Khulna University of Engineering & Technology

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Project Report on: Design and Simulation of a Dual-Band Microstrip Patch Antenna using CST Microwave Studio.

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Submitted To:	***Submitted By:***
Md. Minhajul Islam Arnab Lecturer Department of ECE **Naymur Rahman** Lecturer Department of ECE	**Arian Rahman Aditta** Roll no: 2009028 **Ashrafi Zaman Sami** Roll no: 2009029 **Nushrath Jahan Jene** Roll no:2009030

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Abstract

This project explores the design, simulation, and optimization of a Vivaldi antenna using the powerful CST Microwave Studio. The main goals are to identify the optimal frequency range for specific applications, understand the fundamental principles of the Vivaldi antenna, and use theoretical methods to determine antenna dimensions based on desired operating frequencies. The study involves implementing critical geometrical parameters as variables in CST Microwave Studio to examine their impact on signal strength and directionality. Additionally, a mesh convergence test is performed to assess the relationship between mesh cells, S-parameters, and directivity. The motivation behind this project is to leverage CST software's advanced capabilities to gain a comprehensive understanding of the Vivaldi antenna's architecture, focusing on its wideband capabilities and directional radiation pattern.

Objectives

- To identify the specific frequency range(10 GHz and 21 GHz) required for the dual band patch antenna to work effectively for a specific application.
- To understand the basic working principles of dual band patch antennas, especially how they can operate at two distinct frequency bands simultaneously.
- To describe the theoretical methodology used to calculate the dimensions of different antenna components for the dual band operation based on the desired operating frequency range.
- To implement all critical geometrical parameters of the dual band patch antenna as variables in CST Microwave Studio and by adjusting specific frequency parameters, observe their impact on signal strength and direction.
- To perform a mesh convergence test for all cells per wavelength, counting the mesh cells with respect to the S-parameter (minimum magnitude in dB) and directivity (dB).

Introduction

Antennas are vital components in communication systems as they enable the transmission and reception of electromagnetic waves. They convert electrical signals into radio waves and vice versa, which allows for wireless communication over various distances. Whether it's for mobile phones, Wi-Fi, broadcasting, satellite communication, or radar systems, antennas are essential for achieving signal coverage, quality, and reliability. Their design and efficiency directly impact the performance of the entire communication system. This system aims to centralize all dining-related operations, including student information management, monthly payment tracking, meal adjustments (such as refunds for missed meals), and feedback management. It also facilitates quick query-based reporting to help administrators and hall managers oversee operations seamlessly.

Microstrip patch antennas are a type of antenna with a simple, flat ***metallic patch*** on a dielectric substrate. They're widely used in modern communication systems for their compactness, ease of fabrication, and ability to be integrated with circuitry.

Advantages*:*

1. ***Lightweight and low-profile*****:** Perfect for compact devices.

2. ***Ease of integration***: Can be directly printed on PCB boards.

3. ***Versatile designs***: Suitable for various frequencies and polarization schemes.

4. ***Cost-effective***: Simple manufacturing process reduces costs.

Motivation

1. This project leverages the powerful features of CST software, a leading electromagnetic simulation tool, to design, simulate, and optimize a Vivaldi antenna.

2. By delving into the specifics of Vivaldi antenna architecture, the team aims to gain a comprehensive understanding of its underlying principles, focusing on its wideband capabilities and directional radiation pattern.

Methodology

For the simulation of 1D parameters such as S-Parameters, Z Parameters, and Far field radiation patterns, CST Studio uses the Finite Integration Technique (FIT), a time-domain numerical method based on the integral form of Maxwell's equations. FIT is stable and accurate for extensive numerical calculations involving large grids and many time steps. It maintains physical properties and guarantees unique solutions by adopting integral quantities like voltage and current, which help in evaluating convergence. The first step in FIT discretization involves restricting the electromagnetic field problem to a bounded space region and decomposing it into a finite number of cells, which together form the computational grid. FIT is adaptable to various mesh types, including both orthogonal and non-orthogonal meshes, and enables local mesh refinement. The accuracy of FIT lies in its ability to generate exact algebraic analogs to Maxwell's equations, ensuring stable and physically consistent results.

Theory and Design

Theory:

A **microstrip patch antenna** functions based on the concept of **electromagnetic wave radiation**. Let's break down how it works:

1. **Structure**: It features a flat metallic patch on a dielectric substrate, with a ground plane on the opposite side.
2. **Feeding Mechanism**: The patch is energized by an RF (radio frequency) signal, typically through microstrip lines or a coaxial probe.

3. **Wave Generation**: The applied signal induces surface currents on the patch.
4. **Radiation**: These currents create electric and magnetic fields at the patch's edges, leading to the emission of electromagnetic waves.
5. **Resonance**: The patch is engineered to resonate at a particular frequency, ensuring optimal radiation efficiency and bandwidth.

Equations for Different Parameters:

1. Operating Frequency and Wavelength

The operating frequency (f) of the antenna is a fundamental design parameter. The corresponding wavelength (λ) is determined using the speed of light (c):

$$\lambda = \frac{c}{f}$$

Where:

- C = 3*10^8 m/s (speed of light in a vacuum),
- f = desired operating frequency in Hz.

2. Dipole Antenna Length

The total length (L) of a half-wave dipole antenna is approximately:

$$L = \frac{\lambda}{2}$$

To account for the end effect (practical shortening), the corrected length is:

$$L = \frac{\lambda}{2 \cdot \sqrt{\varepsilon_e}}$$

Where:

- εe = effective relative permittivity of the surrounding medium (approximately 1 for air).

3. Microstrip Patch Antenna Dimensions

a. Width of the patch (W):

$$W = \frac{c}{2f\sqrt{\varepsilon_r + 1}}$$

Where:

- εr = relative permittivity (dielectric constant) of the substrate.

b. Effective Dielectric Constant (εe):

$$\varepsilon_e = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left[1 + 12\frac{h}{W}\right]^{-0.5}$$

c. **Effective Length of the Patch (Leff):**

$$L_{\text{eff}} = \frac{c}{2f\sqrt{\varepsilon_e}}$$

d. **Actual Length of the Patch (L):**

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

Where:

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

4. Ground Plane Dimensions (for Microstrip Patch)

The ground plane dimensions (Lg and Wg) should be larger than the patch:

$$L_g = L + 6h$$

$$W_g = W + 6h$$

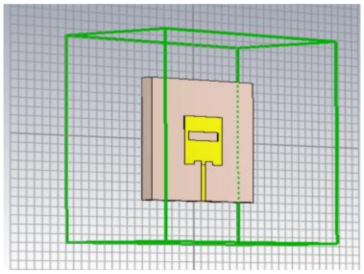
5. Resonant Frequency of an Antenna

The resonant Frequency(fr) id determined by:

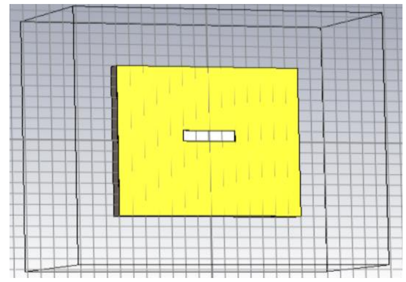
$$f_r = \frac{c}{2L\sqrt{\varepsilon_e}}$$

Design:

Geometry (front):



Geometry (back):



Calculations

STEP - 01 : Patch Width (W_p)

The patch width is calculated using:

$$W_p = \frac{c}{2f_r}\sqrt{\frac{2}{\varepsilon_r + 1}}$$

For 10 GHz:

$$W_p = \frac{3 \times 10^8}{2 \times 10 \times 10^9}\sqrt{\frac{2}{4.3 + 1}} = \frac{0.015}{\sqrt{2.15}} = 0.009214\,\mathrm{m} = 9.21\,\mathrm{mm}$$

For 21 GHz:

$$W_p = \frac{3 \times 10^8}{2 \times 21 \times 10^9}\sqrt{\frac{2}{4.3 + 1}} = \frac{0.007143}{\sqrt{2.15}} = 0.004388\,\mathrm{m} = 4.39\,\mathrm{m}$$

Intermediate (Average):

$$W_p = \frac{9.21 + 4.39}{2} = 6.80\,\mathrm{mm}$$

STEP -02 : Effective Dielectric Constant (ε_{eff})

The effective dielectric constant is calculated using:

$$\varepsilon_{\text{eff}} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left(1 + 12\frac{h_s}{W_p}\right)^{-0.5}$$

For 10 GHz:

$$\varepsilon_{\text{eff}} = \frac{4.3 + 1}{2} + \frac{4.3 - 1}{2}\left(1 + 12\frac{1.2}{9.21}\right)^{-0.5}$$

$$\varepsilon_{\text{eff}} = 2.65 + 1.65(1 + 1.56)^{-0.5} = 2.65 + 1.65 \times 0.640 = 3.705$$

For 21 GHz:

$$\varepsilon_{\text{eff}} = \frac{4.3 + 1}{2} + \frac{4.3 - 1}{2}\left(1 + 12\frac{1.2}{4.39}\right)^{-0.5}$$

$$\varepsilon_{\text{eff}} = 2.65 + 1.65(1 + 3.28)^{-0.5} = 2.65 + 1.65 \times 0.449 = 3.388$$

STEP - 03 : Effective Length (L_eff)

The effective length is calculated using:

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

For 10 GHz:

$$L_{\text{eff}} = \frac{3 \times 10^8}{2 \times 10 \times 10^9\sqrt{3.705}} = \frac{0.015}{1.925} = 0.00779\,\text{m} = 7.79\,\text{mm}$$

For 21 GHz:

$$L_{\text{eff}} = \frac{3 \times 10^8}{2 \times 21 \times 10^9\sqrt{3.388}} = \frac{0.007143}{1.84} = 0.00388\,\text{m} = 3.88\,\text{mm}$$

STEP -04 : Patch Length (L_p)

The patch length is calculated using:

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

For 10 GHz:

$$L_p = 7.79 - 2 \times 0.513 = 7.79 - 1.026 = 6.76\,\text{mm}$$

For 21 GHz:

$$L_p = 3.88 - 2 \times 0.495 = 3.88 - 0.99 = 2.89\,\text{mm}$$

Intermediate (Average):

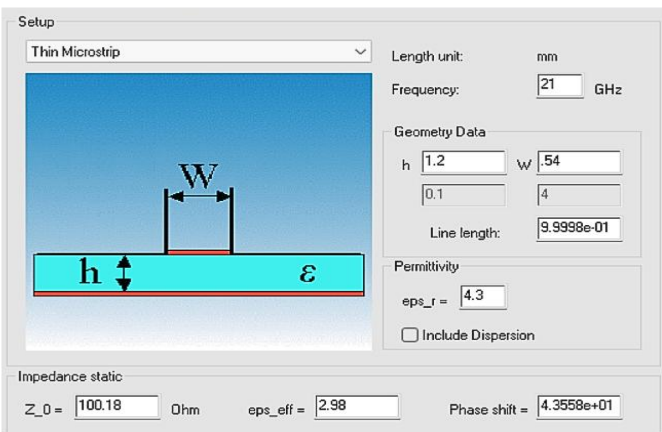
$$L_p = \frac{6.76 + 2.89}{2} = 4.83\,\text{mm}$$

Parameter List:

The parameters we found from the calculations and implemented on our antenna:

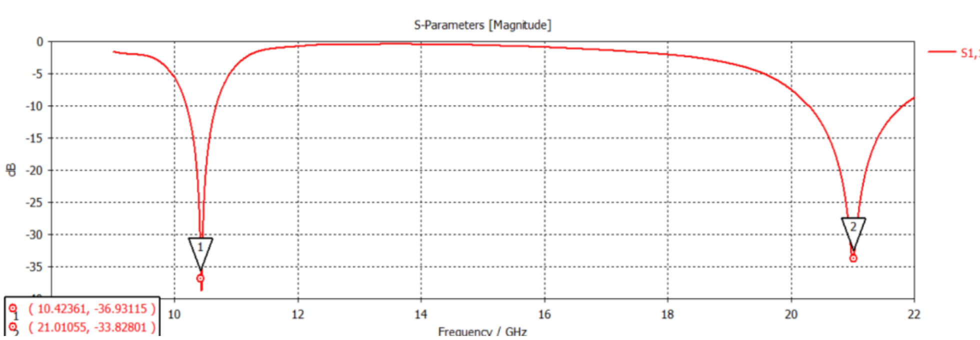
Name	Expression	Value	Description
insl	= .4	.4	Inset Length
txw	= .54	.54	Transmission Line Width
insw	= 1	1	Inset Width
varw	= 1	1	Slot 1 Variable Width
var1w	= 1	1	Slot 2 Variable Width
subd	= 1.2	1.2	Substrate Depth
varl	= 2	2	Slot 1 Variable Length
var1l	= 2	2	Slot 2 Variable Length
antw	= 5.208	5.208	Antenna Width
antl	= 5.559	5.559	Antenna Length
subw	= 14	14	Substrate Width
subl	= 14	14	Substrate Length

And the Setup:



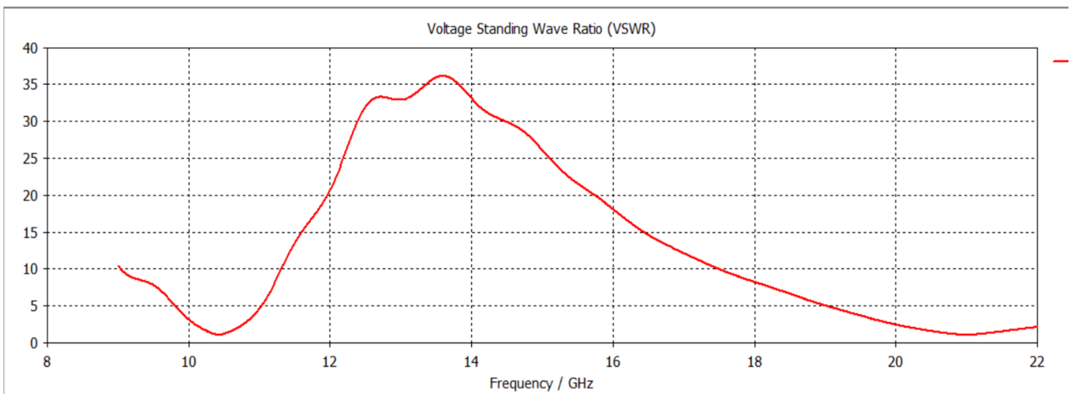
Result and Discussion

S Parameter:



The graph illustrates the S11 parameter (reflection coefficient) of a dual-band patch antenna designed to operate at two resonant frequencies, approximately 10.4 GHz and 21 GHz. At the first resonant frequency of 10.42361 GHz, the S11 value reaches -36.93 dB, indicating excellent impedance matching and minimal power reflection. Similarly, at the second resonant frequency of 21.01055 GHz, the S11 value is -33.83 dB, signifying efficient power transfer and good performance at this frequency as well. The sharp dips in the S11 curve at these frequencies confirm the dual-band nature of the antenna, which is optimized to operate effectively in both frequency bands. The return loss being well below -10 dB at both resonances highlights the antenna's ability to radiate efficiently with minimal signal loss. This design makes it suitable for applications in communication systems, radar, or other technologies requiring dual-frequency operation.

Voltage Standing Wave Ratio (VSWR):

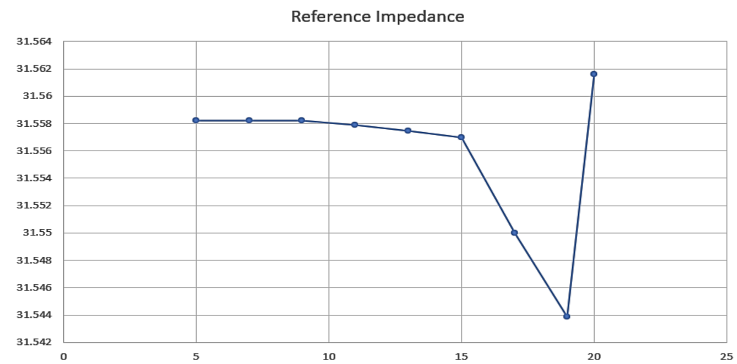


The graph depicts the Voltage Standing Wave Ratio (VSWR) performance of a dual-band patch antenna across a frequency range of 8 GHz to 22 GHz. VSWR indicates the quality of impedance matching between the antenna and its feed line, with lower values representing better matching. In this graph, the VSWR shows significant dips at two distinct frequencies, corresponding to the dual-band operation of the antenna.

At the first resonant frequency, near 10.4 GHz, the VSWR reaches a low value, suggesting excellent impedance matching and minimal power reflection. Similarly, at the second resonant frequency, around 21 GHz, the VSWR also achieves a low value, indicating efficient operation in this band as well. Between and outside these two resonant frequencies, the VSWR rises, reflecting less optimal matching. The sharp reductions in VSWR at the resonant frequencies confirm the antenna's dual-band capability, making it suitable for applications that require operation at these specific frequency bands.

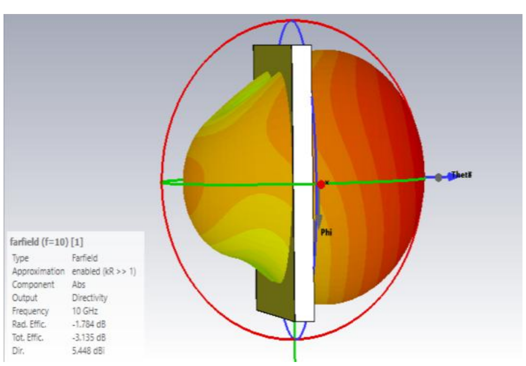
Mesh Convergence Test:

Cells per wavelength	Reference Impedance
5	31.5582
7	31.5582
9	31.5582
11	31.55788
13	31.55744
15	31.55696
17	31.55001
19	31.54389
20	31.56159

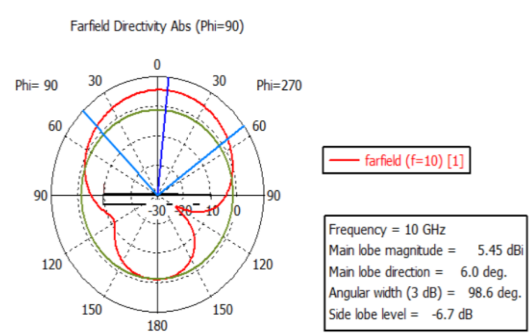


The mesh convergence test evaluates the stability of the reference impedance as the mesh density increases, measured in cells per wavelength. The results show that the reference impedance stabilizes at approximately **31.5582 Ω** for mesh densities ranging from 5 to 11 cells per wavelength, indicating reliable and accurate simulation outcomes in this range. Beyond 11 cells per wavelength, minor variations are observed. At 15 cells per wavelength, the reference impedance decreases slightly to **31.55696 Ω**, dropping further to **31.55001 Ω** at 17 cells per wavelength. A sudden rise to **31.56159 Ω** occurs at 20 cells per wavelength, likely due to numerical noise or an edge effect. These findings suggest that a mesh density of 5 to 11 cells per wavelength is optimal, balancing accuracy and computational efficiency. Increasing the mesh density further provides negligible benefits and may introduce inefficiencies. This ensures confidence in the selected mesh settings for the antenna design simulations.

Radiation Pattern at 10GHz (3D):

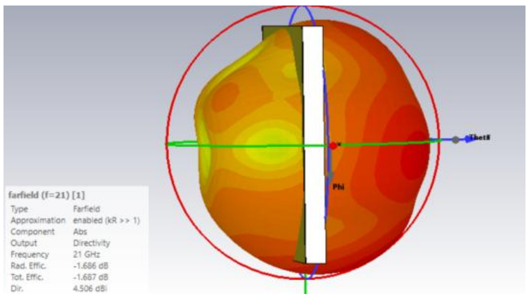


Radiation Pattern at 10GHz (1D):

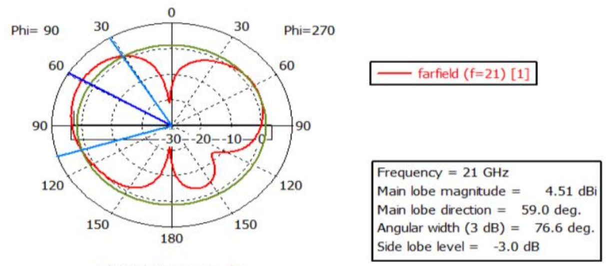


The image depicts the far-field directivity pattern of a patch antenna operating at a frequency of 10 GHz, shown for Phi = 90°. The main lobe of the radiation pattern exhibits a peak magnitude of 5.45 dBi, indicating the antenna's high directivity in the primary radiation direction, which is oriented at 6.0°. The 3 dB angular width, also known as the half-power beamwidth, is 98.6°, demonstrating the spread of the main lobe and providing a balance between focused radiation and coverage. Additionally, the side lobe level is measured at -6.7 dB, significantly lower than the main lobe, ensuring minimal interference in undesired directions. This radiation pattern makes the antenna well-suited for applications requiring focused energy in a specific direction while maintaining reduced side lobe interference.

Radiation Pattern at 21GHz (3D):

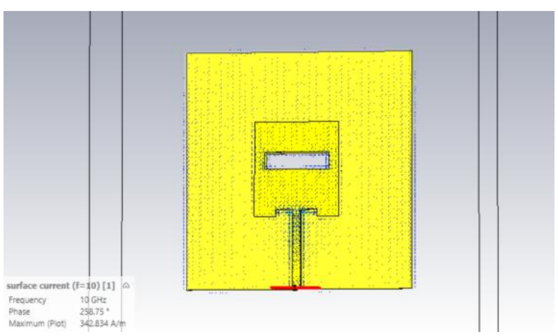


Radiation Pattern at 21GHz (1D):

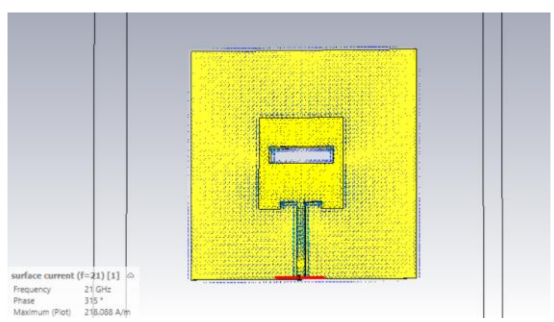


The image illustrates the radiation pattern of a dual-band patch antenna operating at a frequency of 21 GHz. It presents a polar plot of the antenna's far-field radiation characteristics, with the red curve representing the radiation pattern. The main lobe has a peak magnitude of 4.51 dBi, oriented at a direction of 59.0 degrees. The angular width of the main lobe, measured at the 3 dB points, is 76.6 degrees. Additionally, the side lobe level is -3.0 dB, indicating the relative strength of the side lobes compared to the main lobe. The plot also includes angular markers, such as Phi = 90° and Phi = 270°, providing a clear visualization of the antenna's directional performance. The accompanying text box summarizes these key parameters for easy reference.

Surface Current at 10 GHz:



Surface Current at 21 GHz:



The behavior of the antenna's surface currents at its resonance frequencies is analyzed. At 10 GHz, the phase is 258.75° with a maximum current density of 342.834 A/m, while at 21 GHz, the phase is 315° with a maximum current density of 218.088 A/m. The images illustrate how energy distribution varies, with bright regions indicating higher current density aligned with resonant modes for efficient radiation.

Discussion:

Dual-Band Performance

The antenna effectively achieved dual-band operation at 10 GHz and 21 GHz, as confirmed by the S-parameter results. The return loss at both frequencies was significantly below -10 dB, indicating efficient power transfer with minimal signal reflection. Additionally, the Voltage Standing Wave Ratio (VSWR) values were near 1, validating proper impedance matching between the antenna and the feed line. This dual-band functionality makes the antenna ideal for applications requiring communication across multiple frequency bands, such as satellite communications and 5G networks.

Radiation Characteristics

The far-field radiation patterns reveal that the antenna demonstrates directional radiation with notable gain and directivity across both frequency bands. At 10 GHz, the main lobe achieved a magnitude of 5.45 dB with an angular width of 98.6°, while at 21 GHz, the gain was slightly reduced to 4.51 dB, accompanied by enhanced directivity as indicated by a narrower angular width of 76.6°. These directional patterns emphasize the antenna's efficiency in focusing radiated energy, making it highly suitable for high-frequency communication and radar applications.

Bandwidth and Impedance Matching

The impedance bandwidth around the center frequencies was sufficient for the intended applications, ensuring reliable operation across a range of frequencies and providing flexibility for practical use. The optimized slot design played a crucial role in achieving this performance by facilitating dual-band operation and enhancing impedance matching.

Challenges and Limitations

One of the challenges encountered was achieving optimal performance at 21 GHz, as evidenced by the slightly lower gain and wider side lobe levels compared to 10 GHz. This discrepancy can be attributed to increased losses and manufacturing tolerances at higher frequencies. Additionally, while the design successfully operated at dual bands, further miniaturization could be explored to meet the increasing demand for compact antennas in modern wireless devices.

Conclusion

The dual band microstrip patch antenna, designed for 10 GHz and 21 GHz, exhibited efficient power transfer, low return loss, and directional radiation patterns. The incorporation of rectangular slots facilitated dual-band functionality, while the FR4 substrate provided practicality. The antenna showcased high gain and directivity, making it well-suited for satellite communication, radar, and 5G applications. Impedance bandwidth and VSWR measurements validated its excellent performance and stability.

Although there was a slight reduction in gain at 21 GHz, the results were consistent with theoretical predictions. Future improvements, including the use of advanced materials and optimization techniques, could enhance efficiency and broaden the range of applications. This design emphasizes the potential of microstrip antennas in high-frequency communication.

References

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