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DESIGN AND SIMULATION OF INSET FEED MICROSTRIP PATCH ANTENNA

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Abstract: A microstrip patch antenna is a flat, rectangular piece of metal placed on a dielectric substrate, with a larger metal sheet known as the ground plane beneath it. To ensure impedance matching between the patch and the microstrip line, a notch, referred to as an "inset," is strategically incorporated in the patch design. This project focuses on the design and simulation of a microstrip patch antenna for Wireless Local Area Network (WLAN) applications, specifically targeting a resonating frequency of 2.4 GHz. The antenna employs direct contact feeding through a microstrip line on an FR-4 Epoxy substrate with a dielectric constant (εr) of 4.4 and a substrate height of 1.6mm. To match impedance, an inset is introduced in the patch, and Ansys High-Frequency Structural Simulator (HFSS) software is used for design and analysis of antenna and its parameters. These include reflection coefficient, gain, VSWR, and bandwidth. Fabrication is commonly carried out using the photolithographic technique commonly used in PCB design. Actual fabrication of the antenna is not a part of is study. However, a simple walkthrough into the steps involved in antenna design are highlight.

Index Terms **– antenna, microstrip, patch, dielectric, inset, feeding mechanism, impedance, photolithographic, substrate, notch, optimetrics, SMA connector, gain, beamwidth, directivity, bandwidth, return loss, magnetic, electric, field.**

Introduction

Heinrich Hertz, a German physicist, pioneered the first antenna while developing a wireless communication system. He conducted experiments using a dipole antenna to generate electrical sparks, aiming to validate James Clerk Maxwell's electromagnetic wave theory. Following which, in the 1920s, the Yagi Uda antenna, invented by Japanese innovator Shintaro Uda, gained rapid popularity for its high gain and effectiveness. Then came the Horn antennas around the 1930s, offering minimal loss, superior directivity, and improved gain. They saw widespread use during World War II.

Finally, Microstrip antennas, also known as "patch antennas," originated in 1953 but gained significant attention in the 1970s, particularly after the advent of printed circuit boards (PCBs). These low-profile antennas found extensive applications in aircraft, spacecraft, satellites, missiles, and various mobile radio and wireless communication systems.

Now, let's delve further into the precise nature of an antenna. An antenna is a metallic device, taking various forms like rods, wires, or sheets, and is essentially used for emitting and receiving electromagnetic waves. Its operation relies on Maxwell's Equations and Faraday's Law. When excited, it generates a displacement current, creating a time-varying magnetic field governed by Maxwell's fourth law called Ampere's Law. This can in turn produce time varying Electric Field governed by the Faraday's law. We know that time varying magnetic field induces circulating electric field and vice versa. Similarly currents and/or time varying electric field induce circulating magnetic field and vice versa. These dynamic fields induce each other, giving rise to electromagnetic waves propagating perpendicular to them, enabling wireless transmission. When the antenna receives an electromagnetic wave, it induces a voltage/current through changes in magnetic flux linkage, following Faraday's Law. In essence, antennas are fundamental to the world of electromagnetic radiation.

Over the years, many efficient antennas have been designed. Microstrip antennas are popular due to their easy design and fabrication, using techniques like photolithography found in PCBs. However, basic microstrip antennas are not frequently used; instead, variations are preferred. A key challenge in antenna design is achieving impedance matching, adhering to the Maximum Power Transfer Theorem between the load (e.g., SMA connector) and the source (antenna). To sidestep the need for extra circuitry, the inset cut feeding technique is employed. This method entails accurately placing an inset cut in the patch to align the feed line's impedance with that of the patch, streamlining the processes of fabrication, modeling, and impedance matching.

I. Block Diagram

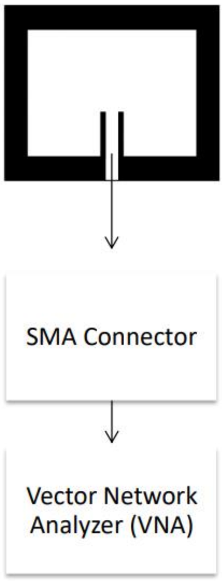

Fig. 1. Block diagram of testing setup of Inset feed microstrip patch antenna

Figure 1 shows the basic setup and main components involved in testing an antenna. Here I have depicted the front view of an Inset feed microstrip patch antenna. A microstrip antenna, often called a printed antenna, is created using photolithography on a PCB substrate. Photolithography is a microfabrication process used to pattern the substrate. A typical microstrip antenna comprises two main components: a metal foil patch with various shapes like square, circle, or annular ring, and a microstrip transmission line for excitation. The patch, with dimensions L_p and W_p, rests on an insulating dielectric substrate of thickness h. Beneath the substrate lies a ground plane made of the same metal as the patch. The thickness of the ground plane is less critical. When the patch radiates energy downward, the ground plane acts as a mirror and reflects it upward. The dielectric constant of the antenna material typically falls within the range of 2.2 to 12, with the length of the antenna constrained to 0.003λ to 0.05λ.

Common dielectric materials include Duroid (εr=2.2), FR-4 epoxy (εr=4.4), or Roger 4350 (εr=3.66). Dielectrics enhance electrical and mechanical stability while reducing antenna size with higher permittivity. Additionally, Copper, silver, or gold are employed for the patch, microstrip line, and ground plane due to their high conductivity. The formation of the patch and feed line includes the application of photoresist material, exposure to UV radiation, and subsequent etching using chemicals such as Ferric chloride. The patch's length should be λ/2 (where λ denotes the wavelength). When excited, waves within the dielectric reflect and radiate from the metal patch edges. The purpose of the inset cut in the patch is to achieve impedance matching between the feed line and the patch, eliminating the need for additional matching components. This impedance matching ensures compliance with the Maximum Power Transfer Theorem, which states that maximum power transfer occurs when the load impedance is the complex conjugate of the source impedance.

SMA stands for Sub Miniature version A and represents semi-precision coaxial Radio Frequency connectors. These connectors offer a fundamental interface for coaxial cables and maintain a 50-ohm impedance, aligning with the Maximum Power Transfer Theorem. Widely utilized in RF applications, SMA connectors employ a screw-type coupling mechanism to ensure uniform contact, minimizing reflections and attenuation. They mainly have two parts; SMA Male/ Plug Connecters and the SMA Female/Jack Connecters.

A Vector Network Analyzer (VNA) is used to analyze networks with one or more ports, where each port can transmit, absorb, and reflect RF energy.

- One-port devices: Examples include antennas.
- Two-port devices: These include components like filters and amplifiers.
- Three-port devices: Devices like mixers and directional couplers fall into this category.

A Vector Network Analyzer injects energy through one port and measures the power received at another port. It also calculates the reflected power by assessing RF energy at the same port. The VNA's output is represented by S parameters, which indicate how RF energy scatters into different ports.

II. Flow Chart

The project consists of two main components: Antenna Design and Antenna Manufacturing. These two processes involve distinct steps, as outlined in the following flowcharts.

3.1 Antenna Design Process

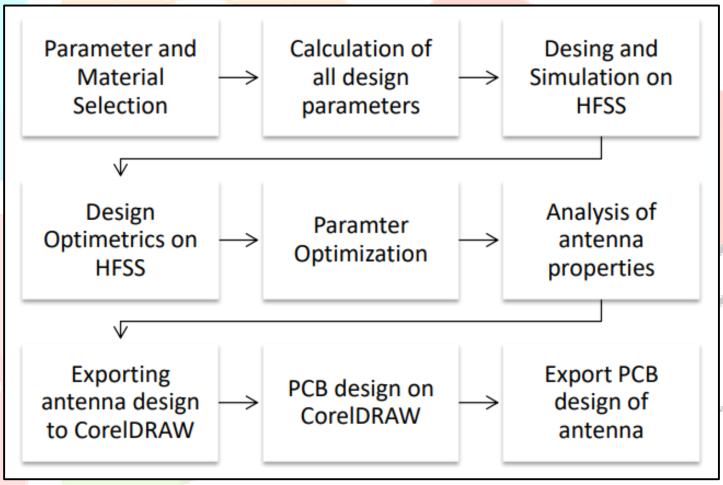

Fig. 2. Flowchart of Antenna Designing process

1. Select Operating Frequency, Substrate Thickness, and its Dielectric Material.
2. Calculate antenna dimensions using standard formulas.
3. Design the antenna using HFSS software (Version 13) with the calculated dimensions.
4. Conduct simulations to obtain antenna parameter results.
5. Implement Optimetrics to analyze parameter variations (e.g., frequency, inset cut depth).
6. Adjust antenna dimensions based on Optimetrics results.
7. Determine values and generate graphs for key antenna parameters (VSWR, Return Loss, Impedance, -3dB Beamwidth, etc.).
8. Export the antenna design as a DXF file.
9. Import the DXF file into CorelDRAW to create the PCB layout.
10. Export the PCB design for photo printing.

3.2 Antenna Manufacturing using Photolithographic Process

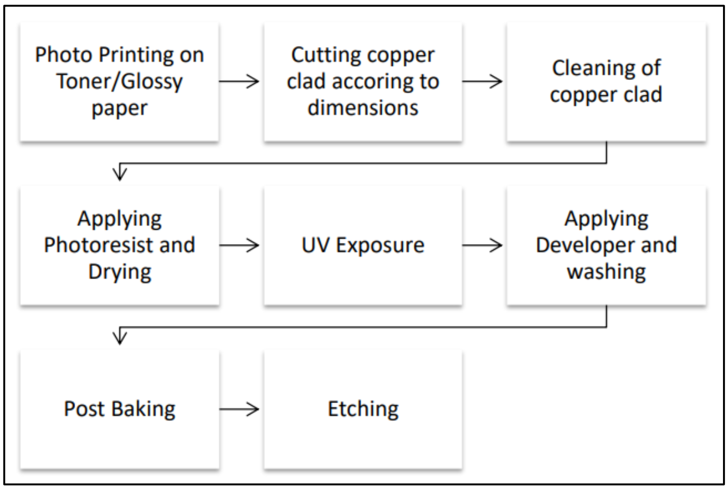

Fig. 3. Flowchart of Antenna Manufacturing process

1. Print the PCB layout onto a negative sheet.
2. Place the negative sheet on the copper-clad substrate and cut the copper to match dimensions.
3. Clean the copper surface to remove oxide deposits using steel wool or pitambari powder.
4. Apply liquid photoresist (E-1020) and dry for approximately 4 minutes.
5. Expose the PCB to UV radiation from both sides (for double-sided PCBs).
6. Dip the PCB in developer solution for 2-3 seconds.
7. Post-bake the PCB by drying it for 2 minutes.
8. Etch the PCB to remove unwanted copper, using an etchant like Ferric Chloride.

III. System Design

4.1 Fundamental Antenna Parameters

1. Radiation Pattern:

- Represents antenna's radiation properties in relation to spatial coordinates
- Includes factors like Polarization, Directivity, and Radiation Intensity

2. Efficiency:

- Accounts for ohmic losses inherent in antennas due to their conductive nature
- Defined as the ratio of Radiated Power to Input Power

3. Directivity and Gain:

- Directivity is the ratio of radiation intensity in a specific direction from the antenna to the average radiation intensity across all directions.
- It's often assumed that antennas ideally radiate equally in all directions, termed an Omnidirectional or Isotropic Radiation pattern.
- Directivity is directly proportional to Gain

4. Beamwidth:

- Beamwidth is the angular separation between the half-power or -3dB points within the main lobe of the radiation pattern.
- It signifies the extent of energy concentration.

5. Bandwidth:

- Bandwidth defines the frequency range where the antenna's performance remains appreciable, considering factors like gain, radiation pattern, and efficiency.

6. Polarization:

- Polarization denotes the orientation of the electric field components of electromagnetic waves relative to the Earth's surface.
- To minimize interference and optimize performance, both transmitter and receiver should have matching polarization.

7. Input Impedance:

- Impedance measures the opposition a circuit or material presents to current flow when voltage is applied.
- Achieving impedance matching between source and load is crucial to adhere to the Maximum Power Transfer Theorem.

8. Effective Length, Area, and Radiation Sphere:

- The length, area, and radiation sphere may slightly change due to the Fringing Effect.

4.2 Fringing Effect

The Fringing Effect is notably observed in magnetic circuits featuring an air gap. When a magnetic core within the circuit is energized, magnetic flux flows through it. However, flux can also extend into the air gap, spreading out or "fringing." This results in an expanded cross-sectional area. Reluctance, which is inversely related to the cross-sectional area, decreases as the area increases. In the context of patch antennas, the Fringing Effect is responsible for radiation, particularly from the width side of the patch. It amplifies radiation and increases the effective length of the patch.

Formulas to Account for the Fringing Effect:

$$\varepsilon\text{reff} = \frac{\varepsilon r + 1}{2} + \frac{\varepsilon r - 1}{2}\left(1 + 12\,\frac{h}{W}\right)^{-\frac{1}{2}} \qquad (1)$$

$$\text{Leff} = \frac{c}{2fr\sqrt{\varepsilon\text{reff}}} \qquad (2)$$

The magnitude of the Fringing Effect:

- Increases with wider patch widths
- Increases with greater substrate heights
- Increases as the permittivity of the substrate material decreases

One notable drawback of the Fringing Effect is its tendency to shift the antenna's operating frequency.

4.3 Inset Feeding Technique

A subset of the Microstrip Line Feeding method, Inset Feeding is categorized under Contact Feeding. In this approach, the microstrip patch directly connects to the conducting microstrip feed line. To achieve impedance matching, a small cut or inset is strategically positioned near the intersection of the feed line and the patch. The purpose of this inset cut is critical. Typically, the edge of the patch antenna exhibits high input impedance. However, by adjusting the inset position from the patch edge towards the center, the impedance decreases rapidly. An impedance mismatch can lead to the formation of standing waves, resulting in power loss and reduced power delivery to the antenna. This reflected power can pose issues, especially when transmitting at high power levels.

IV. Design Calculation

c = speed of the light in free space
λ = wavelength of antenna
ε_r = relative permittivity (dielectric constant) of the substrate
ε_{reff} = effective relative permittivity (accounting for fringing of flux lines at edges)
ε_0 = permittivity of free space
μ_0 = permeability of free space
h = thickness of the substrate

$$c = \frac{1}{\sqrt{\varepsilon_0 \mu_0}} = 3 \times 10^8\ m/s \qquad (3)$$

$$\mu_0 = 4\pi \times 10^7\ H/m \qquad (4)$$

$$\varepsilon_0 = \frac{1}{\mu_0 c^2} \approx 8.854188 \times 10^{-12}\ F/m (5)$$

Width of the patch Wp:

$$W_p = \frac{c}{2fr\sqrt{\frac{\varepsilon_r + 1}{2}}} = 0.038036 = 38.036\text{mm} \qquad (6)$$

Using Equation 1 we can determine the effective relative permittivity of dielectric material:

$$\varepsilon\text{reff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left(1 + 12\frac{h}{W}\right)^{-\frac{1}{2}} = 4.1$$

Using Equation 2 we can determine the effective length of the patch:

$$\text{Leff} = \frac{c}{2fr\sqrt{\varepsilon_{reff}}} = 0.030 = 30mm$$

The extended incremental length of the patch ΔL is

$$\Delta L = 0.412h \frac{(\varepsilon_{reff} + 0.3)(\frac{W}{h} + 0.264)}{(\varepsilon_{reff} - 0.258)(\frac{W}{h} + 0.8)} = 0.0007388 = 0.74mm \qquad (7)$$

Since the length of patch has been extended by ΔL on each side, the actual length of the patch is given by:

$$L = \text{Leff} - 2\Delta L = 28.5mm \qquad (8)$$

By considering the ground plane

$$L_g = 6h + L = 39.042mm \qquad (9)$$

$$W_g = 6h + W = 47.636 \approx 48mm \qquad (10)$$

For providing impedance matching with a 50Ω connector, a curve fit formula for the inset feed depth y_0 is expressed as

$$y_0 = 10^{-4}\{0.016922\varepsilon_r^7 + 0.13761\varepsilon_r^6 - 6.1783\varepsilon_r^5 + 93.187\varepsilon_r^4 - 682.69\varepsilon_r^3 + 2.561 - 4043\varepsilon_r + 6697\}\frac{L}{2} \qquad (11)$$

$$y_0 = 8.907\text{mm} \approx 9mm$$

V. FINE-TUNE DESIGN SPECIFICATIONS USING OPTIMETRICS TOOL:

When analyzing antenna parameters in HFSS simulation software, deviations in values like impedance, voltage standing wave ratio, and operating frequency can be encountered despite using standard microstrip antenna formulas. In this project, while targeting a resonant frequency of 2.4 GHz, I initially addressed the issue of operating frequency variation. HFSS offers an Optimetrics feature, allowing us to simulate the antenna's design and observe how the resonant frequency changes with alterations in antenna dimensions, especially the patch dimensions. This analysis enabled me to fine-tune the patch dimensions to precisely achieve the 2.4 GHz frequency. Furthermore, optimizing impedance is also critical. The real part of impedance relates to radiated or absorbed power, while the imaginary part pertains to non-radiated power (stored near fields). Often, impedance deviates significantly from the desired value (50 ohms). Impedance depends on the inset cut depth, so through Optimetrics, I determined the ideal inset cut depth for the antenna to closely match the desired impedance. Connector selection is another very critical step. Some equipment use unreliable BNC connectors which can depicted the frequency of operation but are unreliable for measurement of the other antenna parameters. In my case, I opted for SMA connectors that provide more accurate and reliable readings.

VI. SIMULATION OF ANTENNA AND RESULTS

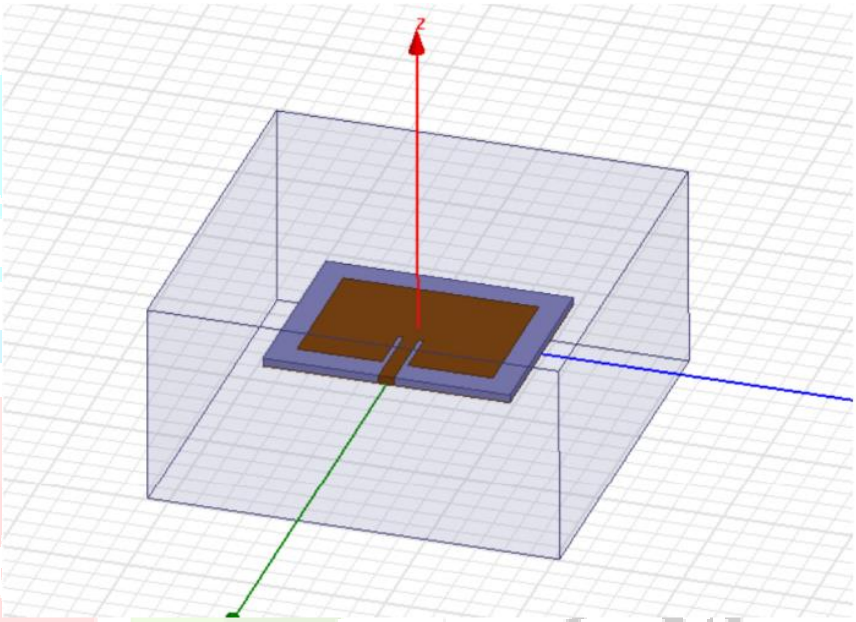

Fig. 4. Inset Feed Microstrip Patch Antenna Design on HFSS

Ansys HFSS is an advanced 3D electromagnetic simulation software designed for the development and simulation of high-frequency electronic products. These products encompass a wide range, including antennas, microwave components, filters and much more. Engineers across the globe rely on Ansys HFSS to create and optimize high-frequency and high-speed electronics utilized in applications such as communication systems.

In this project, I utilized the HFSS software for both designing the microstrip patch antenna based on calculated dimensions and refining the design specifications using its unique feature called Optimetrics. This software provided numerous graphical representations of different antenna parameters, making it easier to understand their relationships with the antenna's fundamental structure. Additionally, the 3D real-time radiation pattern simulation was not only fascinating but also highly informative. Figure 3.2 illustrates the antenna design created using the HFSS software.

Table 7.1 Manual calculations for antenna parameters and parameter values obtained from High-Frequency Structural Simulator

Parameters	**Calculated Values**	**HFSS Results**
Operating Frequency in GHz	2.4	2.4
Return Loss in dB	-33.629	-30
VSWR	1.0425	1.0585
Gain	-	1.8578
Beamwidth	-	98.5461
Bandwidth in KHz	-	52.7
Impedance in ohms	50	52.08

Table 7.1 presents a comparison between critical antenna parameters. It includes manually calculated values based on standard formulas versus the actual antenna design values achieved through HFSS software with Optimetrics.

Table 7.2: Manual calculations for antenna dimensions and dimensions obtained from High-Frequency Structural Simulator

Dimensions	**Calculated Readings in mm**	**Reading after Optimetrics in mm**
Length of Ground (L_g)	39.7812	39
Width of Ground (W_g)	47.636	48
Height of Substrate (h)	1.6	1.6
Length of Patch (L_p)	30.1812	28.4
Width of Patch (W_p)	38.036	38
Inset Cut Depth (y_0)	8.9	9.9
Cut width	5	5
Feedline Width	3	3
Dielectric Constant of Substrate	4.4	4.4

Table 7.2 details the dimension adjustments recommended by the Optimetrics tool to attain the precise parameter values outlined in Table 7.1.

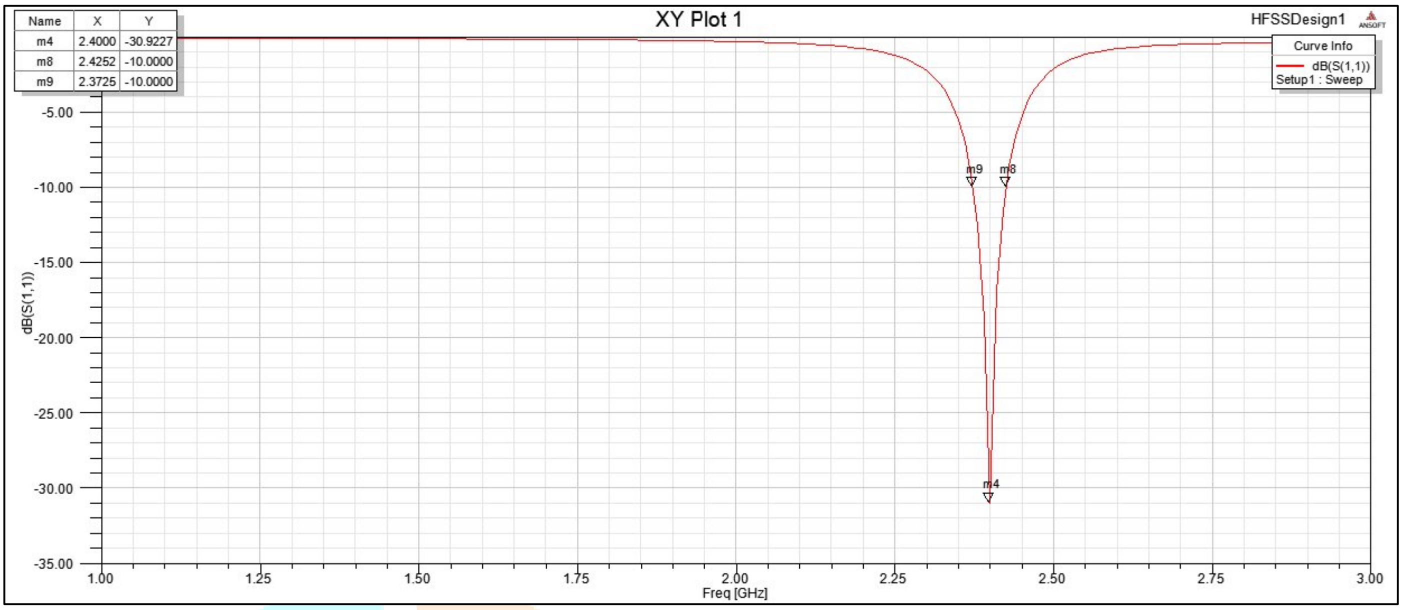

Fig. 5. Operating Frequency, Return Loss and Bandwidth

We've achieved the desired 2.4GHz operating frequency, as shown in the diagram.

To calculate bandwidth, we find the difference between frequencies at the -10dB points on the graph. In practical terms, a negligible impedance mismatch results in 10% of power being reflected, while the remaining 90% is radiated by the antenna. This condition corresponds to a 10 dB difference. Therefore, by making use of markers in the above diagram we can confirm that, the bandwidth is

$$\text{B.W} = \text{marker 8} - \text{marker 9} = 2.4252 - 2.3725 = 0.0527 = 52.7 \text{ KHz} \qquad (12)$$

Return Loss (RL) is the measure of the difference between transmitted and reflected power, expressed in dB, and it's a positive value. In contrast, Reflectance quantifies reflection in dB and is a negative value. A higher positive Return Loss or a more negative Reflectance value is favorable.

$$R_L = 20\log_{10}|\Gamma| = 20\log_{10}|0.02082| = -33.629\text{dB} \qquad (13)$$

Here 'Γ' is the Reflection Coefficient and can be obtained by considering the Characteristic Impedance Zo and the Load Impedance ZL. In this case,

$$\text{Zo} = 52.1264\ \Omega \text{ (obtained from the Impedance magnitude graph)} \qquad (14)$$

$$\text{ZL} = 50\ \Omega \text{ (Standard impedance of SMA Connector)} \qquad (15)$$

$$\Gamma = \frac{\text{ZL} - \text{Zo}}{\text{ZL} + \text{Zo}} = (50 - 52.1264) = -0.02082 \qquad (16)$$

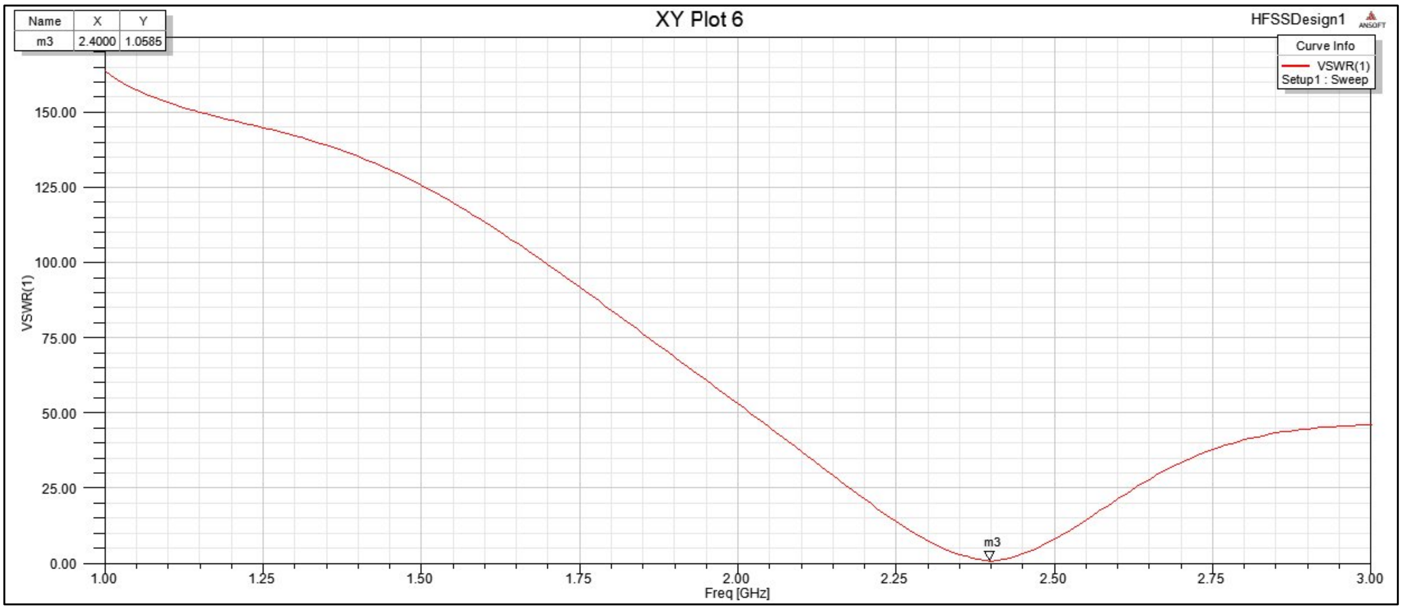

Fig. 6. Graphical Representation: Voltage Standing Wave Ratio vs. Frequency

Figure 6 shows a graphical representation of VSWR, or Voltage Standing Wave Ratio, which measures the ratio between the maximum and minimum voltage (or current) magnitudes on an antenna with standing waves, indicating the presence of impedance mismatch.

$$\text{VSWR} = \frac{1+|\Gamma|}{1-|\Gamma|} = \frac{1+0.02082}{1-0.02082} = 1.0425 \qquad (17)$$

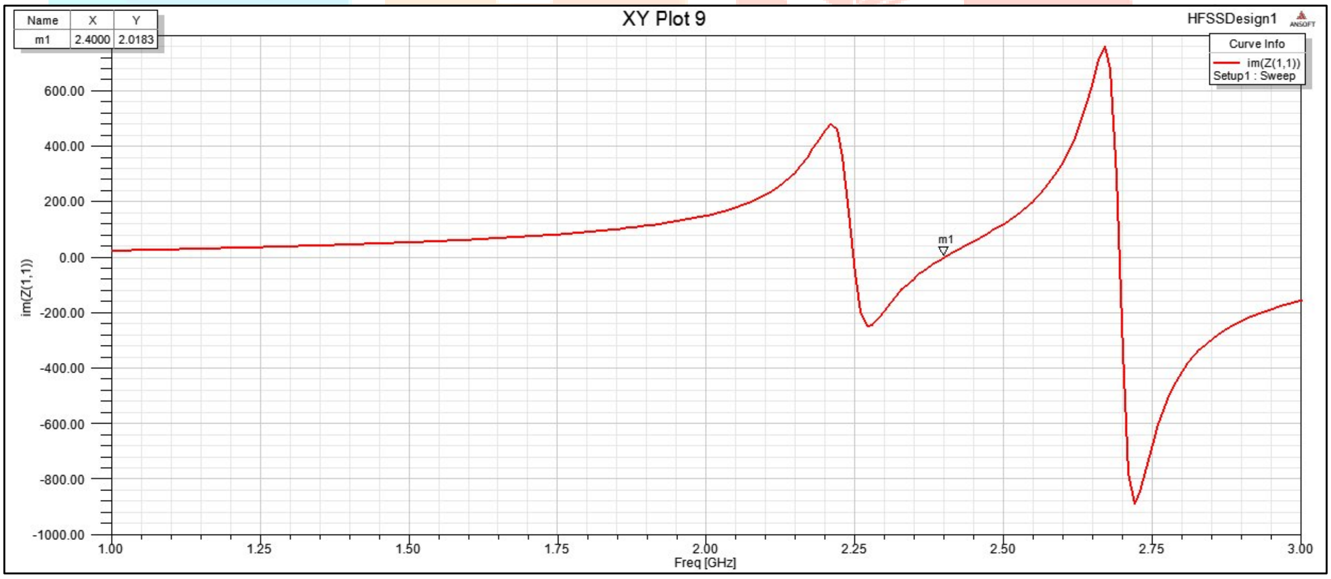

Fig. 7. Graphical Representation: Impedance (Imaginary) vs. Frequency

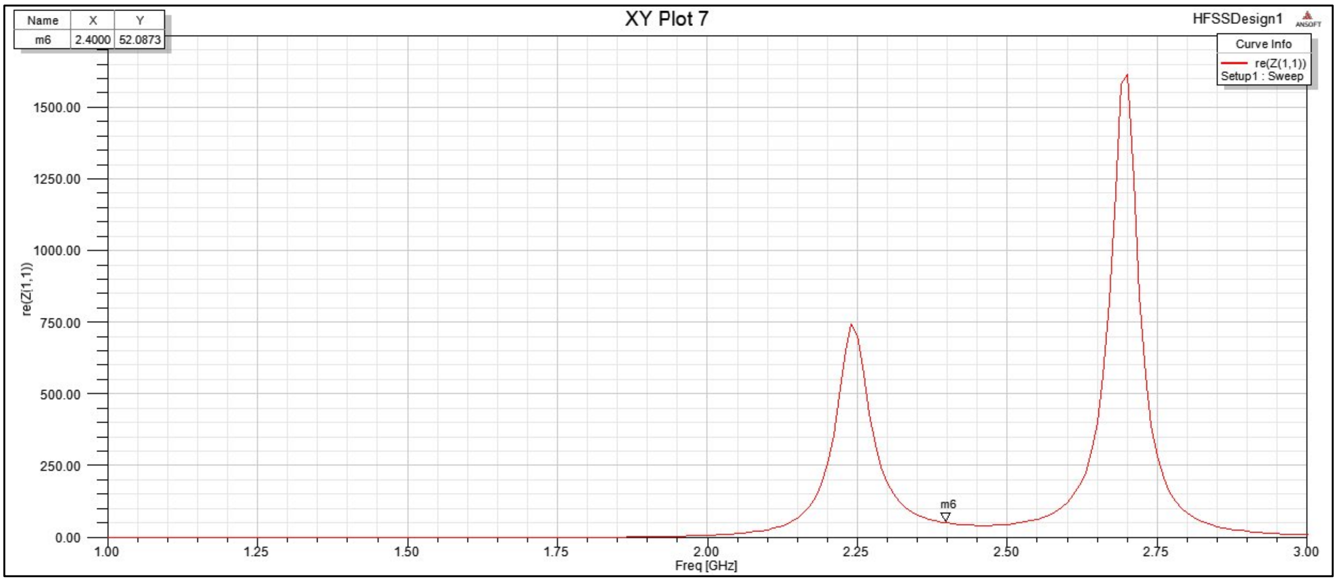

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Fig. 8. Graphical Representation: Impedance (Real) vs. Frequency

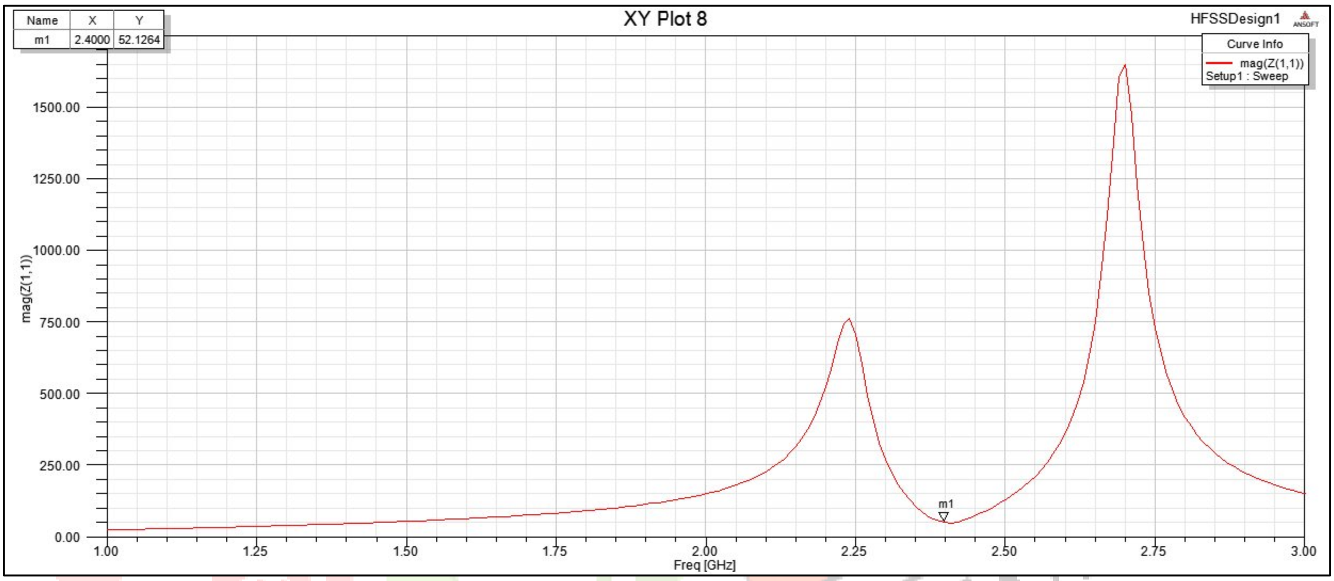

Fig. 9. Graphical Representation: Impedance (Magnitude) vs. Frequency

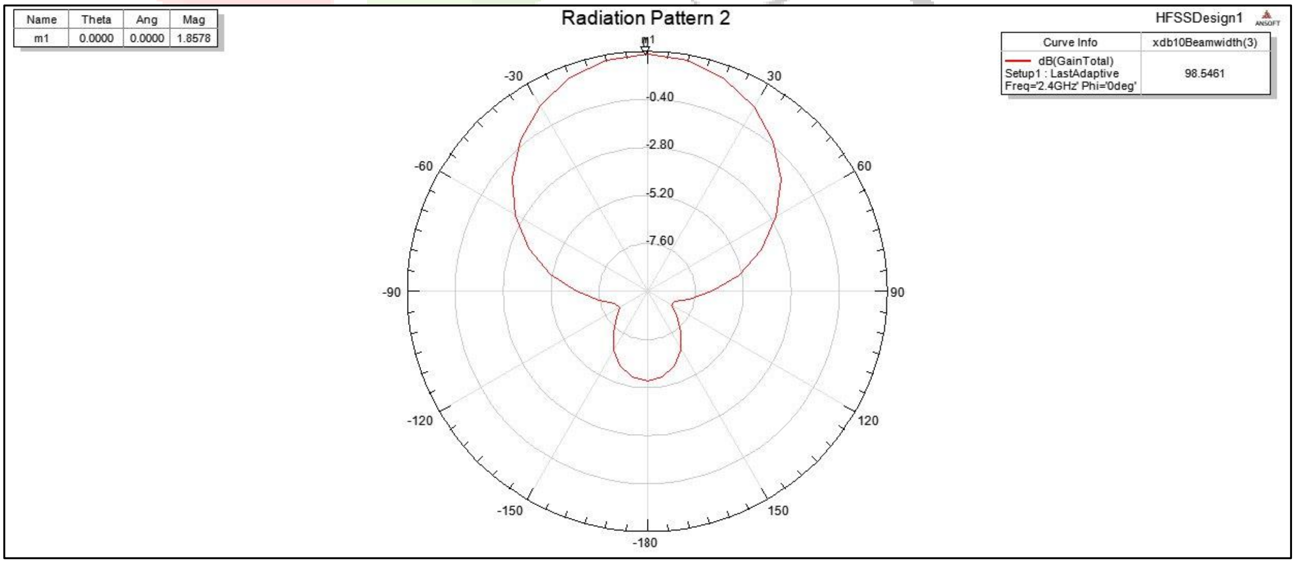

Fig. 10. Graphical Representation: Radiation patter showing Gain and Beamwidth

Beamwidth is the angle between half power / -3dB points of the main lobe. Figure 10 shows that the Beamwidth is approximately 98 degree.

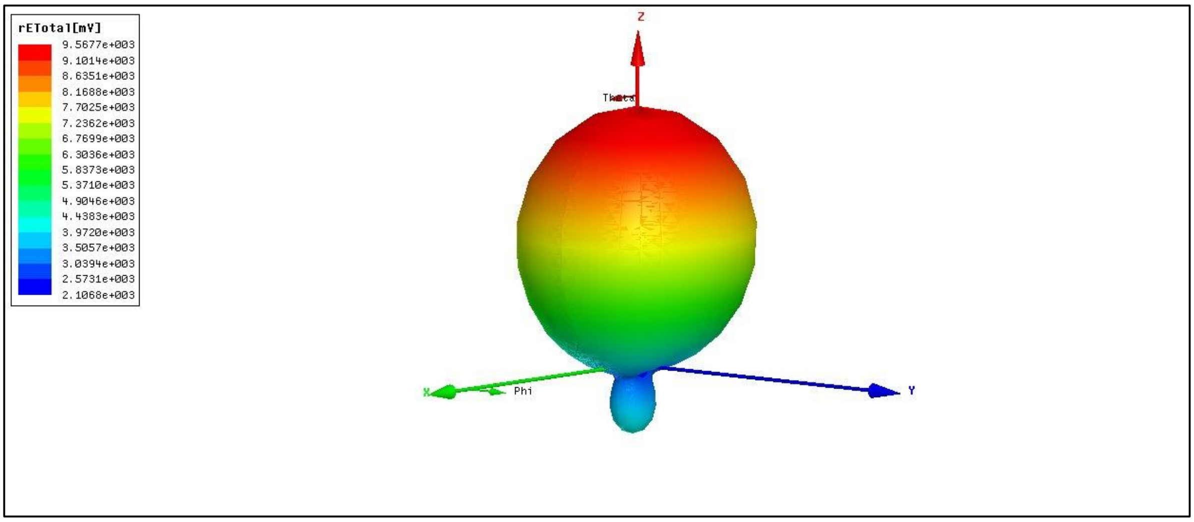

Fig. 11. Graphical Representation: Radiation Pattern

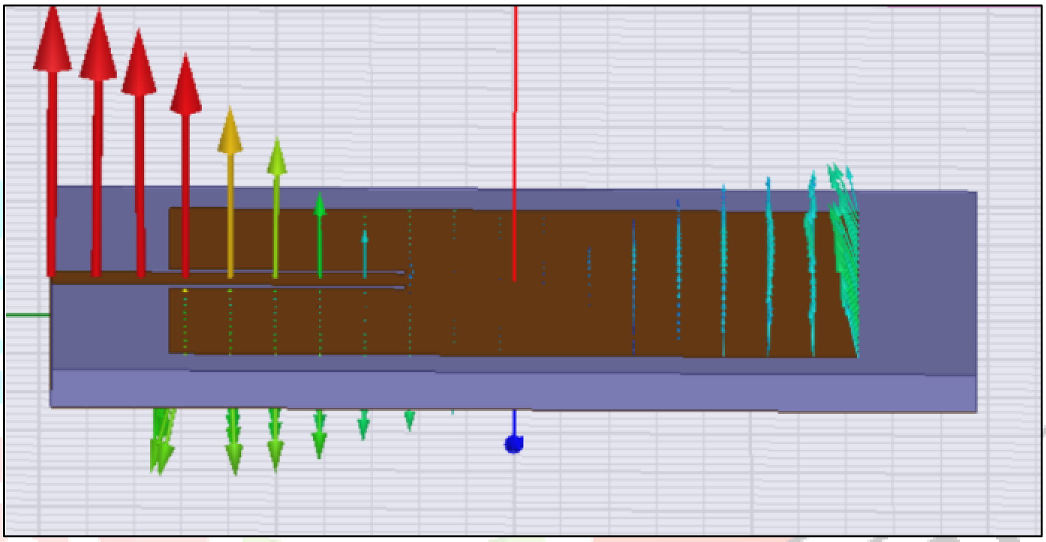

Fig. 12. Electric field variations on antenna

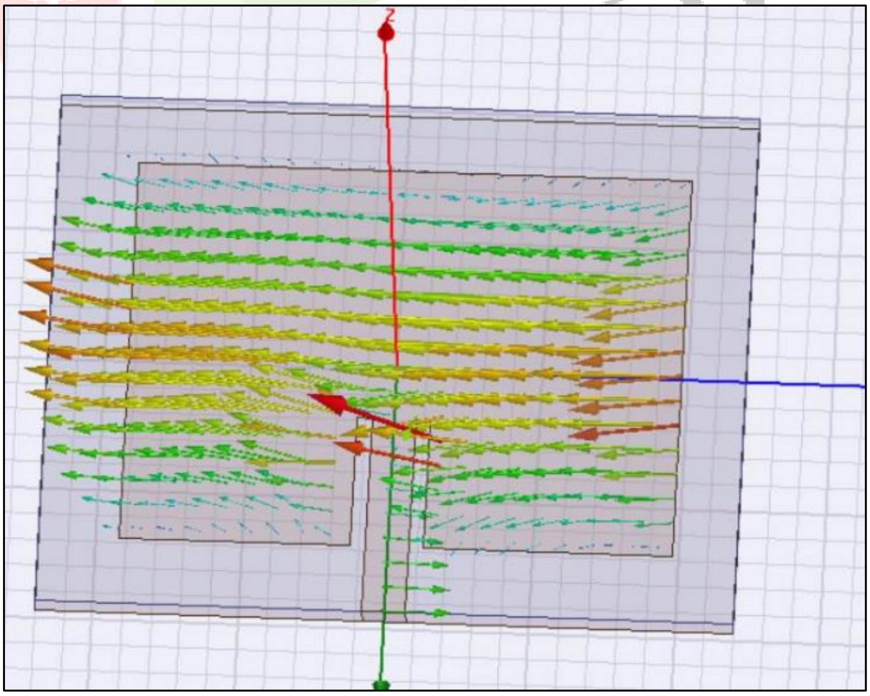

Fig. 13. Magnetic field variations on antenna

VII. Conclusion

In line with the project objectives, I developed an Inset Feed Microstrip antenna, simulating the design with HFSS software. Through Optimetrics testing, I fine-tuned the patch length and inset cut depth to achieve the desired Operating Frequency and Impedance specifications.

For improved performance, I opted for a thicker dielectric substrate with a lower dielectric constant. This choice enhances the Fringing Effect, leading to improved efficiency and radiation characteristics. However, it's crucial to note that this impacts antenna size and, consequently, the Operating Frequency. While the Fringing Effect is desirable for superior antenna radiation, its impact on frequency shift can be drastic.

Impedance Matching is a critical aspect for reliable antenna performance. As the inset cut penetrates deeper into the antenna's core, impedance values increase, making it an adjustable parameter. Careful monitoring of patch width and inset cut depth facilitates better Impedance Matching.

There exists a trade-off between Bandwidth and Gain in antenna design. While our antenna aims for a broader bandwidth, this imposes an upper limit on maximum Gain. Therefore, the three primary parameters to consider when designing a practical antenna are Operating Frequency, Bandwidth, and Antenna Impedance.

VIII. Acknowledgement

I extend my heartfelt gratitude to Dr. Rupesh Jaiswal for his unwavering guidance and mentorship throughout my undergraduate journey at the Pune Institute of Computer Technology. His dedication, valuable insights, and exceptional teaching in the field of Electromagnetics and Wireless Communication inspired me to delve deeply into this subject matter.

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