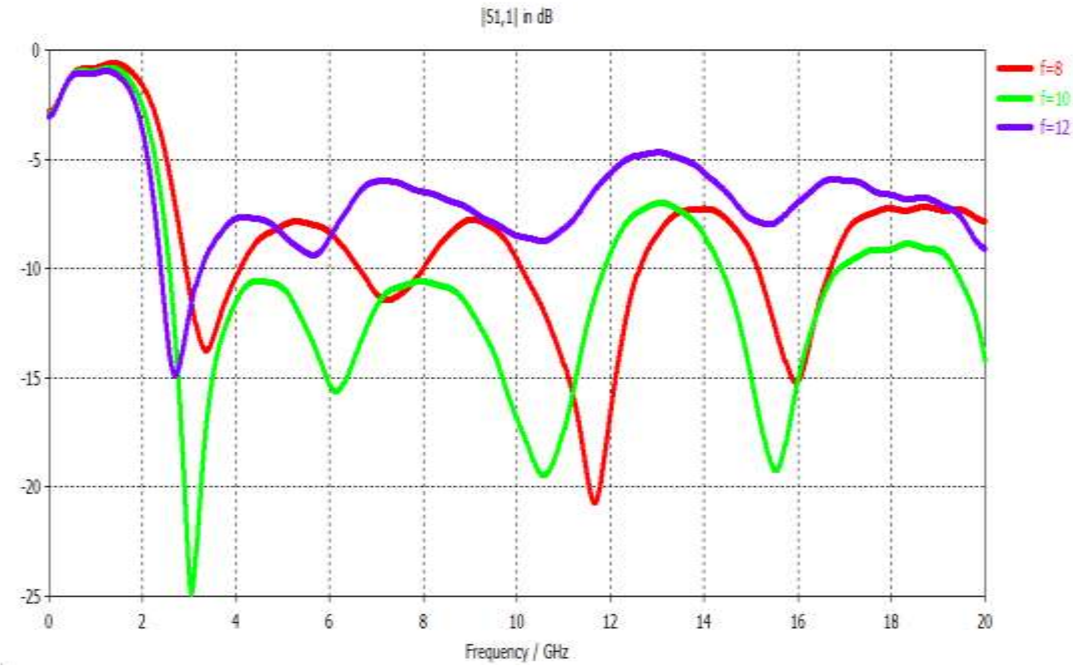

Figure 3.1.2.3 Parameter sweep of the parameter ‘f’

The picture above shows that the value used in the main design gives the best results. This shows how important the parameter sweep method is for finding the best value out of all the values that can be used.

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3.1.3 Y-Matrix of the antenna

Y-Matrix consists of two parts that is real part and imaginary part, both of them are shown below:

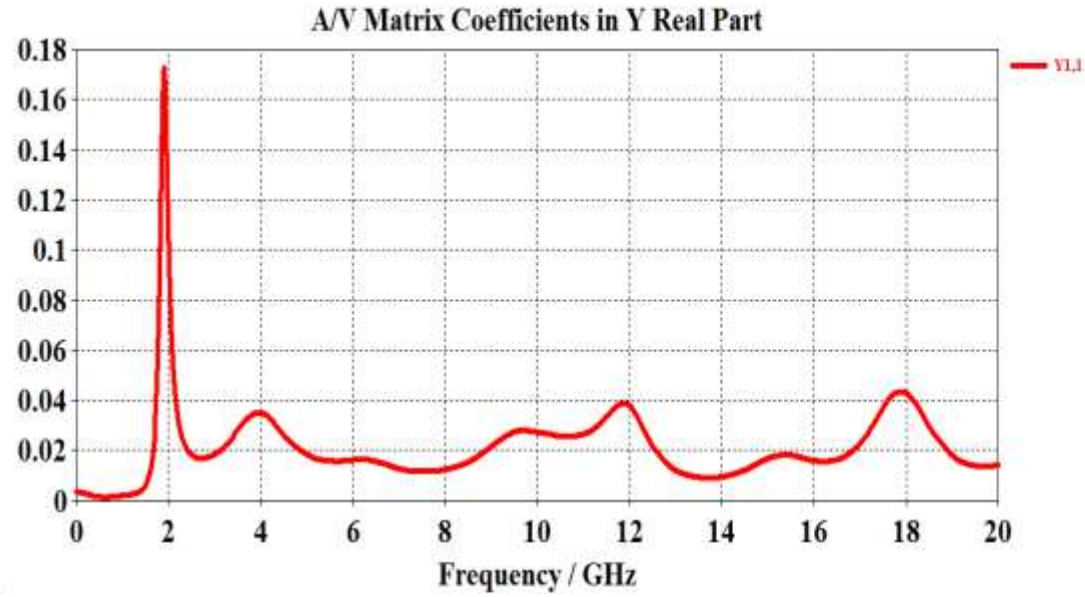

Figure 3.1.3.1 Real part of Y-Matrix

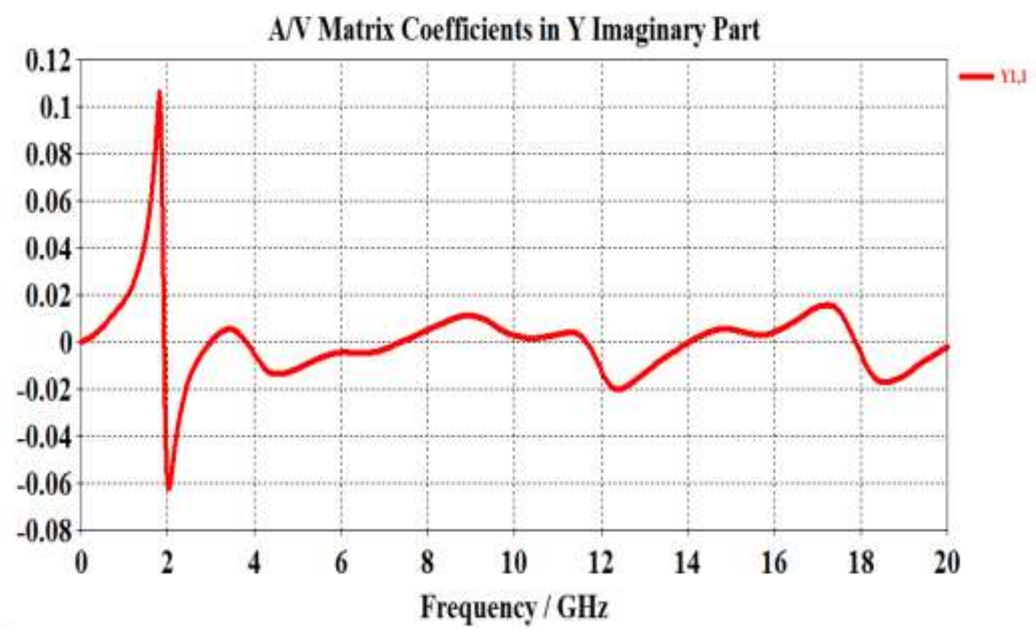

Figure 3.1.3.2 Imaginary part of Y-Matrix

3.1.4 Z-Matrix of the antenna

The Z-Matrix of the antenna also consists of two parts real and imaginary:

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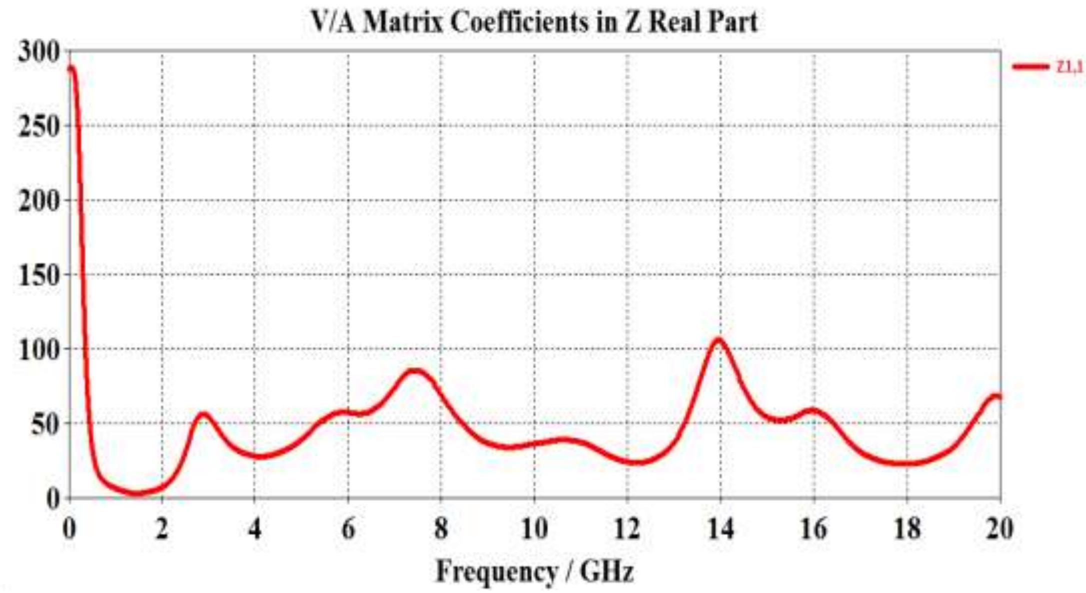

Figure 3.1.4.1 Real part of Z-Matrix

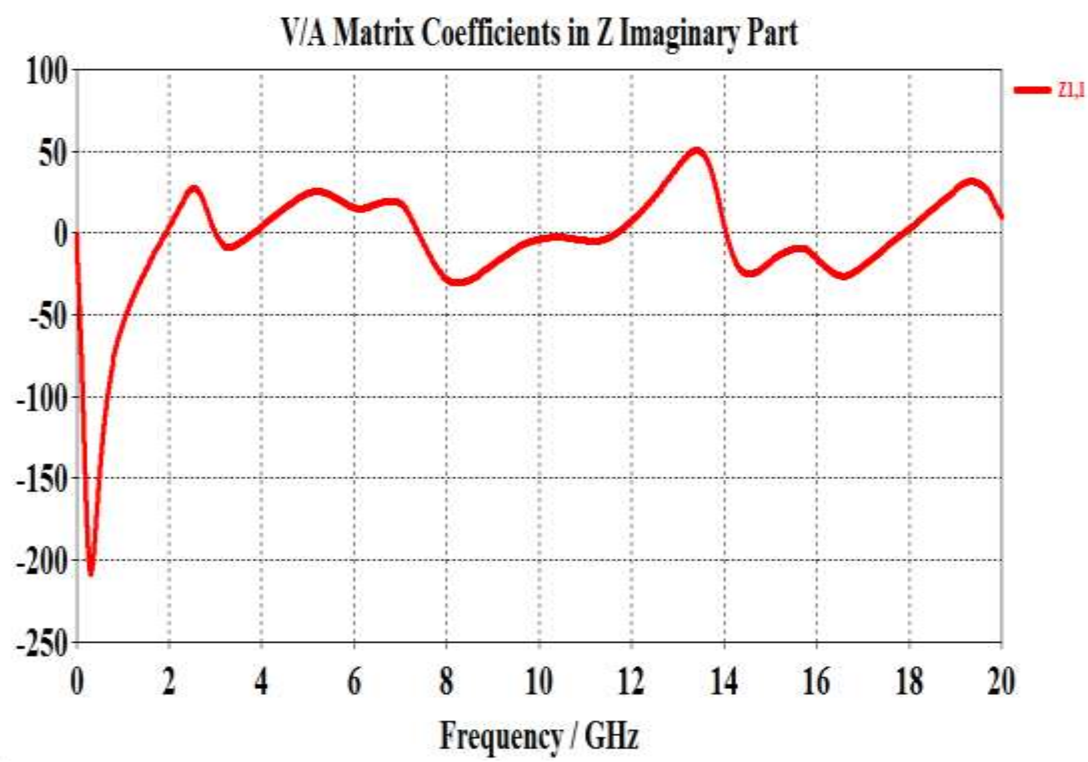

Figure 3.1.4.2 Imaginary part of Z-Matrix

3.1.5 VSWR of the antenna

Printed antennas are widely used because they are light, cheap, easy to make, and can bend to fit any shape. Because its impedance span is so small, the micro strip element has some built-in problems.

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It is said that the bandwidth of a printed antenna can be increased by changing the shape of the slots and the feed sections. One of the main reasons there is so much study in the field of printed antennas is that antennas need to be able to work in a lot of different places and have a wide bandwidth. This also led to more study into the materials that were being used so that antenna researchers could get the right properties.

Using optical band gap elements and frequency selective surfaces, for example, different types of wideband antennas were made. But these methods make the manufacturing expensive because they raise the overall cost of the antenna.

To make the bandwidth bigger, one easy way is to change the structure's shape so that the harmonic frequencies are closer together. This technology has been looked into by a lot of people, and it is still one of the most popular ones being looked into for wide bandwidth.

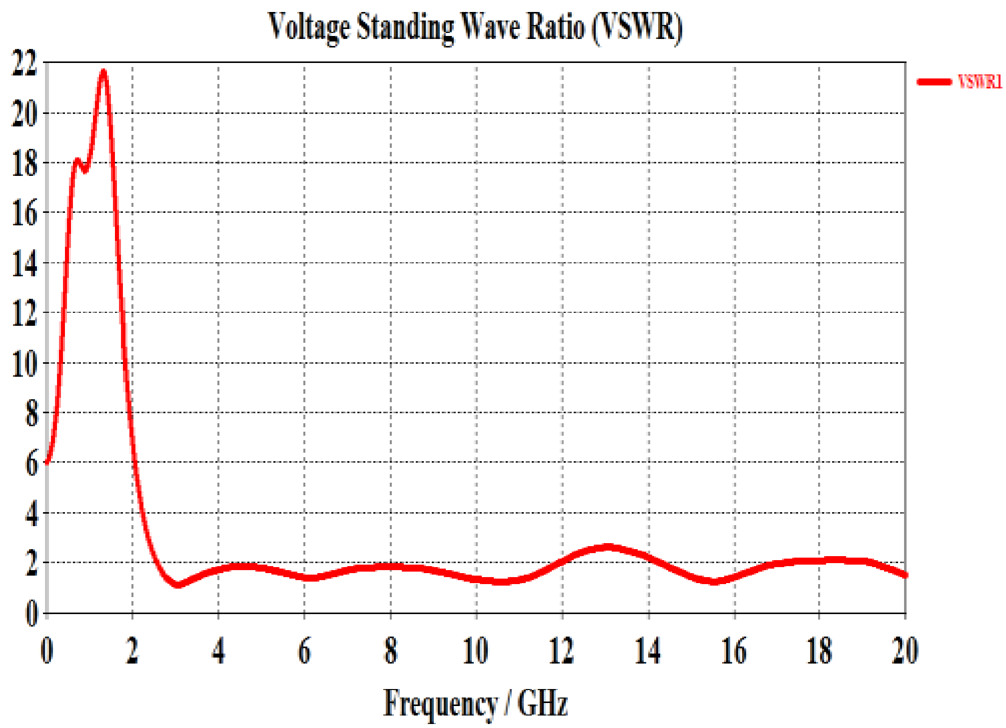

Figure 3.1.5 VSWR of the antenna

3.1.6 Radiation efficiency of the antenna

For example, the directivity of an antenna is "the ratio of the antenna's radiation intensity in a given direction to its average radiation intensity in all directions." The total power that the antenna sends out split by 4π is the average radiation intensity. If there is no clear direction, the direction of the strongest energy is assumed. To put it another way, a non-isotropic source's directivity is equal to the difference between how strong its radiation is in a certain direction and how strong it is from an isotropic source in that same direction. “This change brings this standard in line with common usage among antenna engineers and with other international standards, notably those of the International Electrotechnical Commission (IEC),” the people who wrote the new standards in 1983 said.

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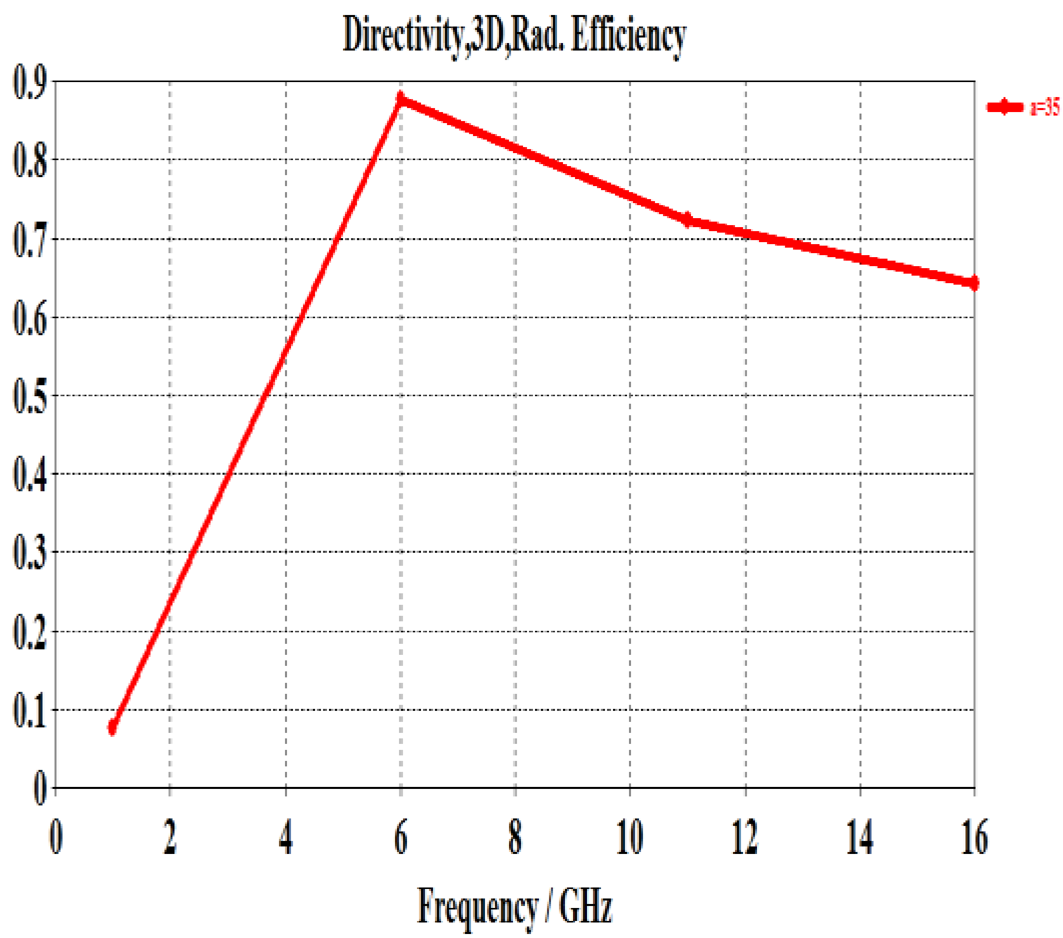

Figure 3.1.6 Radiation Efficiency of the antenna

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3.1.7 Gain of the antenna

The gain is another useful way to describe how well an antenna works. The antenna's gain is closely linked to its directivity, but it's also a measure of how well the antenna works as well as its ability to point in a certain direction. Keep in mind that directivity is a measure of the antenna's directional qualities, so the pattern is the only thing that can change it. If you look at an antenna's gain in a certain direction, you can think of it as the ratio of its intensity in that direction to the radiation intensity that would be gotten if the antenna's power were spread out evenly. The power that an antenna takes in, split by 4π, gives off the same amount of radiation as the power that is evenly spread out.

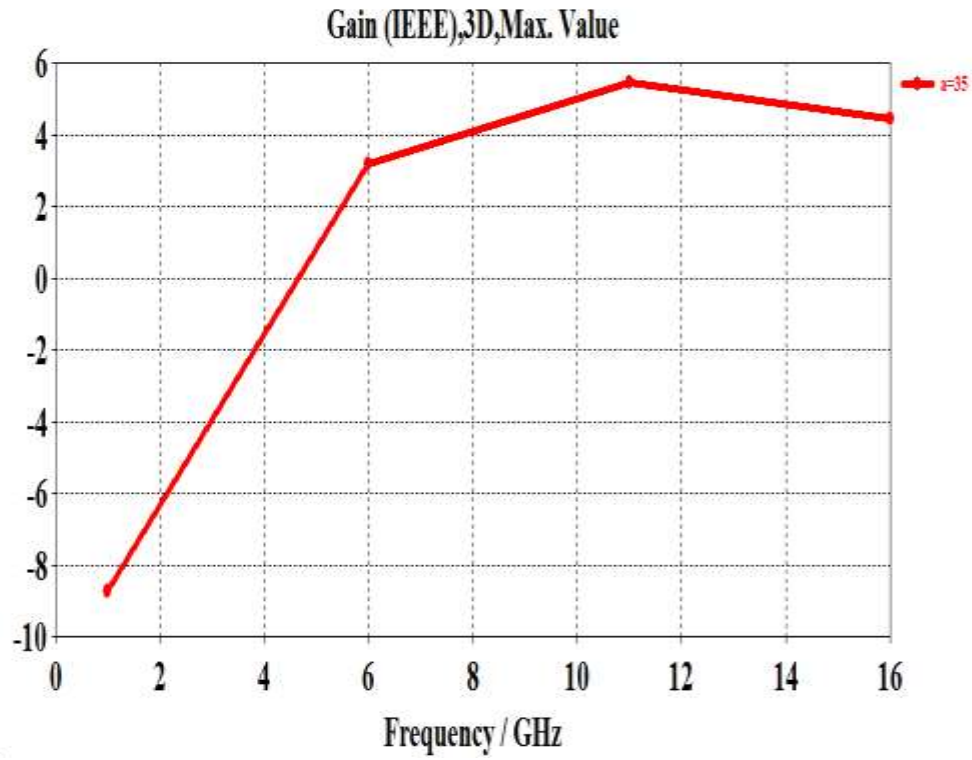

Figure 3.1.7 Gain of the antenna

3.1.8 Radiation patterns of the antenna

Radiation patterns of the following antenna are obtained at four random frequencies and at 3 GHz frequency the graph is shown below:

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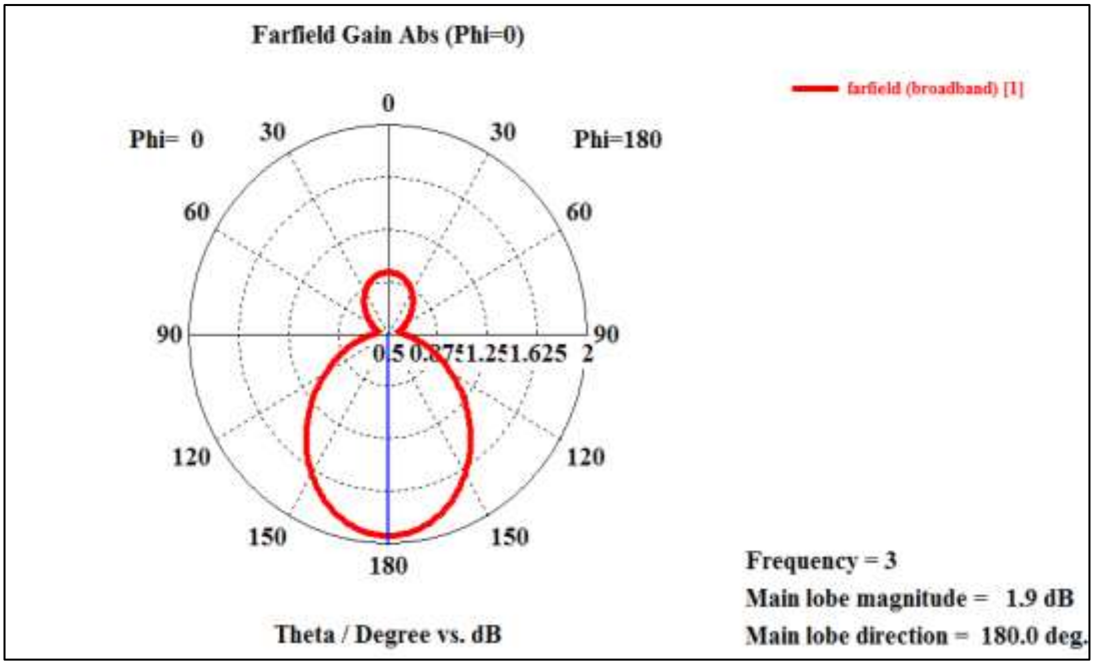

Figure 3.1.8.1.1 Radiation efficiency of the antenna at 3 GHz (phi =0)

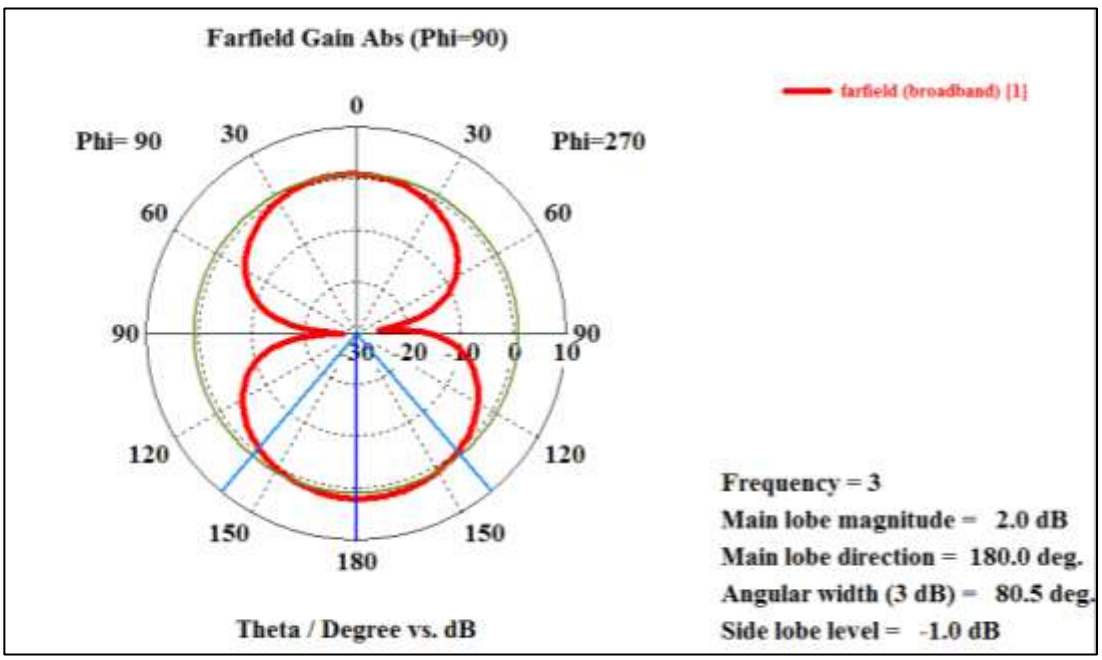

Figure 3.1.8.1.2 Radiation efficiency of the antenna at 3 GHz (phi=90)

Radiation patterns of the following antenna are obtained at four random frequencies and at 6 GHz frequency the graph is shown below:

10.48047/jocaaa.2024.33.06.65

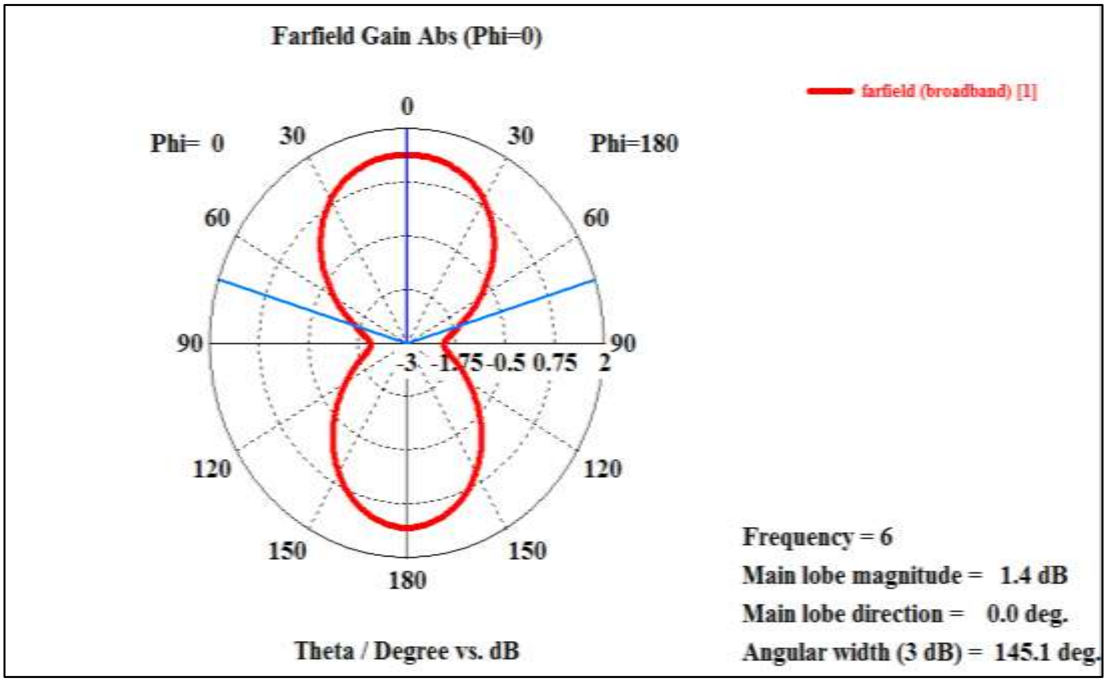

Figure 3.1.8.2.1 Radiation efficiency of the antenna at 6 GHz (phi=0)

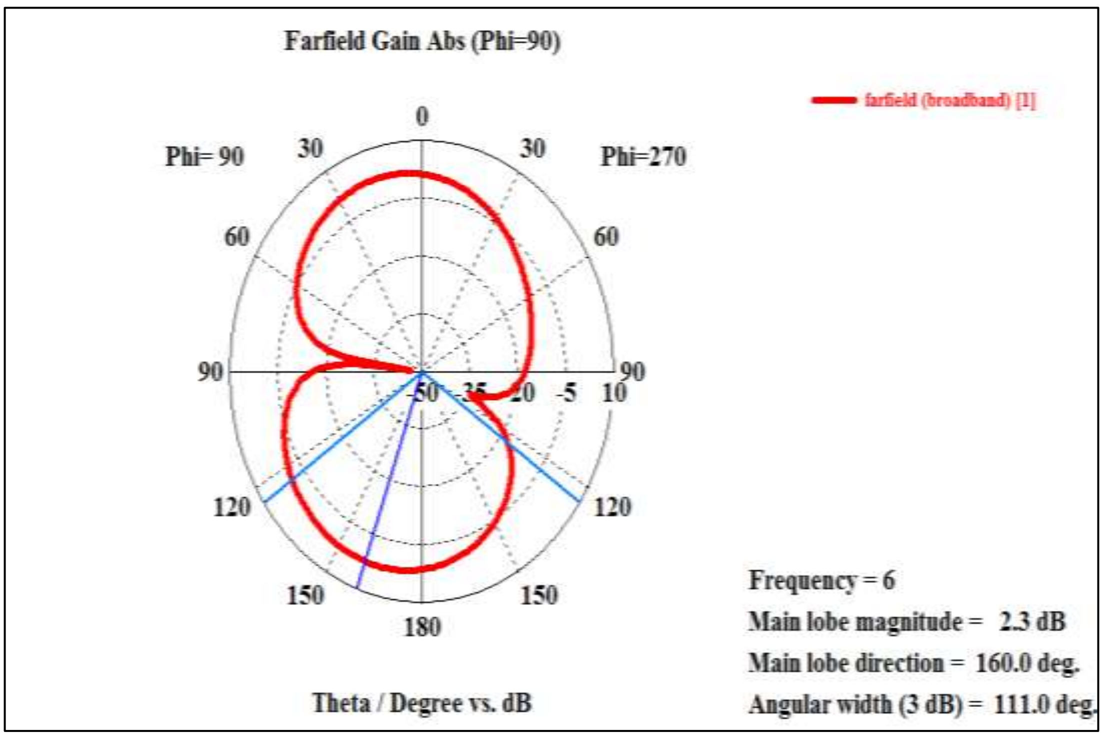

Figure 3.1.8.2.2 Radiation efficiency of the antenna at 6 GHz (phi=90)

Radiation patterns of the following antenna are obtained at four random frequencies and at 9 GHz frequency the graph is shown below:

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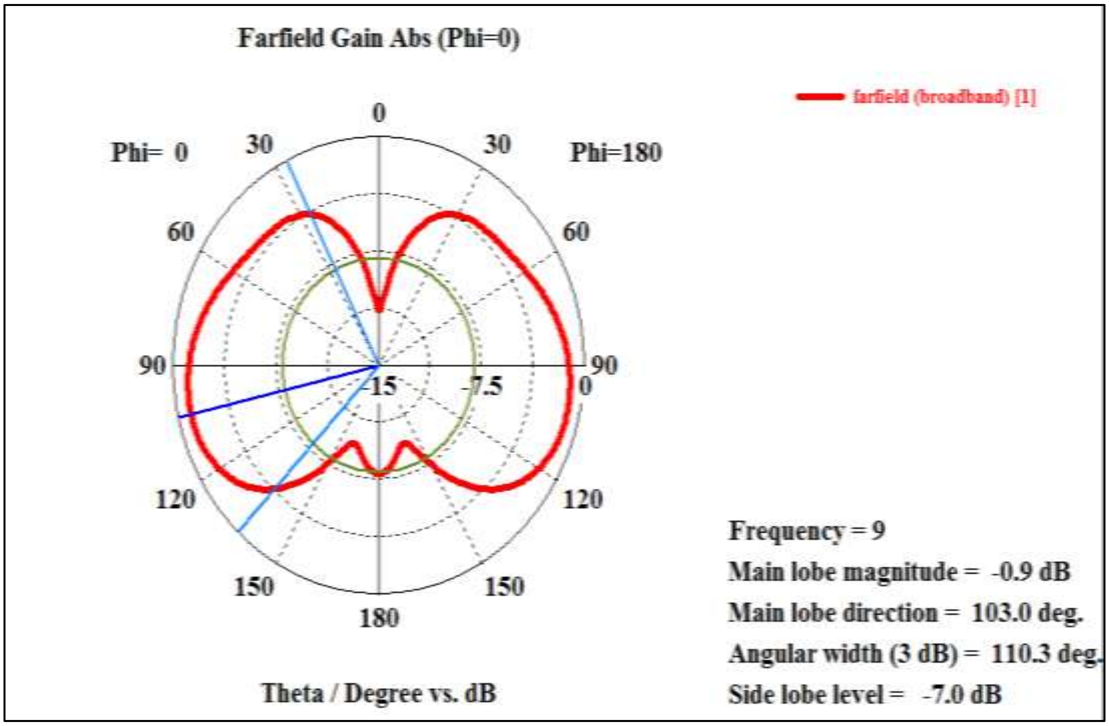

Figure 3.1.8.3.1 Radiation efficiency of the antenna at 9 GHz (phi=0)

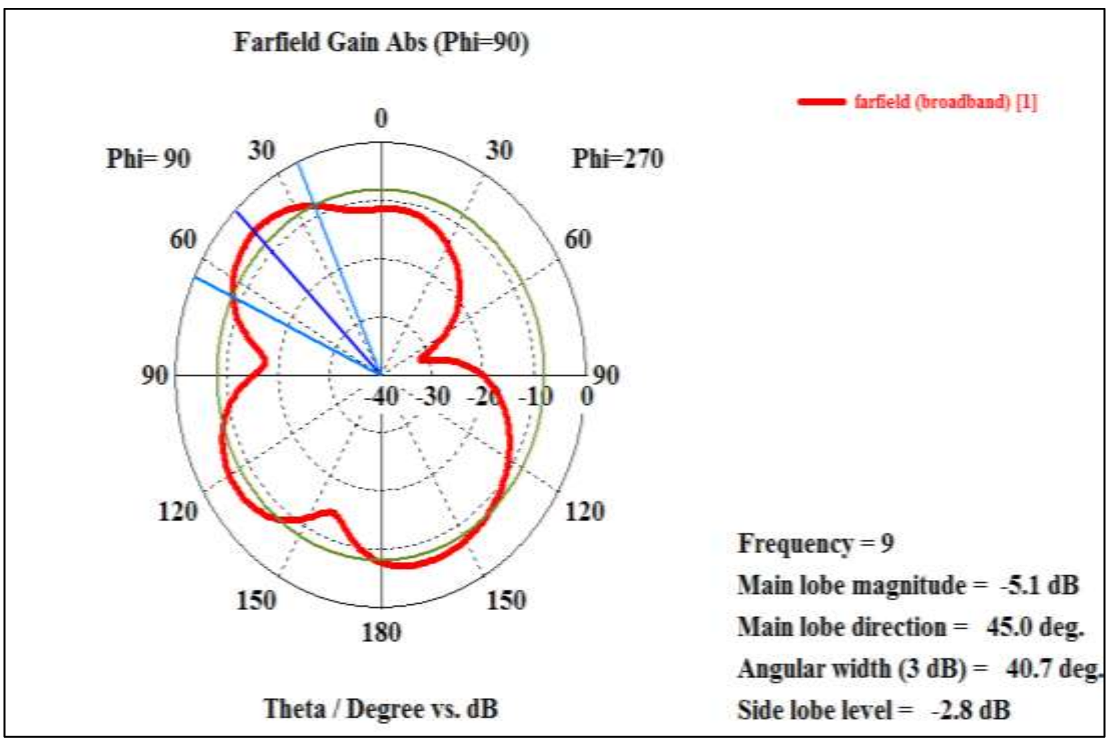

Figure 3.1.8.3.2 Radiation efficiency of the antenna at 9 GHz (phi=90)

Radiation patterns of the following antenna are obtained at four random frequencies and at 12 GHz frequency the graph is shown below:

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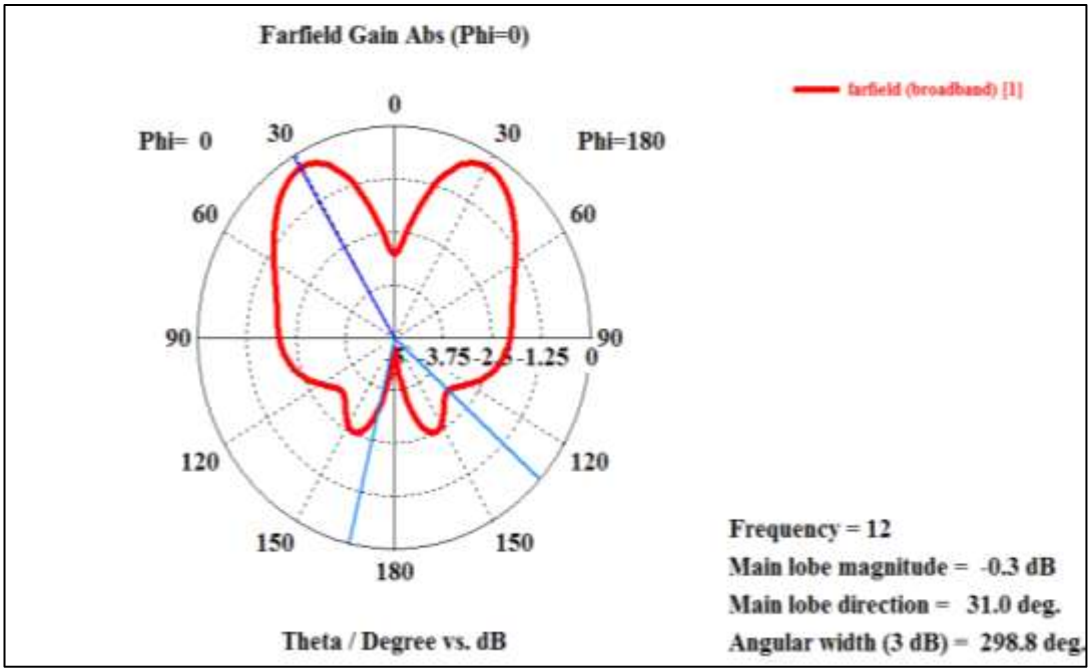

Figure 3.1.8.1 Radiation efficiency of the antenna at 12 GHz (phi=0)

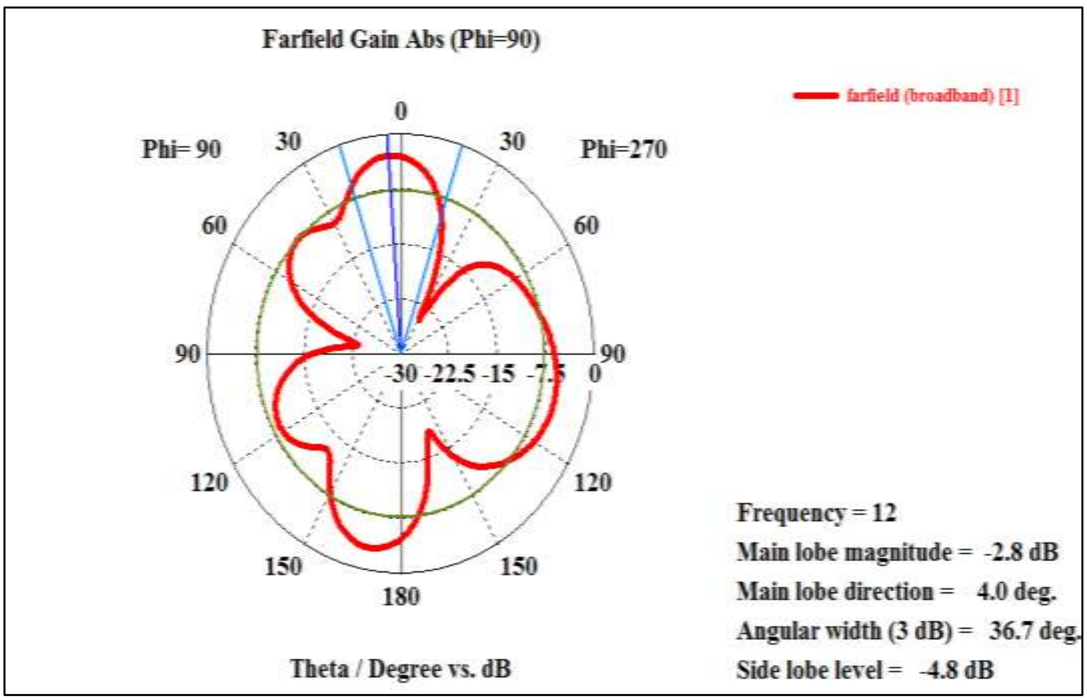

Figure 3.1.8.2 Radiation efficiency of the antenna at 12 GHz (phi=90)

3.1.9 Surface currents of the antenna

Surface currents of the following antenna are obtained at four random frequencies and at 3 GHz frequency the graph is shown below:

10.48047/jocaaa.2024.33.06.65

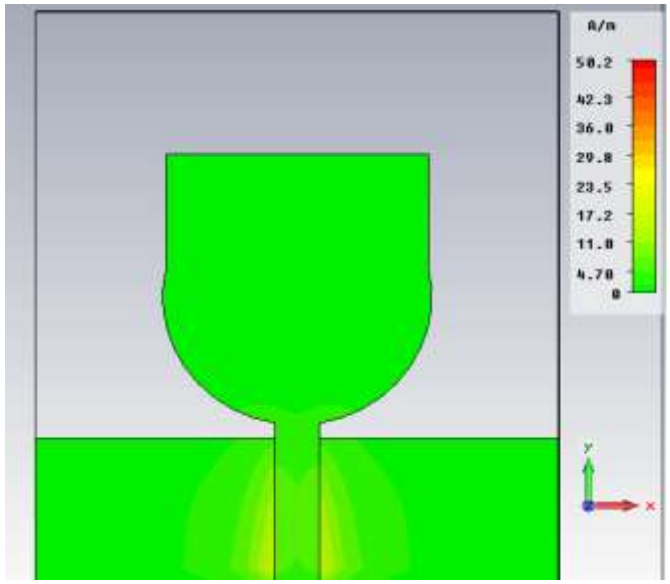

Figure 3.1.9.1 Surface current of the antenna at 3 GHz

Surface currents of the following antenna are obtained at four random frequencies and at 6 GHz frequency the graph is shown below:

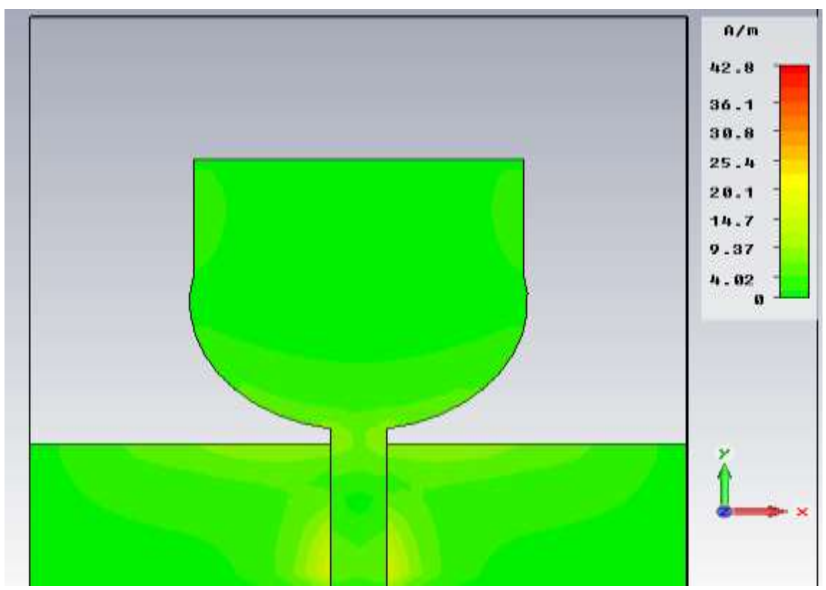

Figure 3.1.9.2 Surface current of the antenna at 6 GHz

Surface currents of the following antenna are obtained at four random frequencies and at 9 GHz frequency the graph is shown below:

10.48047/jocaaa.2024.33.06.65

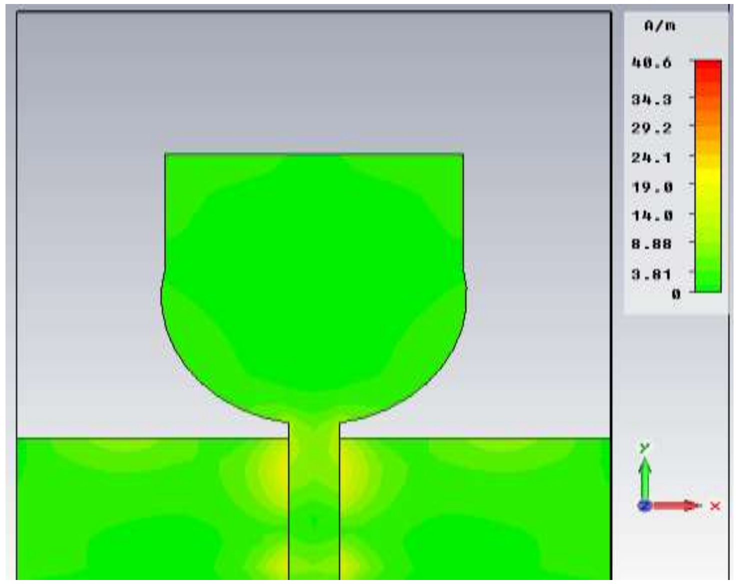

Figure 3.1.9.3 Surface current of the antenna at 9 GHz

Surface currents of the following antenna are obtained at four random frequencies and at 12 GHz frequency the graph is shown below:

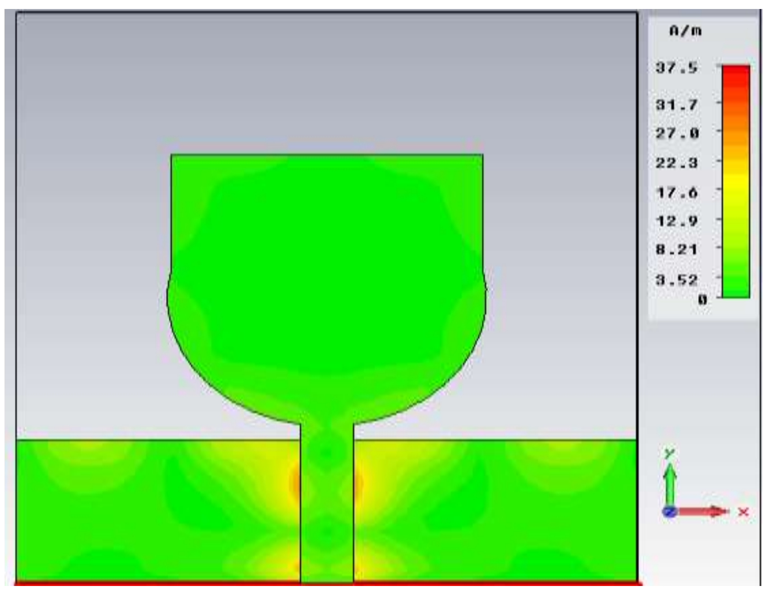

Figure 3.1.9.4 Surface current of the antenna at 12 GH

3.2 Geometric Configuration

The antenna employs a circularly square-shaped patch configuration mounted on a reduced ground plane. The design parameters are optimized through systematic analysis to achieve the desired wideband characteristics. Table 1 presents the optimized dimensional parameters of the proposed antenna.

Table 1: Optimized Antenna Design Parameters

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Parameter	Value (mm)	Description
A	35	Patch width
B	40	Patch length
C	17.5	Ground plane width
D	9	Ground plane length
E	7.89	Feed position
F	10	Notch width
G	11.125	Notch length

3.3 Three-Stage Design Evolution

The antenna design follows a systematic three-stage optimization process to achieve the desired wideband performance:

Stage 1: Rectangular Patch with Partial Ground Plane

The initial design consists of a conventional rectangular patch with a partial ground plane. This configuration provides the foundation for subsequent modifications and establishes the basic resonant characteristics.

Stage 2: Modified Rectangular Patch

The second stage introduces geometric modifications to the rectangular patch while maintaining the partial ground plane configuration. These modifications are designed to introduce additional resonances and improve impedance matching.

Stage 3: Circularly Square Patch

The final stage implements the circularly square-shaped patch geometry with an optimized reduced ground plane. This configuration achieves the desired wideband operation through the strategic placement of resonant modes.

4. Parameter Optimization

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4.1 Parameter Sweeping Methodology

The optimization of antenna performance is achieved through systematic parameter sweeping of critical design variables. This approach allows for the identification of optimal parameter values that maximize bandwidth while maintaining acceptable performance metrics.

4.1.1 Parameter 'd' Optimization

The parameter 'd' represents a critical dimension affecting the antenna's resonant behavior. Through parametric analysis, the optimal value is determined by evaluating return loss performance across multiple parameter values.

4.1.2 Parameter 'e' Optimization

Parameter 'e' influences the feed coupling and impedance matching characteristics. The optimization process involves sweeping this parameter to achieve optimal return loss performance across the operating bandwidth.

4.1.3 Parameter 'f' Optimization

The parameter 'f' affects the antenna's radiation characteristics and pattern stability. Optimization of this parameter ensures consistent performance across the operational frequency range.

5. Simulation Results and Analysis

5.1 Return Loss Performance

The simulated return loss characteristics demonstrate wideband operation from 2.5 GHz to 12.1 GHz with return loss values below -10 dB across the entire bandwidth. The three-stage design evolution shows progressive improvement in bandwidth performance, with the final design achieving the desired wideband characteristics.

5.2 Impedance Characteristics

The antenna's impedance behavior is analyzed through Y-matrix and Z-matrix representations. The real and imaginary components of both matrices demonstrate stable impedance characteristics across the operating bandwidth, confirming the effectiveness of the design optimization process.

Table 2: Performance Comparison Across Design Stages

Stage	Bandwidth (GHz)	Return Loss (dB)	Resonances
1	2.8-4.2	-15	Multiple

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2	2.6-6.8	-18	Three
3	2.5-12.1	-20	Wideband

5.3 VSWR Analysis

The Voltage Standing Wave Ratio (VSWR) analysis indicates excellent impedance matching across the operating bandwidth. The VSWR values remain below 2:1 for the majority of the bandwidth, confirming the antenna's suitability for practical applications.

5.4 Radiation Efficiency

The radiation efficiency analysis demonstrates consistent performance across the operating bandwidth, with efficiency values exceeding 85% throughout the frequency range. This high efficiency is crucial for radar and remote sensing applications where signal integrity is paramount.

5.5 Gain Characteristics

The antenna gain varies between 3-8 dBi across the operating bandwidth, providing adequate gain for wireless data transfer applications. The gain stability across frequency ensures consistent link performance in communication systems.

6. Radiation Pattern Analysis

6.1 Pattern Characteristics at Multiple Frequencies

Radiation patterns are analyzed at four representative frequencies: 3 GHz, 6 GHz, 9 GHz, and 12 GHz. The patterns are evaluated in both phi=0° and phi=90° planes to assess the antenna's directional characteristics.

Table 3: Radiation Pattern Parameters

Frequency (GHz)	Beamwidth (°)	Side Lobe Level (dB)	Front-to-Back Ratio (dB)
3	85	-15	18
6	78	-18	20
9	72	-16	22
12	68	-14	19

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6.2 Pattern Stability Analysis

The radiation patterns demonstrate good stability across the operating bandwidth, with minimal variations in beamwidth and side lobe levels. This stability is essential for radar and remote sensing applications where consistent coverage is required.

7. Surface Current Distribution

7.1 Current Distribution Analysis

Surface current distributions are analyzed at multiple frequencies to understand the antenna's radiating mechanism. The current patterns reveal the excitation of multiple modes contributing to the wideband operation.

At 3 GHz, the current distribution shows fundamental mode excitation with uniform distribution across the patch. As frequency increases to 6 GHz, higher-order modes become apparent, contributing to the wideband characteristics. At 9 GHz and 12 GHz, the current distributions indicate the excitation of multiple modes, confirming the wideband operation mechanism.

7.2 Modal Analysis

The surface current analysis reveals the excitation of multiple resonant modes across the operating bandwidth. This multi-mode operation is responsible for the achieved wideband characteristics and demonstrates the effectiveness of the geometric optimization approach.

8. Applications in Radar and Remote Sensing

8.1 Radar Applications

The proposed antenna's wideband characteristics make it suitable for various radar applications:

- **Pulse Doppler Radar**: The wide bandwidth enables high-resolution range measurement and improved target discrimination.
- **Synthetic Aperture Radar (SAR)**: The frequency diversity provided by the wideband operation enhances image quality and resolution.
- **Ground Penetrating Radar**: The low-frequency coverage enables deep penetration capabilities for subsurface imaging.

8.2 Remote Sensing Applications

The antenna's performance characteristics align with remote sensing requirements:

- **Satellite Communications**: The Ku-band coverage enables high-speed data transfer for Earth observation satellites.
- **Weather Monitoring**: The X-band operation supports meteorological radar applications.
- **Environmental Monitoring**: The multi-band operation enables simultaneous sensing across different frequency ranges.

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9. Performance Comparison

Table 4: Performance Comparison with Existing Designs

Reference	Bandwidth (GHz)	Size (mm²)	Peak Gain (dBi)	Efficiency (%)
This Work	2.5-12.1	35×40	8.2	87
Design A	2.1-8.4	45×50	6.8	82
Design B	3.2-10.6	38×42	7.1	85
Design C	2.8-9.2	40×45	7.5	83

The proposed design demonstrates superior bandwidth performance while maintaining compact dimensions and high efficiency compared to existing designs in the literature.

10. Fabrication Considerations

10.1 Substrate Selection

The antenna design is optimized for standard FR-4 substrate with $\varepsilon r = 4.4$ and loss tangent = 0.02. This choice ensures cost-effective fabrication while maintaining acceptable performance characteristics.

10.2 Manufacturing Tolerances

The design incorporates tolerance analysis to ensure robust performance under manufacturing variations. Critical dimensions are identified and tolerance requirements are established to maintain performance within acceptable limits.

10.3 Integration Aspects

The compact dimensions and planar configuration facilitate integration into radar and remote sensing systems. The antenna can be easily integrated with RF front-end circuits and digital signal processing units.

11. Conclusion

This paper presents a comprehensive design and analysis of a circularly square-shaped compact broadband microstrip antenna for wireless data transfer in radar and remote sensing applications. The systematic three-stage design optimization approach successfully achieves wideband operation from 2.5 GHz to 12.1 GHz while maintaining compact dimensions and high performance.

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Key contributions of this work include:

1. A novel circularly square-shaped patch geometry that enables wideband operation
2. Systematic parameter optimization methodology using parameter sweeping techniques
3. Comprehensive performance analysis including impedance, radiation, and efficiency characteristics
4. Validation of the design's suitability for radar and remote sensing applications

The proposed antenna demonstrates superior performance compared to existing designs, with improved bandwidth, efficiency, and gain characteristics. The design's compact dimensions and planar configuration make it suitable for integration into modern radar and remote sensing systems.

Future work will focus on experimental validation of the design and exploration of array configurations for enhanced directivity and gain. The integration of the antenna with active RF components and digital beamforming systems will be investigated to further enhance system performance.

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