Cairo University, Faculty of Engineering
Electronics and Electrical Communications
Department (EECE)

Antenna Engineering

ELC3050 Project

Design a 2-Element Array of Slot-Fed Microstrip Patch Antenna Operating at 35 GHz

Under the supervision of prof: **Eslam A.Eshrah**

Presented By:

Name	Sec	ID
Khaled Ahmed Hamed	2	9220276
Dalia Mohamed Soliman	2	9220285
Zeyad Ashraf Abdelaziz	2	9220323
Zeyad Antar Othman	2	9220331
Sarah Abdelatty Ibrahem	2	9220349
Ali Mohamed Mohamed Said	2	9210687

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1. Framework

1.1. Abstract:

the design and simulation of a 2-element slot-fed microstrip patch antenna array operating at a center frequency of 35 GHz, targeting millimeter-wave applications such as 5G communications, radar systems, and high-speed wireless networks. The microstrip patch antenna design is based on a rectangular configuration, with slots introduced to enhance bandwidth and improve impedance matching. The array configuration is employed to achieve higher gain and better directional radiation characteristics compared to a single patch element.

The feeding mechanism employs a slot-coupled approach, which provides design flexibility and minimizes surface wave losses. A low-loss substrate with a dielectric constant of εr and thickness t is used to optimize performance while maintaining a compact form factor. Simulation results, obtained using electromagnetic modeling tools, highlight key performance parameters:

- **Gain:** The array achieves a peak gain of 6.9833 dBi, ensuring efficient signal transmission and reception.
- **Return Loss:** A return loss better than -12 dB ensures excellent impedance matching.
- **Radiation Pattern:** The antenna exhibits a unidirectional radiation pattern with minimal side lobe levels, making it ideal for focused signal applications.

The proposed antenna is compact and lightweight, making it suitable for integration into modern high-frequency devices. This work underscores the potential of slot-fed microstrip patch antenna arrays in addressing the growing demands of millimeter-wave communication systems, combining high performance with ease of fabrication and scalability.

1.2. Introduction:

In today’s world, high-frequency communication plays a critical role in achieving high data rates for a variety of applications, including cellular networks, modems, GPS devices, and radar systems. These advancements are made possible by microstrip patch antennas, known for their compact size, ease of fabrication, and capability to integrate seamlessly into antenna arrays. Microstrip patch antenna arrays are particularly significant in radar systems, enabling precise beam steering and target detection through beam manipulation.

This work focuses on the design of a 2-element slot-fed microstrip patch antenna array operating at 35 GHz. The slot-fed configuration consists of three primary layers: the feeding network (transmission line), ground plane, and radiating patch element. To optimize performance, the design incorporates two substrates with varying dielectric constants and thicknesses, resulting in a compact antenna with reduced dimensions. The primary objectives include achieving a return loss (S11) of less than -10 dB at 35 GHz, a dominant front lobe in the E-plane radiation pattern, and an omnidirectional pattern in the H-plane.

Slot-fed patch antennas offer significant advantages by isolating the radiating patch from the feeding network, thereby minimizing interference and unwanted radiation. They improve bandwidth through enhanced impedance matching and coupling while maintaining a planar, compact design suitable for millimeter-wave applications. The use of this technique also enables flexible design and integration into arrays, making it ideal for high-frequency applications such as 35 GHz communication systems.

We provide a detailed description of the design process, including the challenges encountered and their resolutions. It outlines the calculation of design parameters, ensuring the antenna meets the required specifications. Additionally, simulation results are presented and analyzed to validate performance, accompanied by an equivalent circuit model for the antenna. The report concludes with a reflection on the design's progress and the lessons learned, highlighting the broader implications of this work for future advancements in high-frequency communication systems.

1.3. Problem definition:

Modern communication systems demand antennas that are compact, efficient, and capable of supporting high-speed data transmission for advanced applications such as 5G, satellite communications, and radar systems. The design of antennas operating at high frequencies, specifically at 35 GHz, presents significant challenges due to the stringent requirements for compact size, high precision, and optimal performance.

This project focuses on designing a two-element slot-fed microstrip patch antenna array, addressing critical challenges to ensure the antenna meets performance expectations. Key objectives include:

Impedance Matching: Achieving a return loss (S11) below -10 dB across the target frequency range for effective impedance matching and minimal signal reflection.

Radiation Pattern: Designing a radiation pattern with a dominant front lobe in the E-plane for directional communication and omnidirectional coverage in the H-plane for broader connectivity.

Substrate Optimization: Selecting and utilizing substrate materials with appropriate dielectric constants and thicknesses to optimize bandwidth, efficiency, and overall antenna performance.

Array Integration: Ensuring precise alignment and interaction between the two antenna elements to enhance gain and directionality, supported by a T-section feeding network for uniform power distribution and minimal losses.

Precision Manufacturing: Designing antenna dimensions to meet the high precision required for manufacturing at 35 GHz, addressing fabrication limitations without compromising performance.

Loss Minimization: Reducing energy losses in the feeding network while suppressing unwanted radiation and interference to maintain a high-efficiency design.

By addressing these challenges, the proposed design aims to deliver a high-performance, compact antenna array capable of meeting the stringent requirements of modern high-frequency communication systems, offering improved gain, bandwidth, and directional capabilities for advanced applications.

2. Design procedure

2.1. Substrate Section:

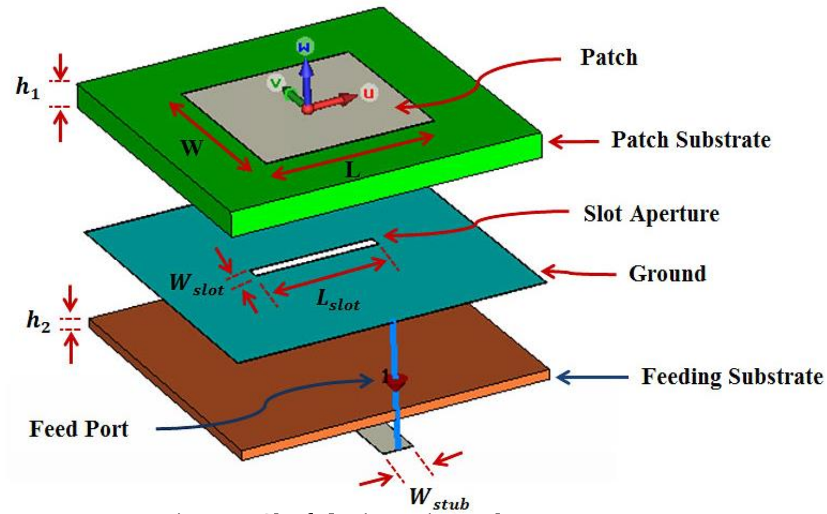

Figure 1: Slot fed Microstrip Patch antenna Layers

2.1.1. First: Choosing the substrate materials:

We chose a low-loss material such as Rogers RT/duroid 5880 with a low Loss tangent in order to reduce ohmic losses with dielectric constant (ε_r) of 2.2 and loss tangent $\tan(\delta) = 0.0009$ [1].

- The substrate height should balance the tradeoff between performance and practicality:

A thinner substrate minimizes surface wave losses and improves impedance matching for the microstrip feedline. A thicker substrate increases bandwidth and improves radiation efficiency for the patch, so as an initial estimate we chose:

First substrate: Height (h_1): **0.254 mm**

Second substrate: Height (h_2): **0.4 mm**

2.1.2. Second: Choosing the design parameters for Patch:

We start the simulation by the parameters calculated as follows, we had a good estimation of the patch dimensions from an online calculator [2] as shown, then we got parameters of (substrates, slot, feed) using the equations from reference paper and then we started to optimize the dimensions to obtain the wanted results.

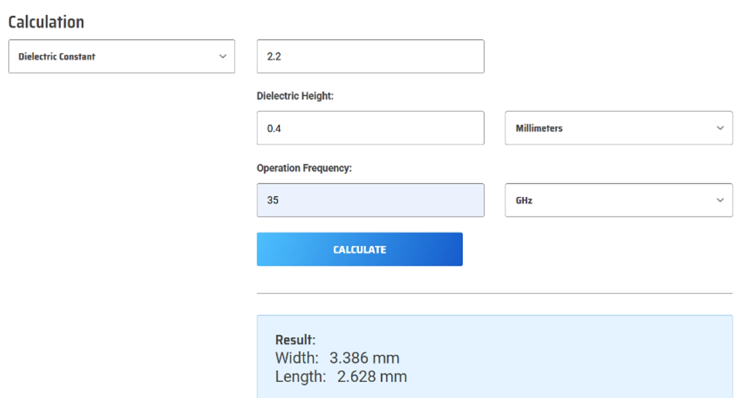

Figure 2: Using online calculator to get an estimate for Patch dimension

2.1.3. Third: Choosing the design parameters for Substrate:

The substrate dimensions should extend beyond the radiating patch to minimize edge effects and ensure proper radiation. Typically, the substrate width and length are at least 6x the height of the substrate plus the patch dimensions [3], so:

$$w_{sub} = w_{patch} + 6h = 3.386 + 6(0.4 + 0.254) = 7.31mm$$
$$l_{sub} = l_{patch} + 6h = 2.628 + 6(0.4 + 0.254) = 6.552mm$$

2.2. Ground Section:

2.2.1. Fourth: Choosing the design parameters for Slot:

Using the equations given from reference paper, we could get the equations to calculate slot dimensions [3] as shown:

$$\lambda_0 = \frac{c}{f_0} = \frac{3 \times 10^8}{35 \times 10^9} \approx 8.57 \text{ mm}$$
$$w_a = 0.16 * \lambda_0 = 1.37mm$$
$$L_a = 0.1 * w_s = 0.137mm$$

2.3. Microstrip Section:

2.3.1. Fifth: Choosing the design parameters for Microstrip:

We needed initial values of microstrip dimensions to start iterations with so:

- Used following formula to determine initial value for W of feed (formula from online Calculator) [4]:

$$w = \frac{7.48 * n}{\exp(z\frac{\sqrt{\varepsilon_r + 1.41}}{87})} - 1.25 * t$$

- Used following formula to determine initial value for L of feed [3]:

$$L_m = \frac{\lambda_g}{4} = \frac{\lambda_0}{4\sqrt{\varepsilon_{reff}}} = \frac{c}{4f_r\sqrt{\varepsilon_{reff}}}$$

- Initial Length to start with: 1.4447 mm
- Final length after iteration and matching: 3.6 mm
- Initial Width to start with 0.63628 mm
- Final Width after iteration and matching: 0.1604

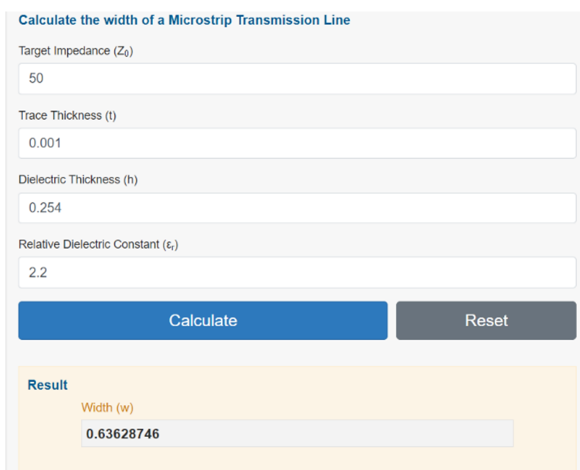

Figure 3: Using online calculator to get an estimate for microstrip dimension

2.4. Power divider Section:

2.4.1. Sixth: Choosing the design parameters for Power divider:

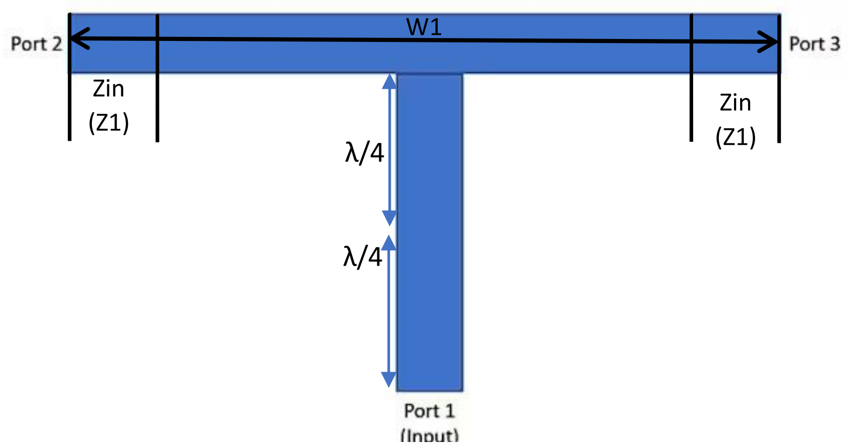

Figure 4: T-Junction Microstrip Power divider and its impedance

We have:

- Input impedance: 50Ω
- Matching impedance 50 Ω.

Calculate Intermediate Impedance (Z1)

- We use the formula:

$$z_1 = \frac{z_m^2}{Z_{in}}$$

Match the Horizontal Line Impedance

- Select (width of the horizontal line) to achieve the required gain and matching

Design Quarter-Wavelength Transformer

- Calculate the characteristic impedance Z of the quarter-wavelength transformer:

$$\boldsymbol{Z = \sqrt{Z * Z}}$$

Determine Microstrip Widths

- Use input patch width corresponding to 50 Ω.
- Use for the quarter-wavelength transformer width, also corresponding to 50 Ω.
- Final impedance after matching and setting width between antenna’s was Zo=41 Ω
- Final Width of lateral Microstrip to achieve gain and matching was 2.9 mm

We run using these initial dimensions and study how each dimension affects different specs, and then we have to tune the dimensions given above in order to get the proper radiation pattern, gain, and get reasonable S11 at a frequency of 35 GHz.

So, the parameters were tuned as shown in the following table:

Parameter	Initial estimate(mm)	Final value(mm)
h_{sub1}	0.254	0.254
h_{sub2}	0.4	0.4
w_{patch}	3.386	2.37
l_{patch}	2.628	2
w_{slot}	1.37	1.98
L_{slot}	0.137	0.16
w_{sub}	7.31	8
l_{sub}	6.552	5
$w_{microstrip}$	0.63628	1604
$l_{microstrip}$	1.4447	3.6

3. Results

3.1. First: Verification for the tool:

Verification of electromagnetic (EM) tool is a critical step in ensuring the accuracy and reliability of antenna design process, we use HFSS tool in our project and we verified it by simulating a λ/2 Monopole antenna operating at 1.85 GHz.

3.1.1. λ/2 Monopole antenna design:

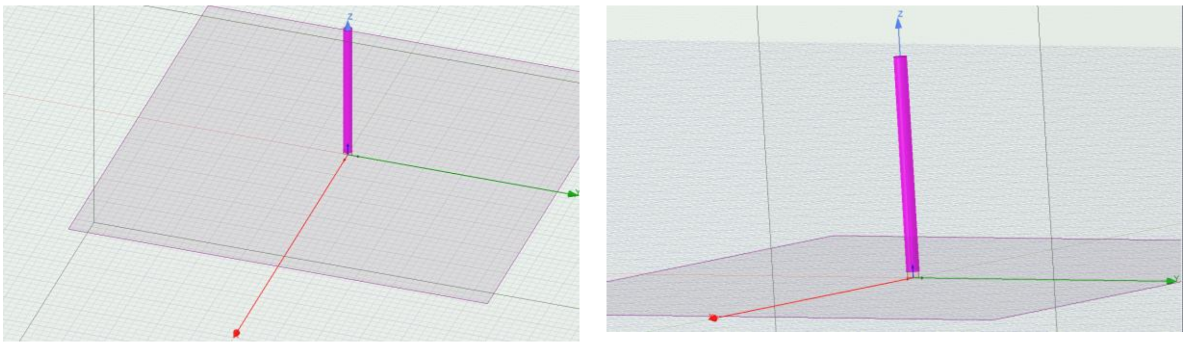

Figure 5: Monopole antenna

3.1.2. Results of monopole:

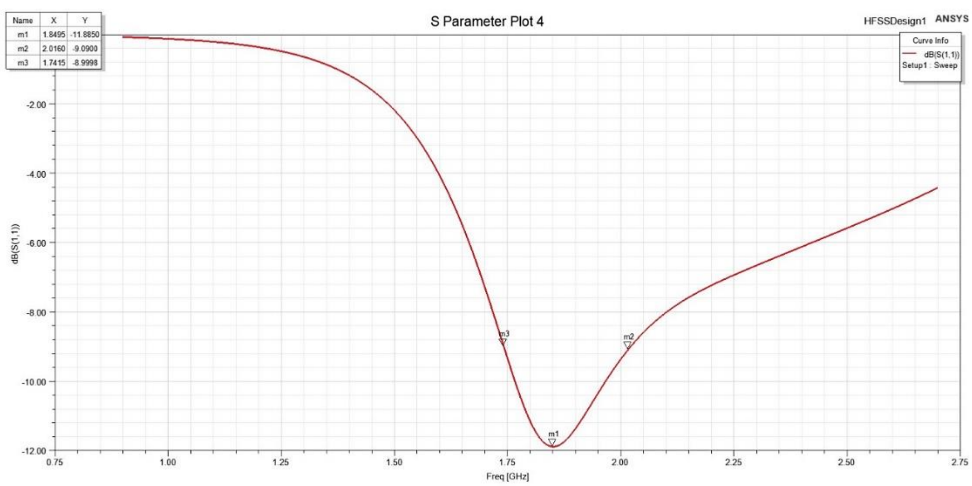

Figure 6: monopole antenna S11

Resonant Frequency:

The S11 plot shows a significant dip near 1.8495 GHz, identifying the resonant frequency of the antenna. This confirms that the antenna is well-matched to the feed line at this frequency, ensuring minimal reflection and maximum radiation efficiency.

Return Loss:

At resonance, the return loss is below -10 dB, indicating efficient impedance matching and excellent energy transfer from the feed to the antenna.

Bandwidth:

The -10 dB bandwidth (frequency range where S11 is below -10 dB) is centered around 1.85 GHz.

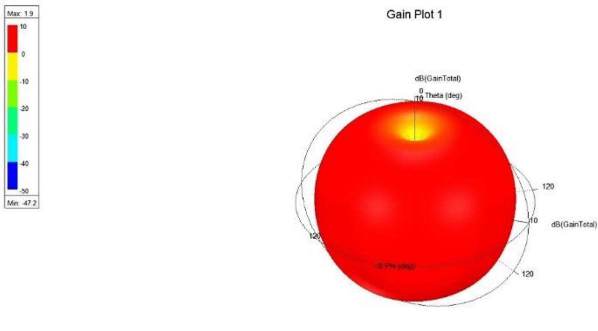

Figure 7: Gain plot 3D for monopole

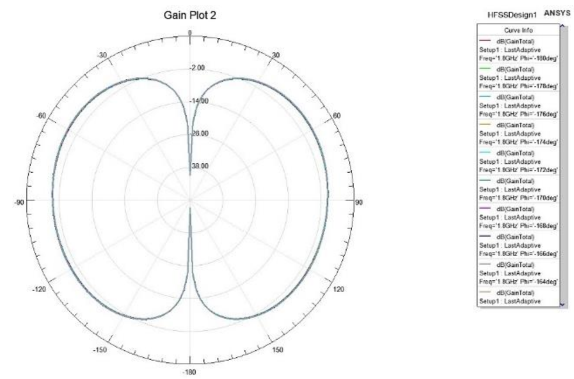

Figure 8: Gain plot 2D for monopole

Radiation Pattern:

The gain plot indicates that the monopole antenna exhibits an omnidirectional radiation pattern in the azimuthal plane (ϕ=0). This behavior is consistent with the expected characteristics of monopole antennas. Additionally, the maximum gain is concentrated along the zenith (θ=0), highlighting strong directivity and effective vertical polarization.

Maximum Gain:

The antenna demonstrates a maximum gain of approximately 13 dBi, which suggests high efficiency and effective power radiation. This makes the antenna suitable for applications requiring focused energy in specific directions.

At 1.8585 GHz, the real part of the impedance is around 35.7212Ω. This is close to the expected theoretical value for a monopole antenna, which is around 36.5 Ω as R Monopole = 0.5 * R Dipole and R Dipole equals to 73 Ω.

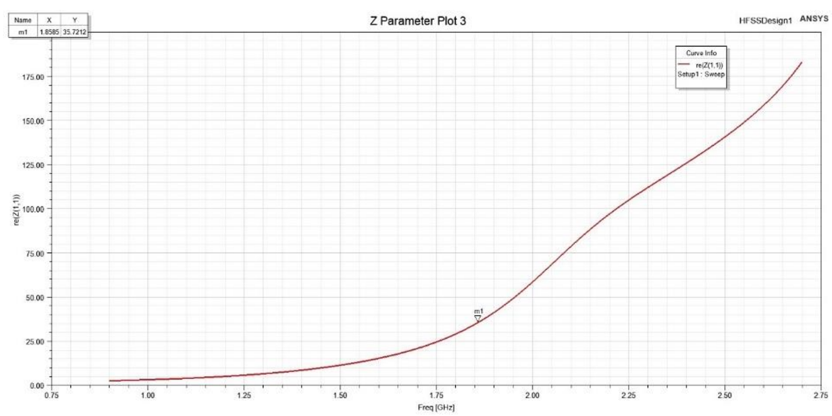

Figure 9: Zin for monopole

3.1.3. Verification results summary:

The simulation results closely align with our predicted outcomes. The radiation pattern exhibits a hemispherical with maximum gain occurring at θ=90, confirming omnidirectional behavior in the H-plane. Additionally, the return loss is less than -10 dB at the intended frequency, The real part of the input impedance Z11 is approximately 36 Ω and the imaginary part is zero at the resonance frequency of 1.85 GHz, which is close to the theoretical value for a monopole antenna. This ensures efficient power transfer and validates the resonance condition indicating good impedance matching. Based on these results, we have successfully verified the tool and are ready to proceed with the design phase.

3.2. Simulation and analysis for for 2-element array:

This section considers the design, simulation, and fabrication efforts for the two-element array slot-fed antenna, concerning on its 35 GHz performance. The analysis evaluates real results. Detailed graphs include radiation patterns and impedance matching, studying their impact on the antenna at 35 GHz. The antenna is being analyzed with respect to:

- Antenna & Radiation characteristics.
- System-level considerations.
- practical use-case.

3.2.1. Return loss (S_{11}):

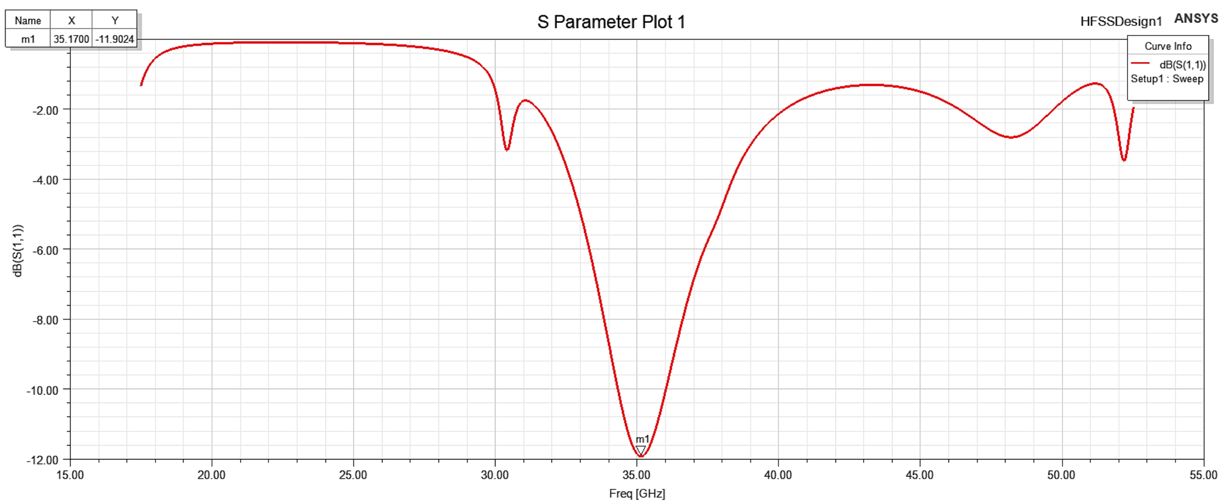

Figure 10: Return loss(S11) for 2-element array

- We managed to achieving a return loss of ≈ -12dB @ 35.17 GHz with a bandwidth of ≈ 2 GHz as required. This result helps the antenna to work as a resonator @ this frequency with a low signal reflection.

3.2.2. Input impedance:

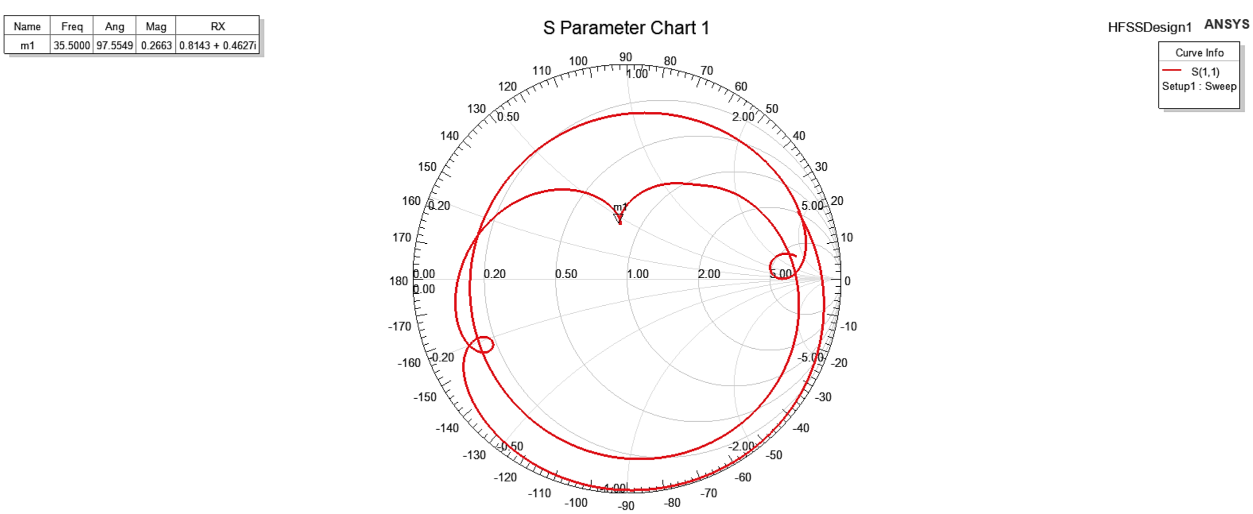

Figure 11: Smith chart for input impedance for 2-element array

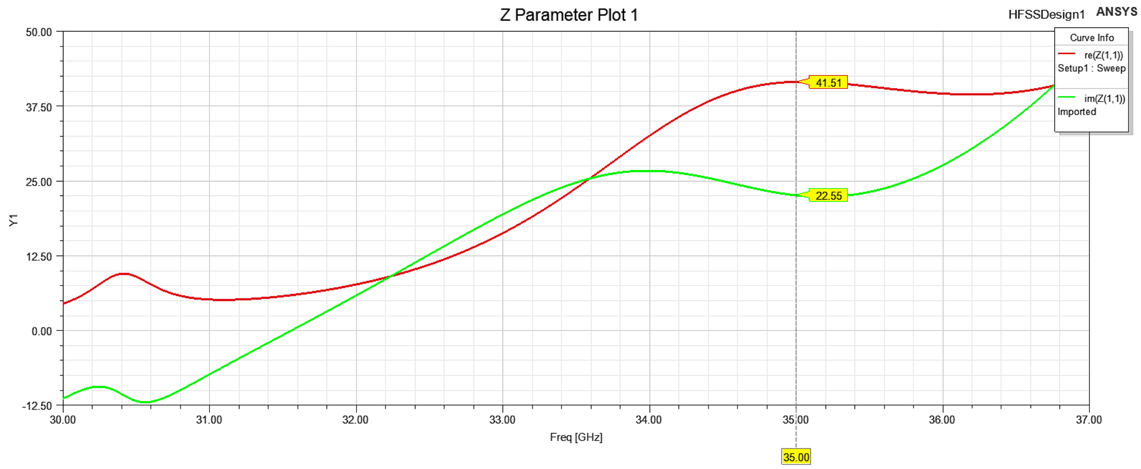

Figure 12: Real and imaginary part of the input impedance

- Obtaining an input impedance of 41.51 + j22.55 ohms gives the required matching and return loss (S11 = -12 dB). But this leads to the presence of a system level requirement which is a matching network proceeds the antenna to be able to achieve standard requirements for optimal power transfer and signal integrity within the specified frequency range.

3.2.3. <u>The radiation pattern in E and H planes:</u>

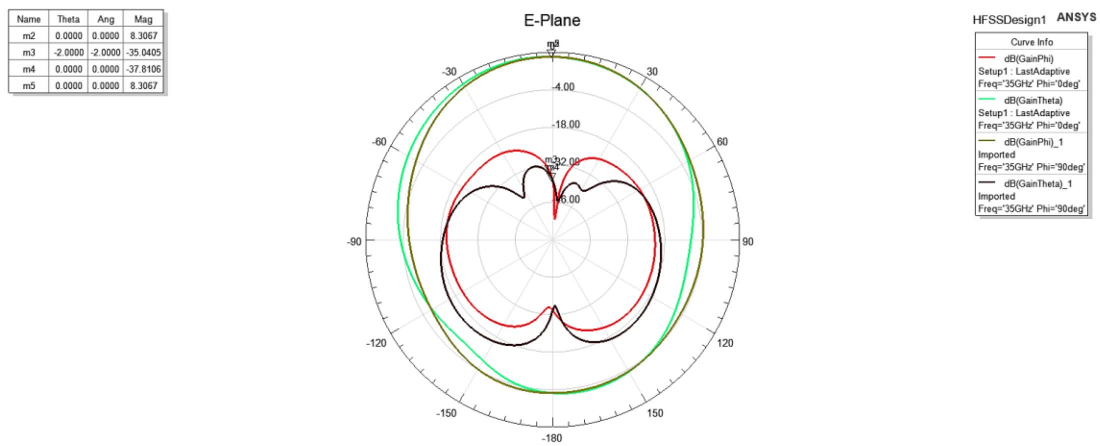

Figure 14: E and H plane

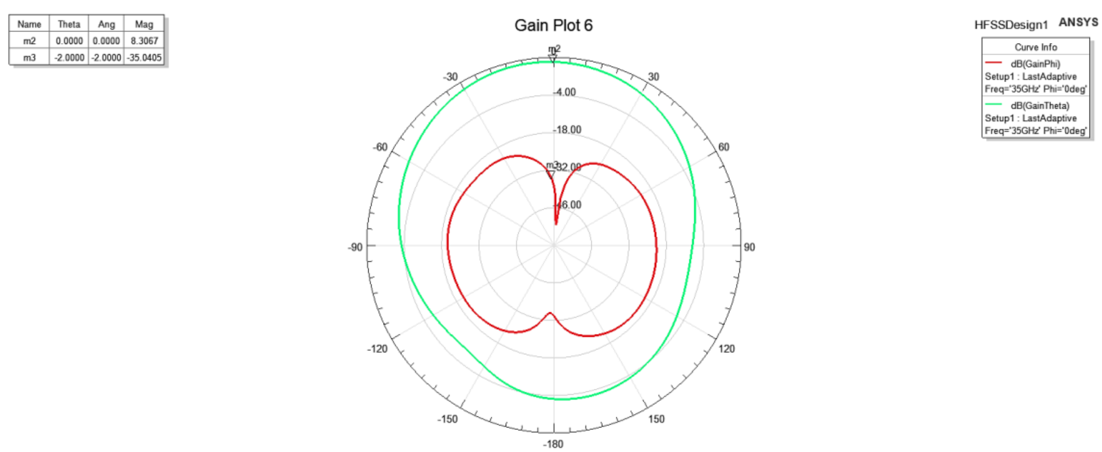

Figure 13: E plane

- The feed line is parallel to the x-axis which cases the current flow along the x-direction, positioning the E-plane within the XZ plane at a phi of zero degrees. The design achieved a cross-polarization of -35.04 dB in E-plane at theta = 0 degree.

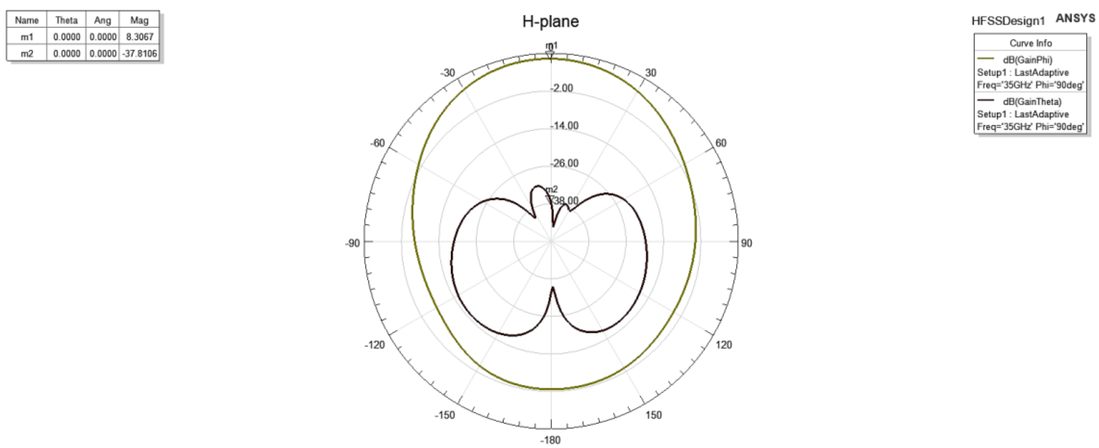

Figure 15 : H plane

- The feed line is parallel to the x-axis which cases the current flow along the x-direction, positioning the H-plane within the YZ plane at a phi of 90 degrees. The design achieved a cross-polarization of -37.81 dB in H-plane at theta = 0 degree.

3.2.4. <u>The gain and radiation efficiency:</u>

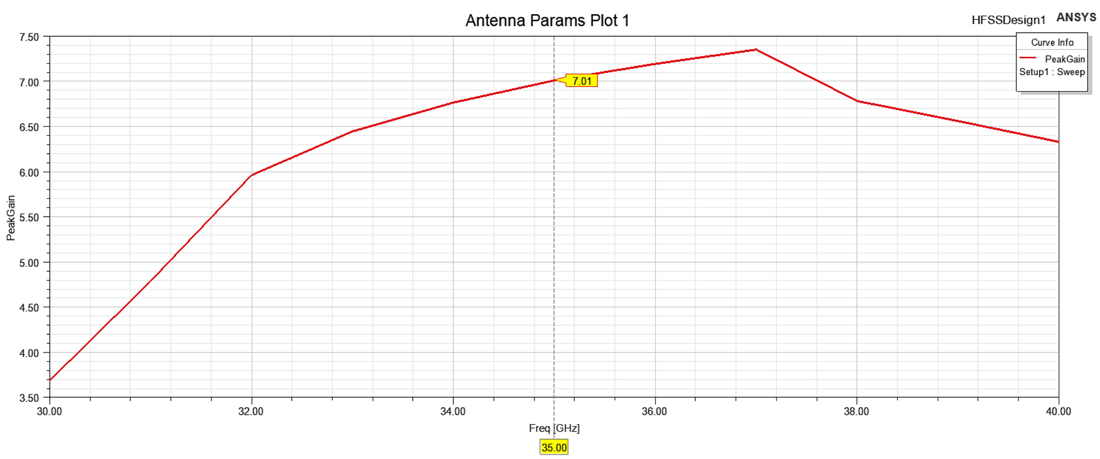

Figure 16: Peak gain vs frequency

- Achieving a gain of 7.01 at 35 GHz ensures an excellent directivity at this frequency range which gives the indication that the antenna's capability of amplifying the signal and direct in the desired direction with high efficiency.

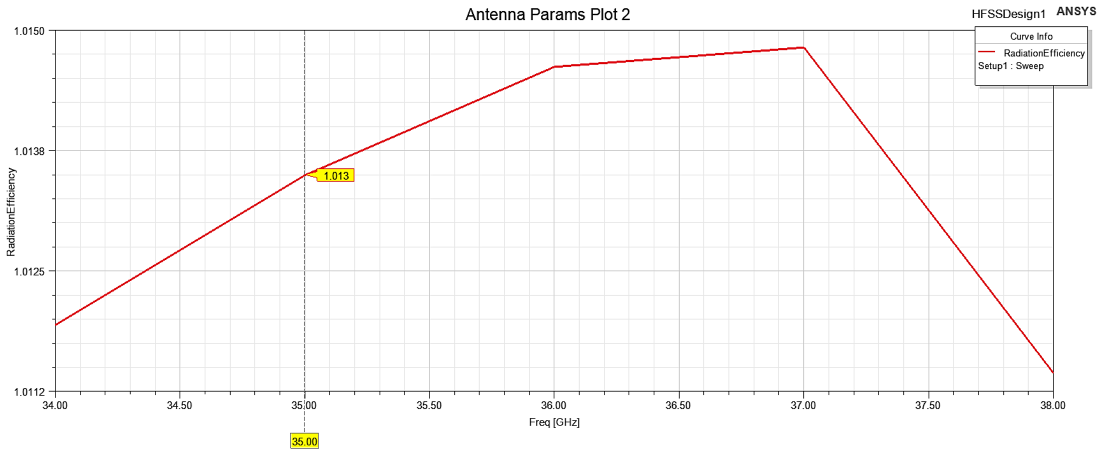

Figure 18: Radiation efficiency vs frequency

- As shown in the graph the radiation efficiency @ 35 GHz is 1.013 which indicates an excellent conversion of the input power into radiation which is required to have high benefit of the antenna.

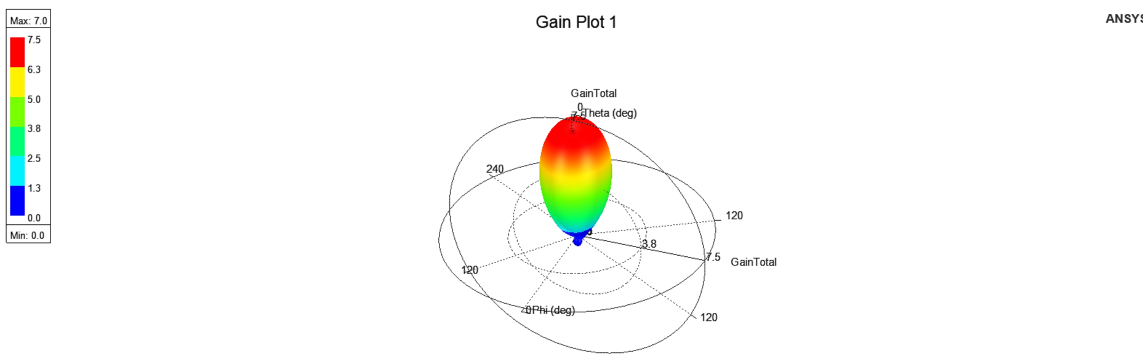

Figure 17: 3D gain

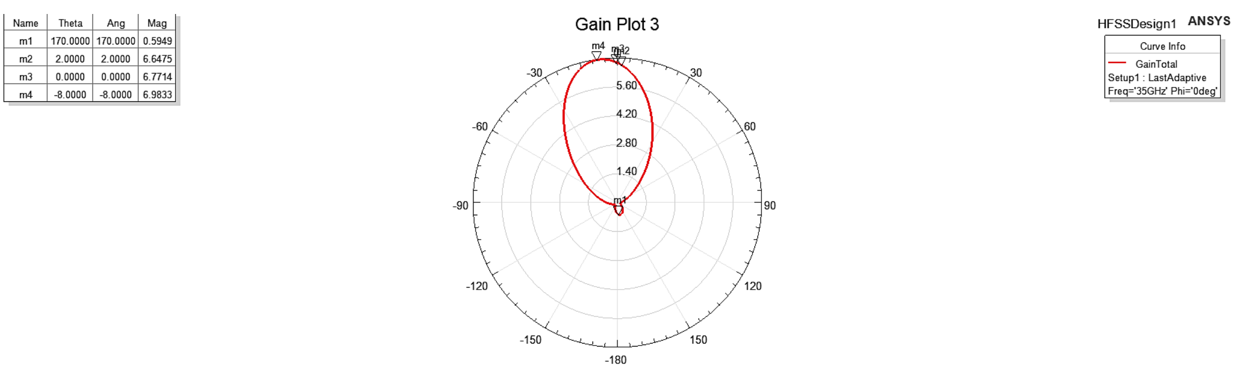

Figure 19: Gain plot 2D

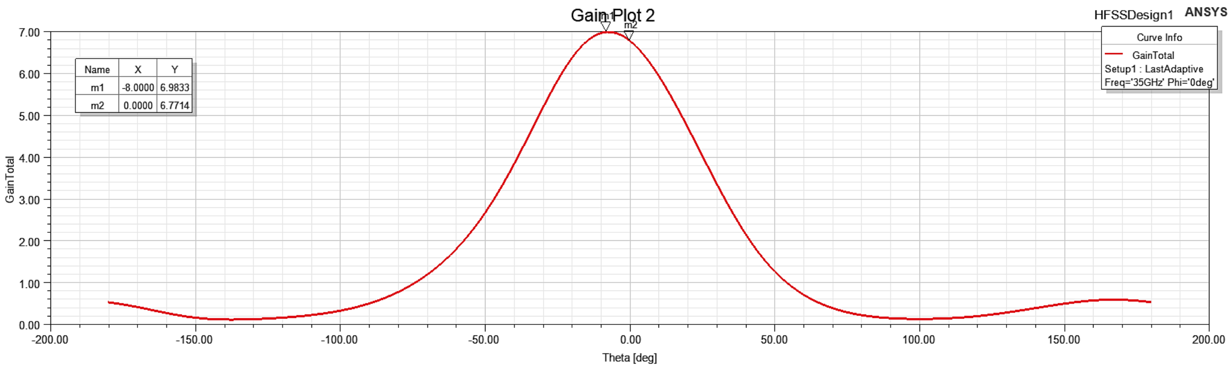

Figure 20: Gain plotting vs frequency

3.2.5. Other parameters:

a) Front-To-Back ratio:

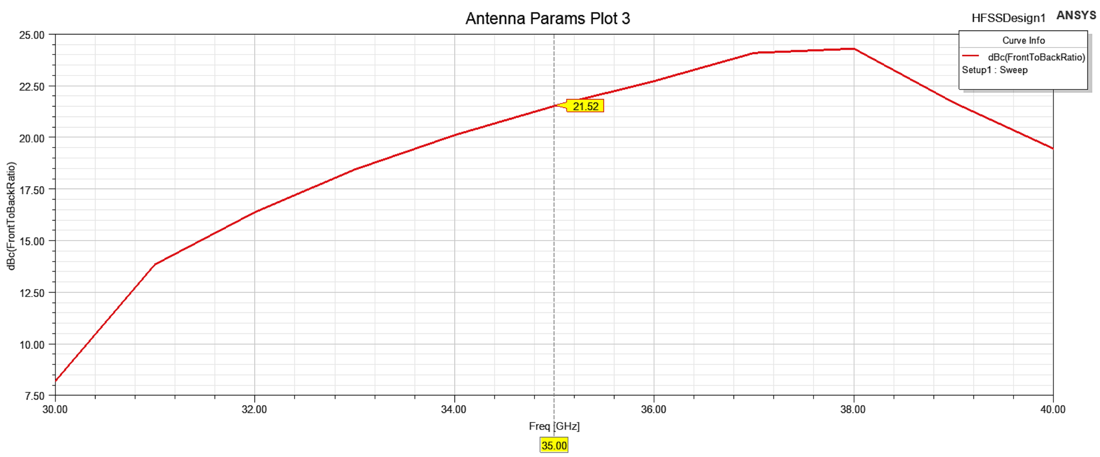

Figure 21: Front-To-Back ratio vs frequency

- The obtained Front-To-Back ratio is 21.52 dB @ 35 GHz which is a good achievement indicates that the antenna selects to receive signal from certain direction (which is the desired ones) than the other. This enhances the interference reduction.

b) VSWR:

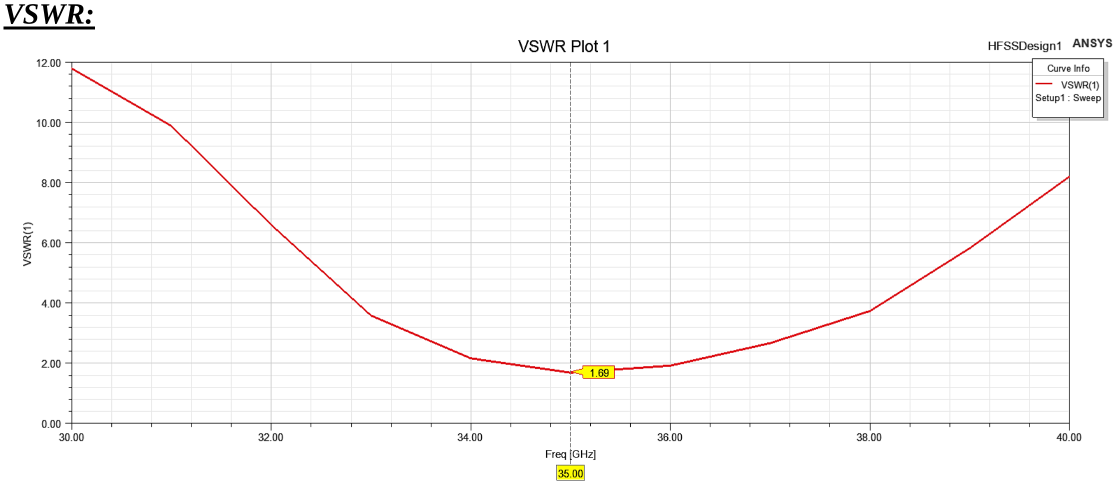

Figure 22: VSWR vs frequency

- VSWR is 1.69 at frequency = 35 GHz, this shows a good signal loss due to reflection even. This is an advantage for high frequency applications.

4. **Equivalent circuit model:**

To develop an equivalent circuit model for our designed antenna, we began by exporting the return loss plot data, which represents the antenna's S11 performance. This data was then imported into ADS for further analysis. Using the imported return loss as a reference, we set optimization goals to fine-tune the circuit component values and closely match the antenna's behavior.

We added goals to enhance the circuit's performance. These included maximizing the return loss (S11) at the resonant frequency to ensure optimal matching and achieving acceptable performance over the desired bandwidth then we started the optimization process.

4.1. **Design on ADS:**

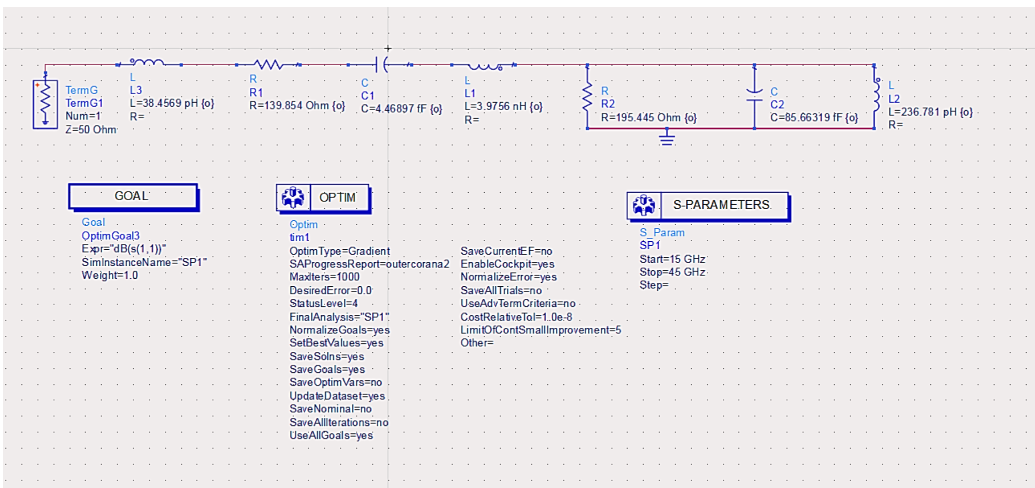

Figure 23: Design of equivalent circuit

4.2. **Results:**

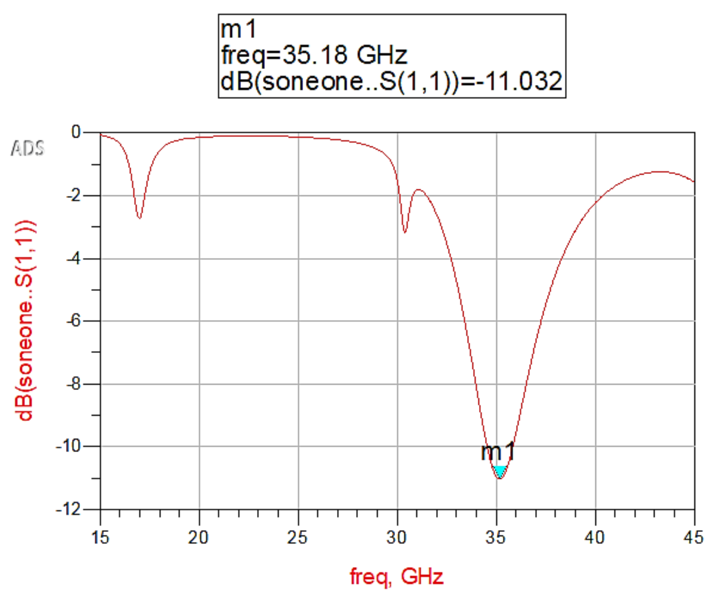

Figure 24:S11 for equivalent circuit

4.3. Equivalent circuit model summary:

By incorporating multiple goals and constraints into the ADS optimization process, the software iteratively adjusted the component parameters. This allowed us to refine the equivalent circuit, ensuring that its simulated response closely aligned with the actual antenna performance across the entire frequency range of interest.

Parameter	Value
R1	139.854 ohms
R2	195.445 ohms
L1	3.9756 nH
L2	236.781 pH
C1	4.46897 fF
C2	85.66319 fF

5. Effect of distance on gain and matching

The distance between the two array elements controls factors like the mutual coupling between them and the gain also the scan range that the antenna can operate in with no other lobes that make the main beam less in power by 3db and the distance is calculated from the center of the slot.

5.1. With high distance

Increasing the distance between patches in a 2-element slot-fed microstrip patch antenna array enhances gain and directivity by reducing mutual coupling, as seen with a peak gain of 5.24 dBi. It also improves impedance matching, achieving a mutual coupling of -17.58 dB at 35 GHz. However, excessive spacing may introduce grating lobes and phase errors, degrading radiation performance and beamforming. While high separation reduces interaction between elements, it can affect the array's compactness. Optimizing the spacing to approximately λ/2\lambda/2λ/2 ensures a balance between performance and size constraints.

Advantages:

- Improved gain and directivity due to reduced mutual coupling.
- Better impedance matching and reduced interaction between elements.

Disadvantages:

- Potential introduction of grating lobes if the separation exceeds λ/2\lambda/2λ/2.
- Reduced compactness, which might not be ideal for size-constrained applications.
- Phase errors and uneven power distribution can degrade radiation performance.

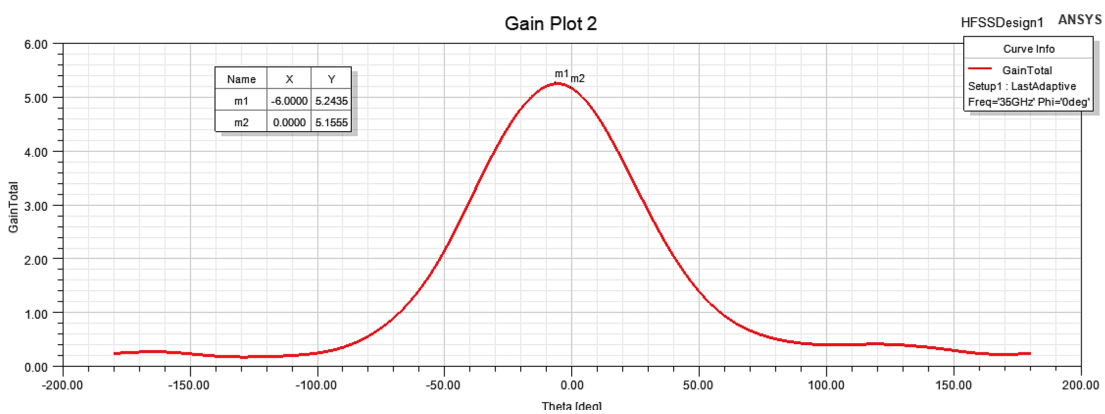

Figure 25: Gain plot for high distance

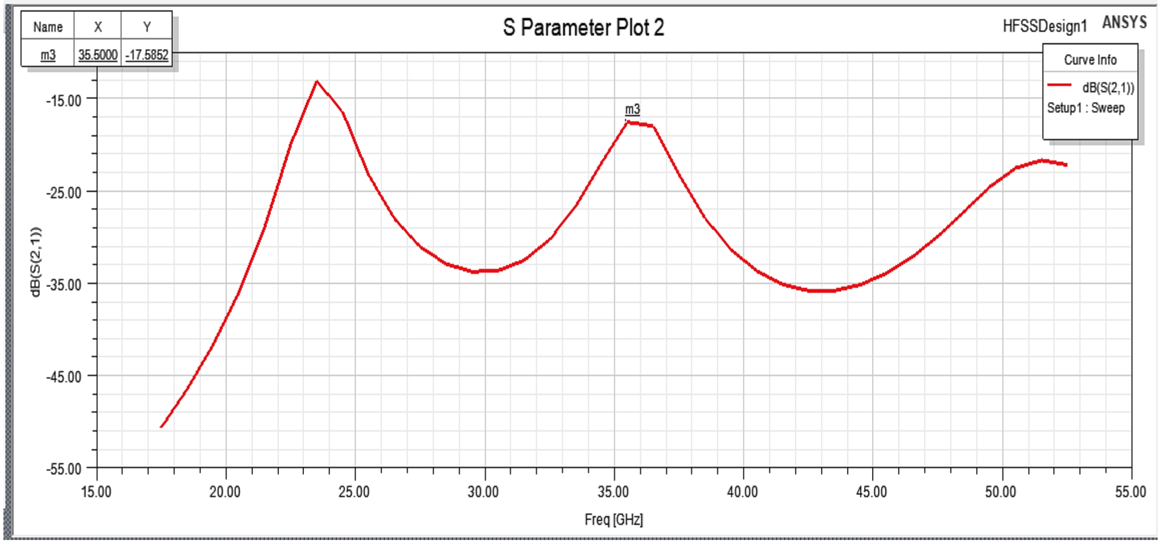

Figure 26:S parameter for high distance

5.2. With low distance

With a low distance between patches, the performance of the 2-element slot-fed microstrip patch antenna array is influenced as follows:

Gain Plot (Figure 28): The peak gain is approximately 4.41 dBi, lower than the gain observed for high patch distances. This indicates increased mutual coupling between the elements, which limits constructive interference and reduces the overall directivity.

S-Parameter Plot (Figure 29): The Mutual Coupling (S21) at 35 GHz is approximately **-**14.45 dB, which is mutual coupling, and it get higher by decreasing the distance.

- **Advantages:** Compact array size and reduced risk of grating lobes.
- **Disadvantages:** Increased mutual coupling, reduced gain, and slight degradation in return loss.

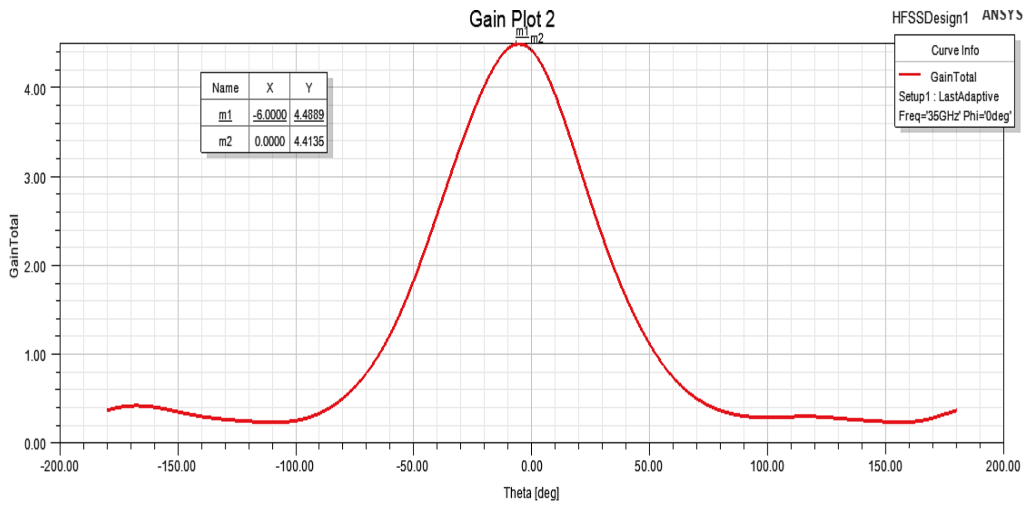

Figure 28: Gain plot for low distance

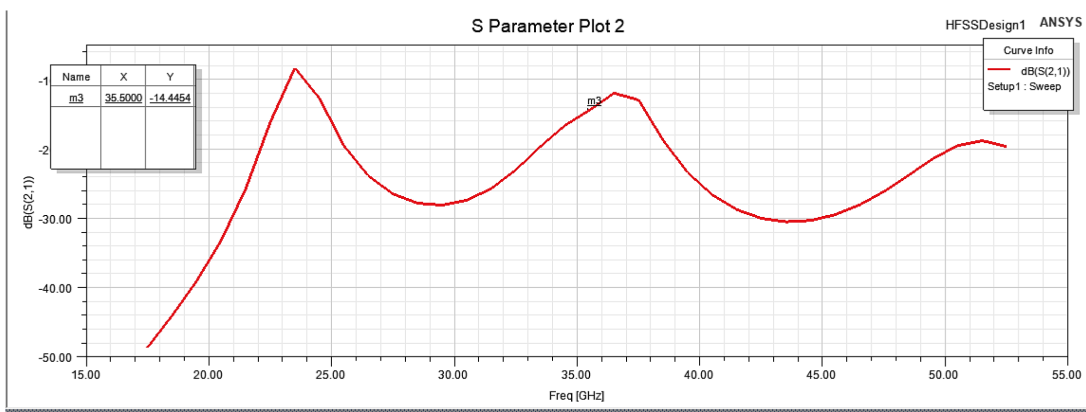

Figure 29: S parameter for low distance

5.3. Mutual coupling:

- **Trade-off Analysis:** Increasing the distance improves isolation (lower mutual coupling) and gain, but it also increases the array size and can potentially introduce grating lobes at very high spacings.
- **Optimal Design Recommendation:** For practical applications, the distance between elements should be chosen to minimize mutual coupling while maintaining compactness, typically around λ/2\lambda/2λ/2 at the operating frequency.
- The relationship between gain and distance can be described as

$$G\ \alpha \left(\frac{Nd}{\lambda}\right)^2$$

- The relationship between Mutual coupling and distance can be described as

$$S_{21}\alpha - 20\log_{10}\left(\frac{d}{\lambda}\right)$$

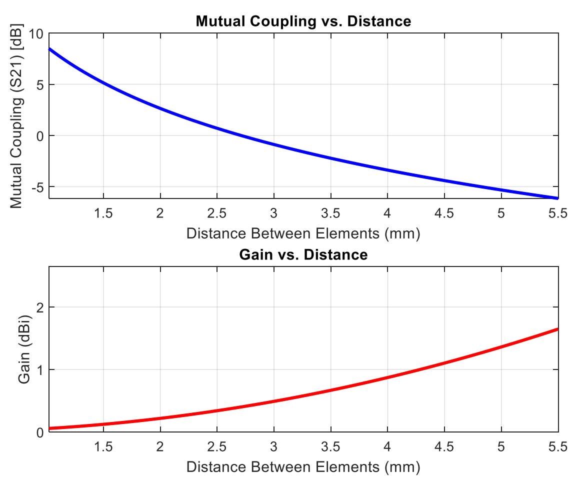

Figure 30: Mutual coupling graphs

6. Final design layout

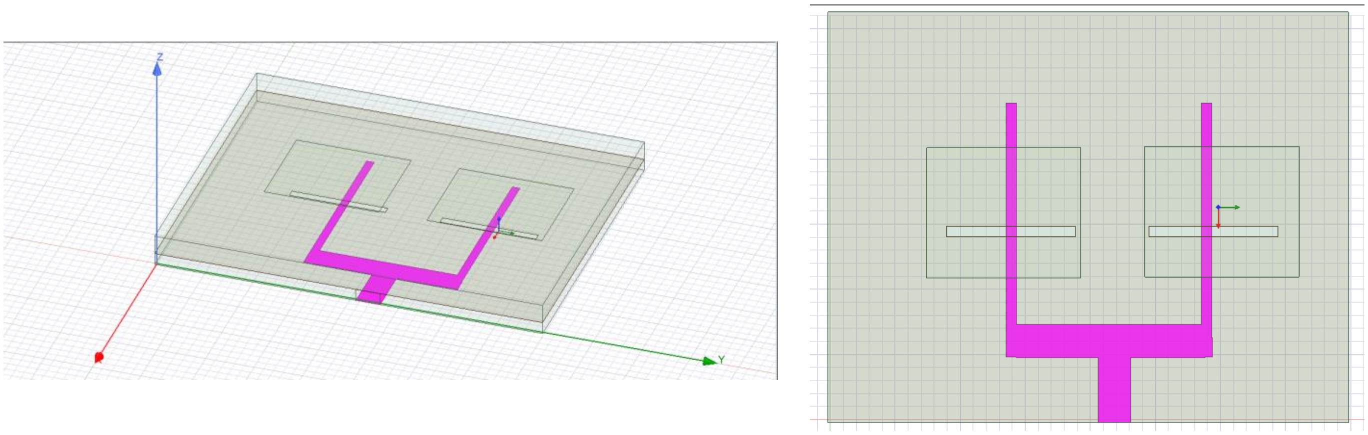

Figure 31: Design layout

7. Conclusion and Future Work

This project focused on designing a two-element slot-fed microstrip patch antenna array optimized for 35 GHz. Through selection of materials, dimension tuning, and use of feeding techniques, we achieved a return loss of approximately -12 dB and a gain of 7.01, alongside acceptable radiation efficiency and directional control. The process involved detailed simulations, iterative design adjustments, and performance verification, input impedance, and radiation patterns. The results prove the antenna's capability for high-frequency applications.

We discussed the effect of the distance between elements on the antenna radiation pattern and gain and tried to get the best result from this.

7.1. For future work, we might think of

a) **Beamforming Integration**: Expand the design to a larger array for dynamic beam steering applications, enhancing coverage.
b) **Multi-Band Operation**: Modify the design for multi-band functionality to support many applications, reducing the need for multiple antennas.
c) **Advanced Feeding Networks**: Try to apply another method of feed and power divide techniques to improve impedance and bandwidth.

These improvements can extend the antenna's applicability and efficiency in modern high-frequency communication systems.

8. References

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