A logo with a black background

Description automatically generatedA logo of a person sitting on a chair

Description automatically generated

**Department of Electronics and Electrical Communication Engineering.**

**Faculty of Engineering Cairo university**

**2-element slot-fed microstrip patch   
antenna array**

**Antenna and waveguides**

**ELC 3050 – Fall 2024**

|  |  |  |  |
| --- | --- | --- | --- |
| **Student Name** | **ID** | **Sec** | **BN** |
| بلال رمضان حلمي صميدة | 9220205 | 1 | 38 |
| عبدالرحمن محمد صلاح الدين ابو هندي | 9220473 | 2 | 39 |
| محمد عصام عبدالعظيم ابراهيم | 9220720 | 3 | 31 |
| محمود عبدالسلام عبدالصادق عبدالفتاح | 9220785 | 3 | 38 |
| نور اشرف احمد ماهر | 9220917 | 4 | 21 |
| يارا اسامة مهتدى ادريس | 9220954 | 4 | 26 |

**Under the supervision of:  
Dr. Islam A. Eshrah**

# Introduction and Problem description

## Introduction

Microstrip Patch Antennas (MPAs) are widely used in modern wireless communication systems due to their low-profile, lightweight, and ease of integration with other circuit components. These antennas are particularly useful in high-frequency applications such as 5G and millimeter-wave (mm Wave) communications, where bandwidth demand and system performance are critical.

A microstrip patch antenna typically consists of a conducting patch placed on a dielectric substrate with a ground plane on the opposite side. The shape of the patch, the substrate material, and the dimensions are chosen to meet specific resonance conditions, providing efficient radiation at a given frequency.

In this project, the focus is on designing a **two-element array** of **slot-fed microstrip patch antennas** operating at a frequency of **26 GHz**, which is a key frequency band for 5G and future wireless communication systems. The array configuration aims to improve the antenna's gain and directivity, essential for high-frequency applications that require precise and high-performance communications.1

## Problem description

The goal of this project is to design and analyze a two-element array of slot-fed microstrip patch antennas operating at 26 GHz. The primary objective is to achieve the desired radiation characteristics, including a specific gain, directivity, and impedance matching, while also addressing the challenges associated with high-frequency operation.

Key aspects of the project include:

1. **Antenna Design**: Design of individual slot-fed microstrip patch antennas, including the selection of patch shape, size, and dielectric material to ensure resonance at 26 GHz.
2. **Slot Feeding**: The use of slot feeding for the antenna, where the excitation is achieved through a slot in the ground plane. This method offers benefits such as reduced spurious radiation and better impedance matching.
3. **Array Configuration**: The two-element array configuration must be designed to achieve constructive interference, enhancing the antenna’s gain and directivity. The array elements must be spaced appropriately to prevent undesirable interference or mutual coupling.
4. **Impedance Matching**: Ensuring that the antenna’s impedance is matched to the transmission line to maximize power transfer and minimize reflections at the operating frequency of 26 GHz.
5. **Simulation and Optimization**: Using simulation software (such as CST Microwave Studio, HFSS, or others) to model the antenna array, simulate its performance, and optimize its design for optimal radiation characteristics.
6. **Performance Analysis**: Evaluating the antenna array’s performance based on parameters such as return loss, gain, radiation pattern, and bandwidth to ensure that it meets the specifications for 26 GHz operation.

The problem involves not only designing the antenna itself but also considering the effects of the operating frequency, material properties, and array configuration on overall performance. Additionally, challenges such as minimizing loss, optimizing the array layout, and managing mutual coupling between elements must be addressed.

By successfully designing this two-element array of slot-fed microstrip patch antennas, the project aims to contribute to the development of efficient antenna solutions for high-frequency applications in next-generation communication systems, such as 5G and beyond.2

# Design Procedure

In this section, we will discuss the design procedure we followed to reach our final design. We actually worked on **two designs** in this project so we will discuss both of them, but we will divide the design procedure into two main stages, and each stage into multiple sections as follows:

1. **Single element slot-fed microstrip patch antenna.**
   1. Feeding structure
   2. Substrates material and thickness
   3. Slot dimensions
   4. Patch dimensions
2. **2-element array of the same antenna.**
   1. Feeding network
   2. Substrate and ground dimensions
   3. Elements spacing

## Single element design

In this stage we worked on the single element alone before instantiating it in the full antenna system.

First, we will explain the feeding structure for **the slot-fed microstrip patch** antenna.

A diagram of a microstrip

Description automatically generated

Figure 1: Slot-fed microstrip patch antenna structure

### Feeding structure

The feeding structure is simply composed of microstrip feed line, feeding slot – which is known as coupling aperture – and the radiating microstrip patch in addition to two substrates: feed substrate and antenna substrate as illustrated in **figure 1**. The microstrip technology is simple, with just two different-shaped conductors and a substrate between them. So, we worked with the information we have, to initially build the single element structure. And that applies to both designs.

### Substrates thickness

For the substrates material we used **Rogers RO4350B** with dielectric constantin the first design and **Rogers RO4003C** with dielectric constantin the second design. The used materials dielectric constant is typically between 3 and 4, where in this range the dimensions and the cost are acceptable as there is a trade-off between them in choosing material, as increases the dimensions decreases and the cost increases. We used the same material for both feed and antenna substrates.

For the substrates thickness, in the first design we chose from Rogers RO4350B standard thickness3 to make it irradiative , and to make it radiative .

In the second design we got the substrates thicknesses from **E. A. Soliman, A. Vasylchenko, V. Volski, G. A. E. Vandenbosch, and W. De Raedt** research paper4, and.

### Slots dimensions

For the slot dimensions, in the first design we got its dimensions from **E. Setijadi** research paper1 as a starting point before tuning. and .

For the second design we got its dimensions from **E. A. Soliman** research paper.4 and .

### Patch dimensions

For the patch dimensions, in the first design we used an online calculator to make it operate at the required frequency 26 GHz with 50 to be matched with the typical sources and we did the same for the microstrip feed line then we tuned the patch length to get the desired resonating frequency – where theoretically but it doesn’t apply accurately so we used the online calculator – and tuned its width to get the desired input impedance 50 . And finally, we got   
and.

In the second design we tested **E. A. Soliman** research dimensions4 and it worked well,   
 and .

Now, after we designed a single slot-fed microstrip patch antenna operating at 26 GHz with 50 as shown in **figures ---**, we instantiated it to build a 2-element array, but it was not that easy. So, in the next section we will explain its design procedure.

## 2-element array

### Feeding network

The feeding network in the first design is a T-splitter then two quarter-wave sections, one in each branch and the lines impedance is as shown in **figure -**.

The second design is series fed and matched using one quarter-wave section as shown in **figure -**. The space between the two antennas centers is a multiple of the wavelength to make the two elements in phase.

A diagram of numbers and squares

Description automatically generated

Figure 2: First design feeding network

A diagram of a diagram

Description automatically generated

Figure 3: Second design feeding network

### Substrate and ground dimensions

The substrate and ground dimensions influence the gain and radiation pattern. We chose the dimensions to be **---** in the first design and **---** in the second design.

### Elements spacing

Elements spacing is a strong factor for the gain and radiation pattern. As the spacing increases the mutual coupling decreases but the microstrip line losses increases, and at higher spacing – in concern to the radiation pattern – a side lobe starts to appear and attenuate the intended gain beam. So, we found that **10 mm** spacing is a sweet spot for the first design, while the spacing in the second design is chosen such that the gain is optimum and no phase difference between the two elements.4

# Results and Discussion

## Verification of EM tool results

Before discussing our results, we should verify the EM tool we used in the project. So, in this section we are willing to verify the EM tool results by benchmarking against another well-Known source. We designed a dipole and observed the output if it’s close to the excepted one ideally.

We used the material of the antenna (dipole) as copper and the radiation medium is air.

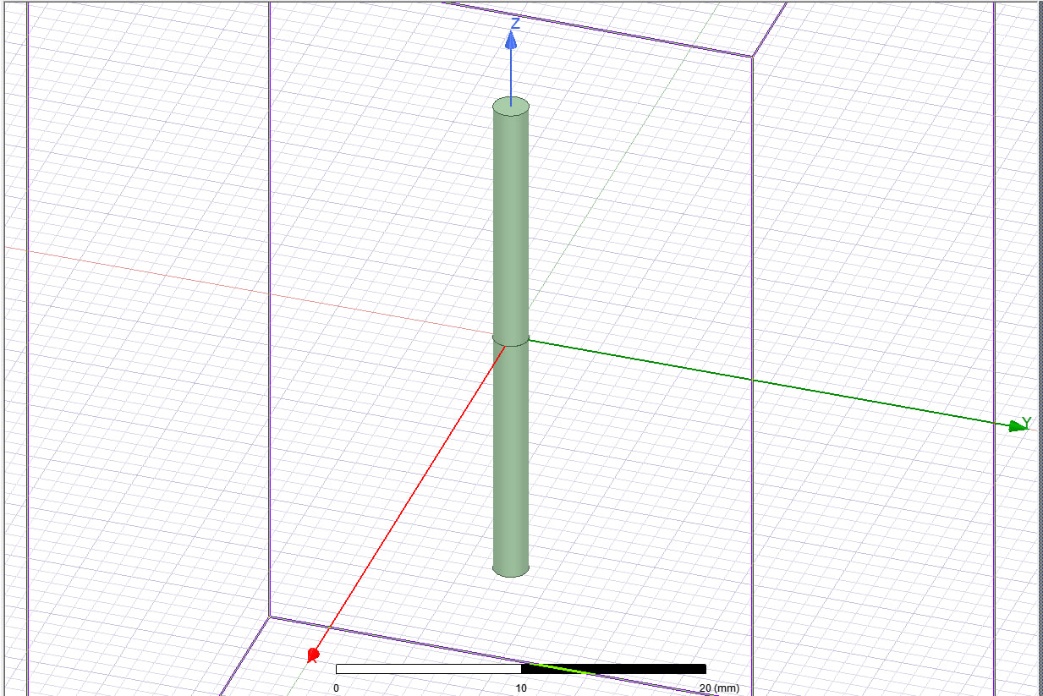


Figure 4: dipole structure

In the first simulation we adjusted the diameter of the dipole to and its length to and the gap between the two wires - due to the supposed feeding – to . The dipole structure is shown in **figure 1**.

From the dipole length we will get the resonance frequency as follows:

, .

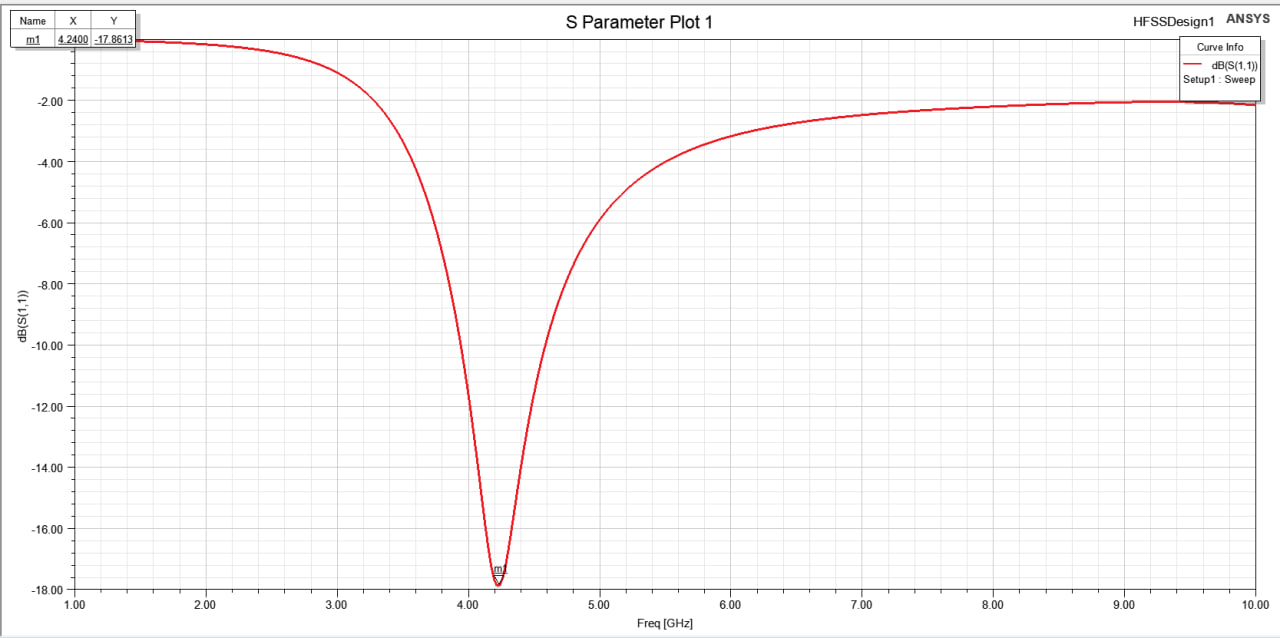


Figure 5: dipole return loss

As we see in **figure 2**, it is resonant at far from the desired frequency as a result of the non-ideality due to the wire diameter and the gab between the two wires which are both ideally zero, so we reduced them to the minimum possible values for the current mesh size.

The parameters for the next simulation are and the gap

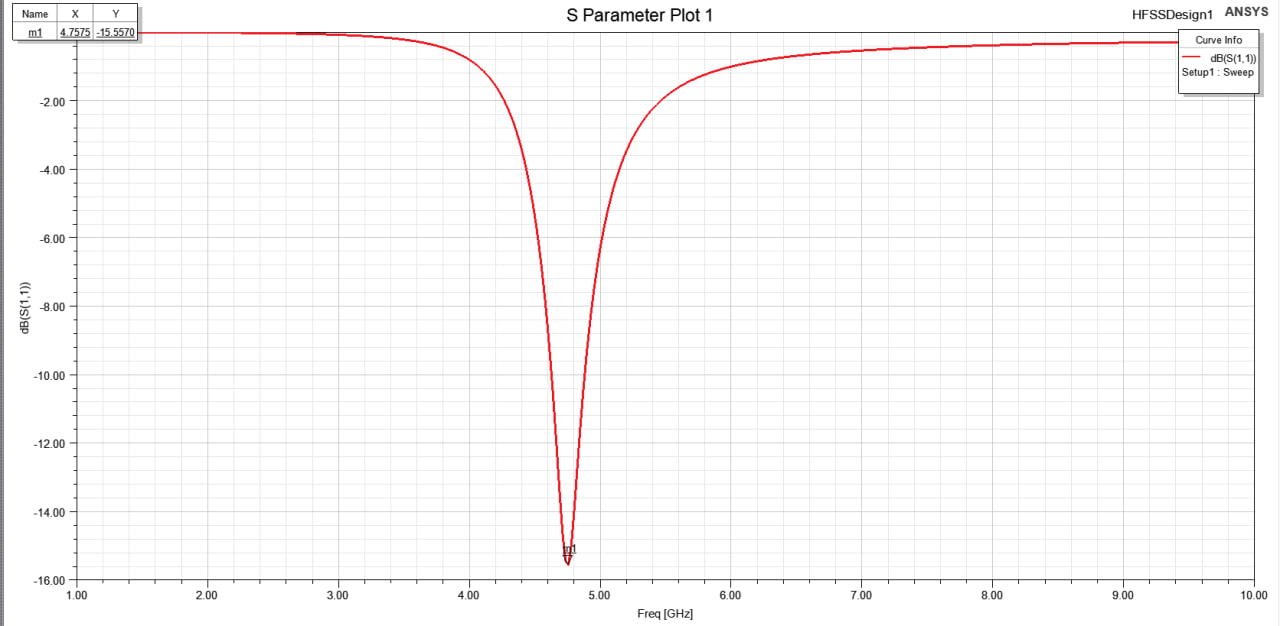


Figure 6: New dipole return loss

As shown in **figure 3**, the frequency became closer to the ideal frequency.

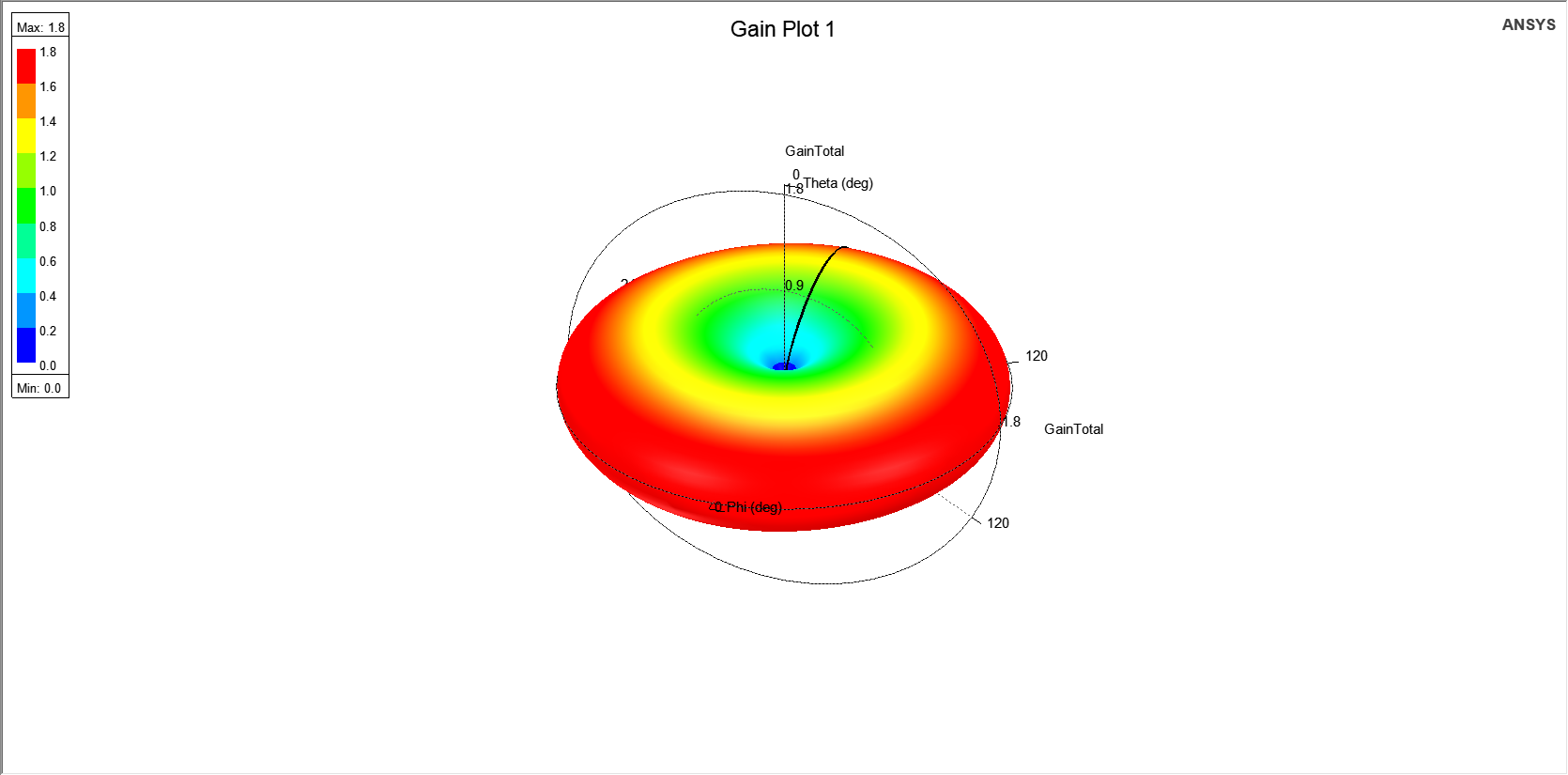


Figure 7: dipole gain (directivity)

For the radiation pattern, it is the same in both simulations and same as the expected shape from the lectures which is the donut shape as shown in figure 4. But it’s more directive with directivity 1.8 due to non-ideallty as we discussed above.

Note that the illustrated figure is the dipole gain but it’s the same as the directivity because it’s matched with the source.

Now, after we verified our EM tool we will present and discuss our simulation results for both designs in this project.

## Return loss

This part will be the first results discussion for our designs focusing on the return loss. The return loss is a very important antenna parameter, as it provides critical insights into the performance of the antenna. Specifically, it indicates the level of matching between the antenna and the transmission line at the operating frequency. A well-matched antenna will exhibit a high return loss (typically a negative value, indicating low reflection), which is essential for efficient power transfer.

In addition to matching, the return loss also provides information about the matching bandwidth around the operating frequency. This bandwidth is the range of frequencies over which the antenna maintains acceptable matching (typically less than -10 or -12 dB).

Furthermore, analyzing the return loss curve reveals the antenna's behavior outside the operating bandwidth. This includes identifying any potential secondary resonances, unintended reflections, or poor matching at frequencies beyond the intended range. These characteristics can influence the antenna's overall performance and help guide further optimization.

By examining the return loss graphs for our designs in **figures 8** **&9**, we can tell that the first design has a return loss of **-17.65 dB** at 26 GHz and a matching bandwidth of **3.5 GHz** (from 24.88 GHz to 28.38 GHz), i.e., **13.4 %** relative matching BW, while the second design has a return loss of **-31.75 dB** at 26 GHz and a matching bandwidth of **7.95 GHz** (from 24.81 GHz to 32.76 GHz), i.e., **30.5 %** relative matching BW.

Therefore, the second design has better return loss results in terms of achieving a higher return loss value, which indicates improved matching at the operating frequency and offers a slightly wider return loss bandwidth, which may be advantageous for applications requiring broader frequency coverage. For example, in ultra-wideband communication systems or 5G networks that need to accommodate multiple channels or frequency bands, the wider bandwidth ensures reliable performance across a broader spectrum.

A graph with red lines and yellow and blue text

Description automatically generated

Figure 8: First design return loss

A graph with red lines and numbers

Description automatically generated

Figure 9: Second design return loss

## The radiation pattern (co-pol and x-pol) in the E and H planes.

### First design:

Figure 10: First design Radiation pattern in the xz-plane

`

Figure 11: First design Radiation pattern in the yz-plane

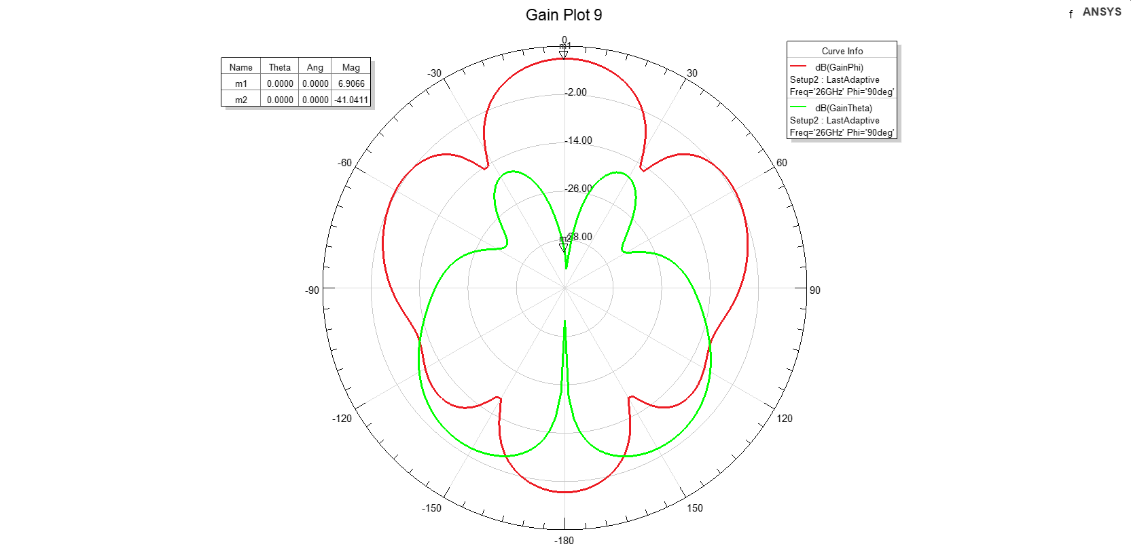
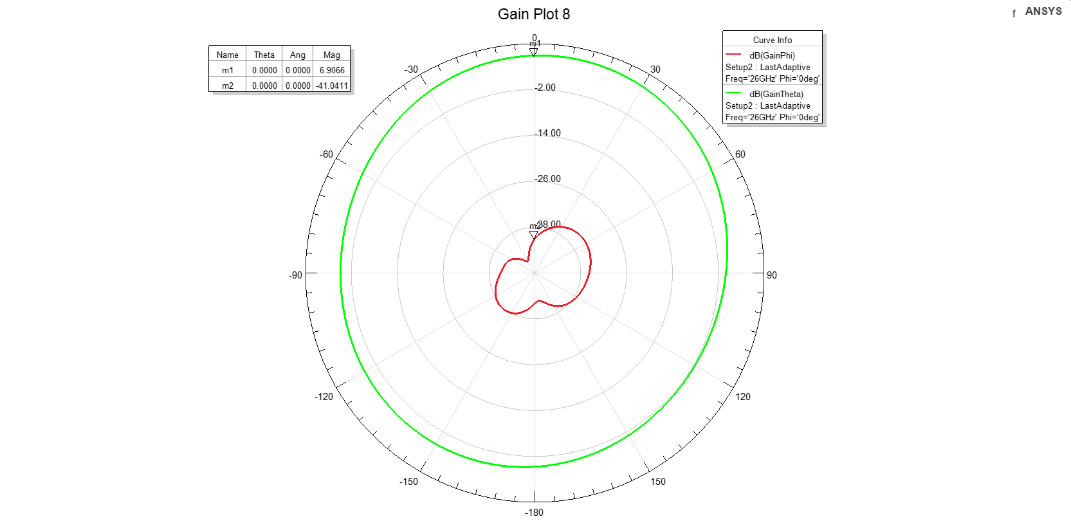


Figure 12: First design Co & Cross Polarized Fields in E-Plane

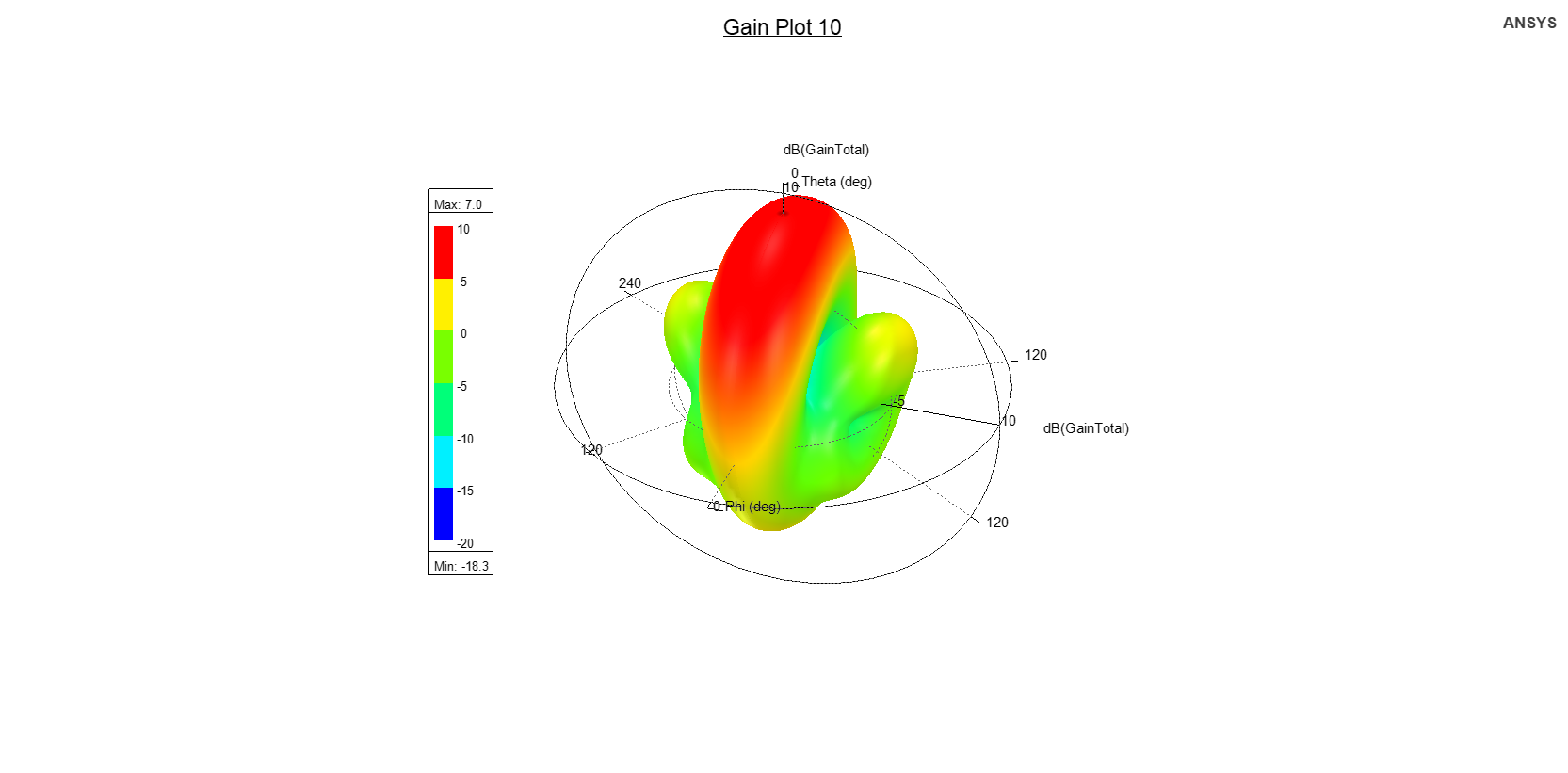


Figure 13: First design 3D Polar Plot of Gain (dB)

Figure 14: First design Co & Cross Polarized Fields in H-Plane

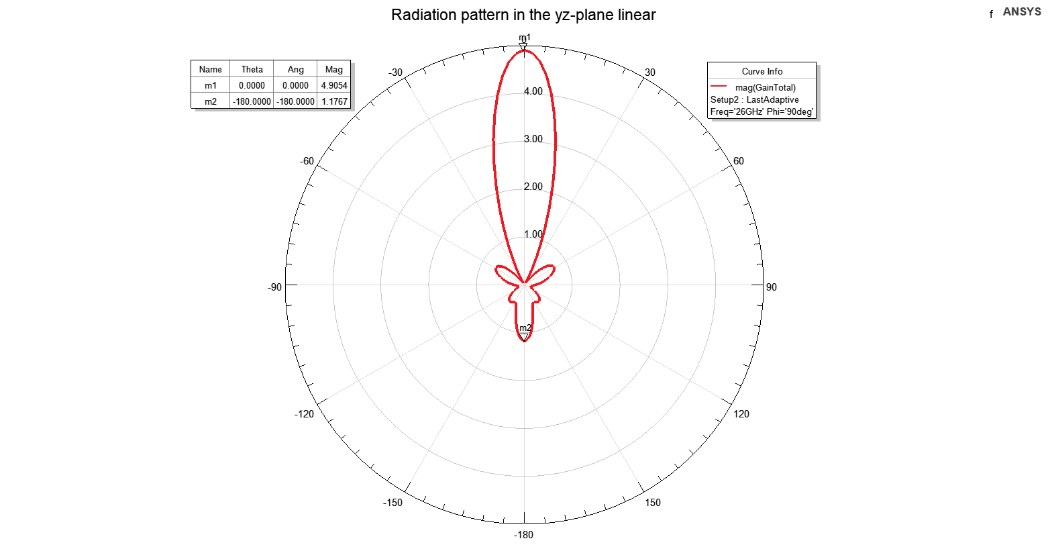
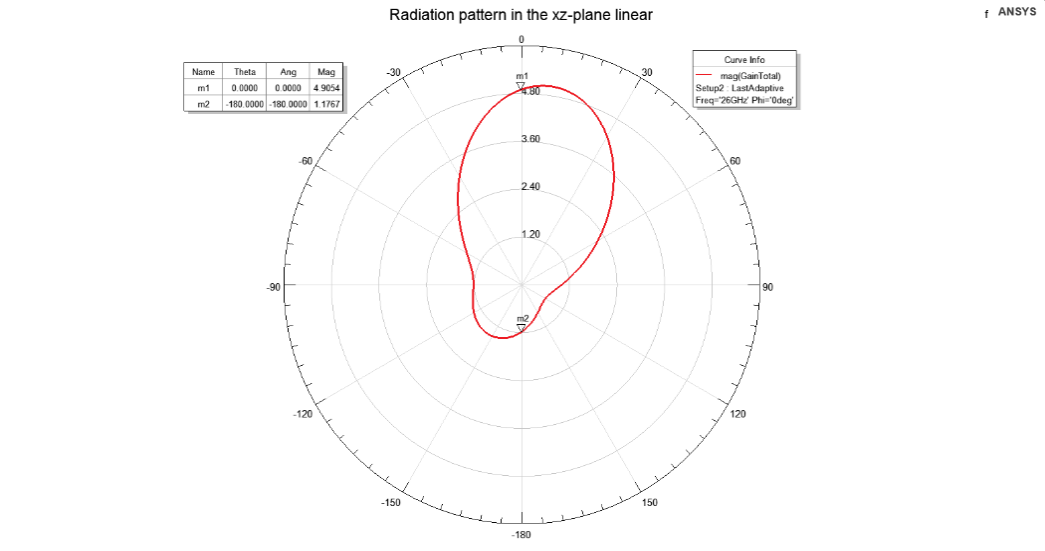


Figure 15: First design Radiation pattern in the xz-plane (linear)

Figure 16: First design Radiation pattern in the yz-plane (linear)

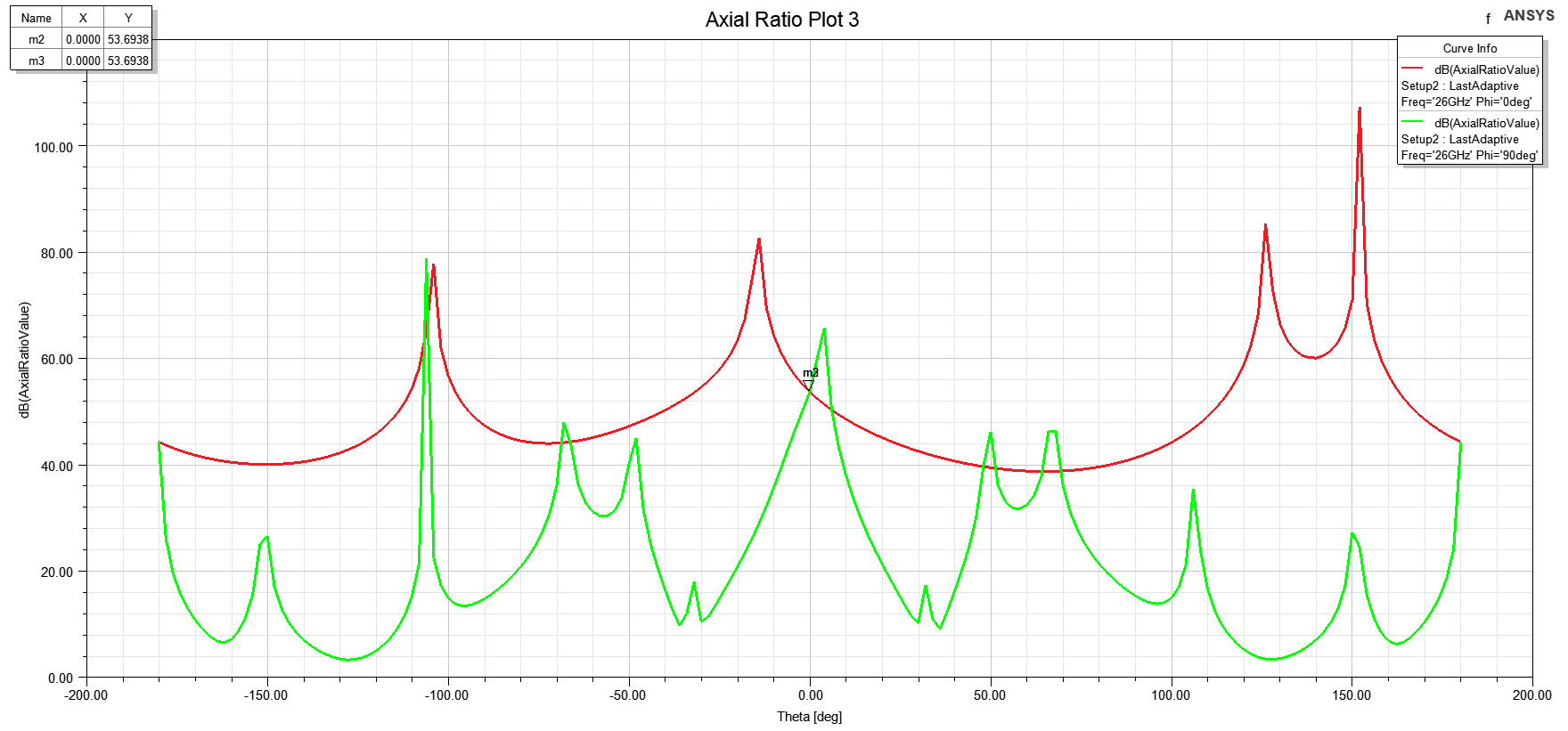


Figure 17: First design Axial ratio vs theta

A graph of a graph

Description automatically generated with medium confidence

Figure 18: First design Beam bandwidth

### Second design:

Figure 19: Second design Radiation pattern in the xz-plane

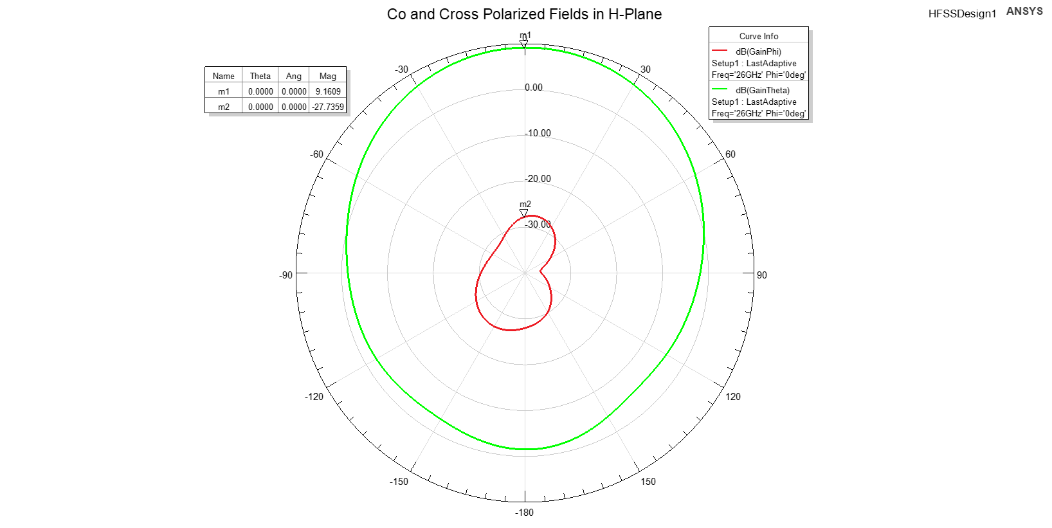


Figure 20: Second design Co & Cross Polarized Fields in H-Plane

`

Figure 21: Second design Radiation pattern in the yz-plane

A diagram of a flower

Description automatically generated

Figure 22: Second design Co & Cross Polarized Fields in E-Plane

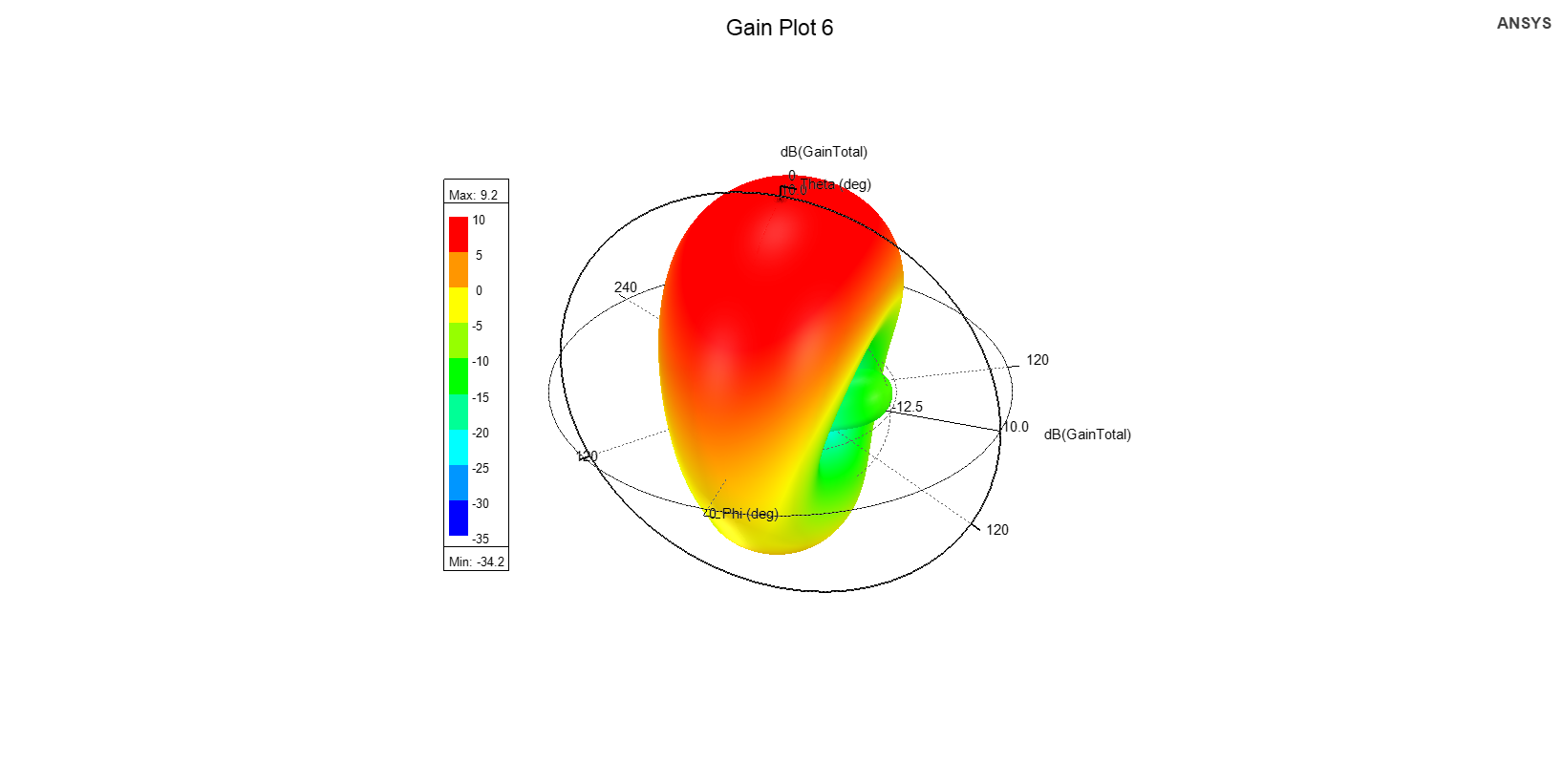
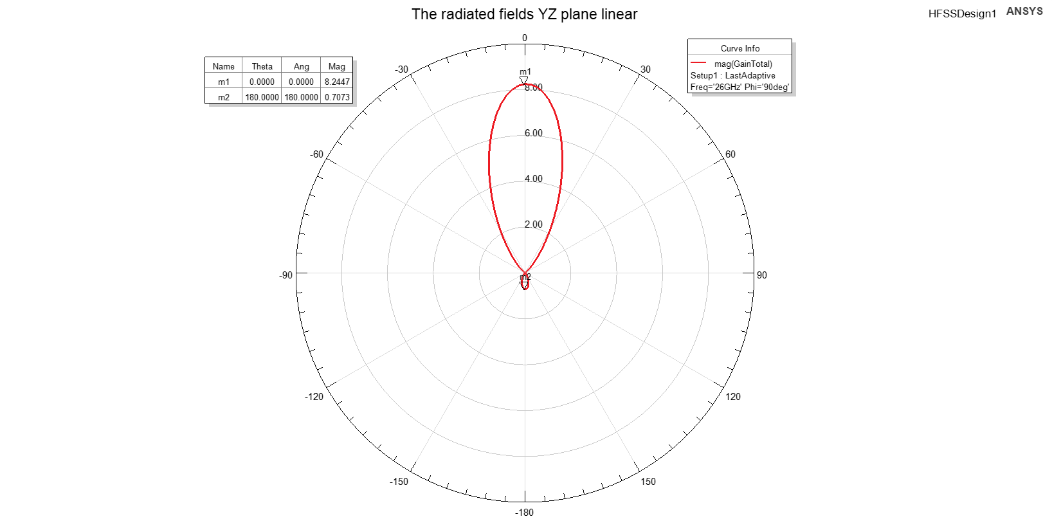


Figure 23: Second design 3D Polar Plot of Gain (dB)

A circular graph with a red circle

Description automatically generated

Figure 24: Second design Radiation pattern in the xz-plane (linear)

Figure 25: Second design Radiation pattern in the yz-plane (linear)

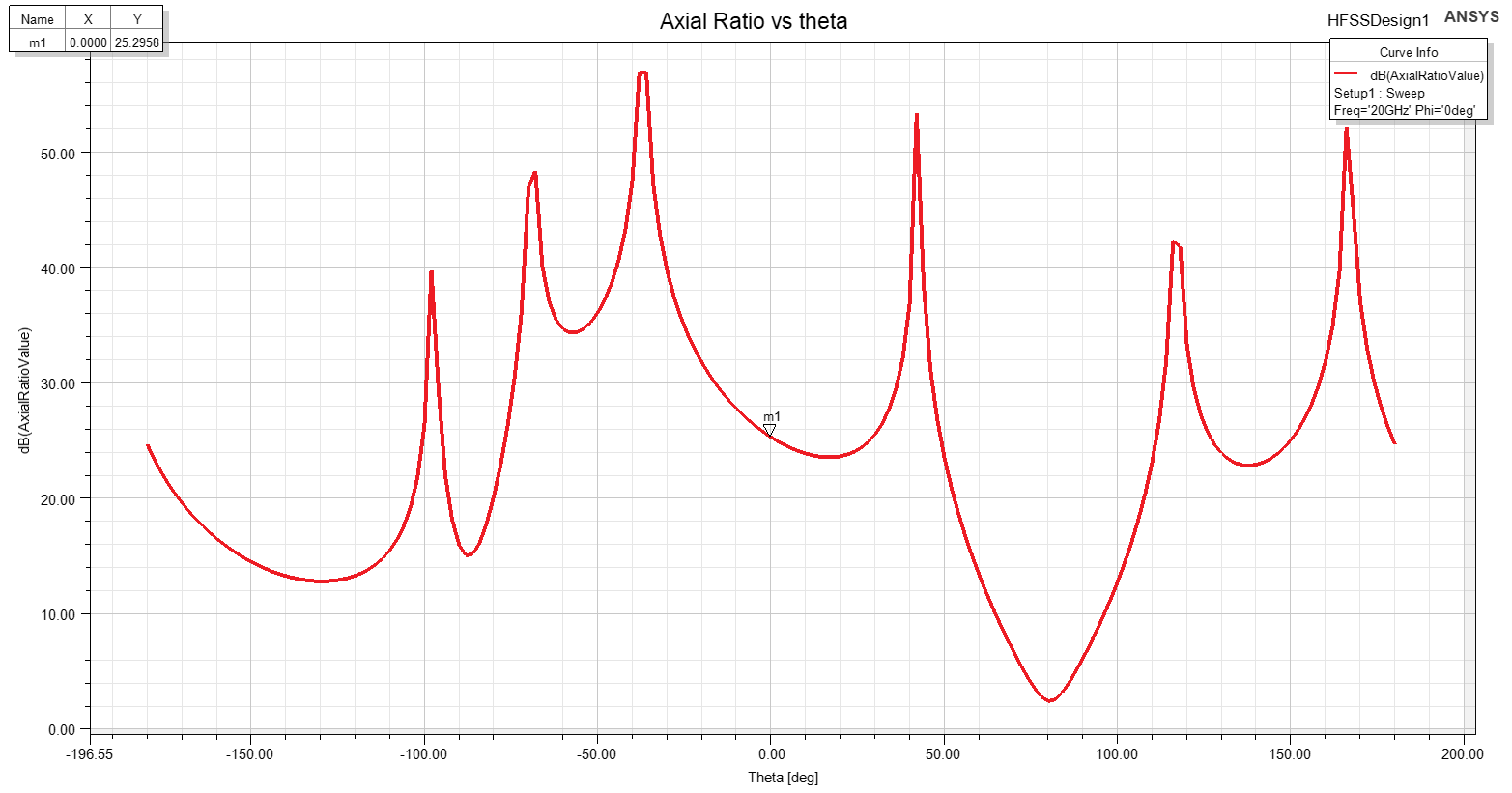


Figure 26: Axial ratio vs theta

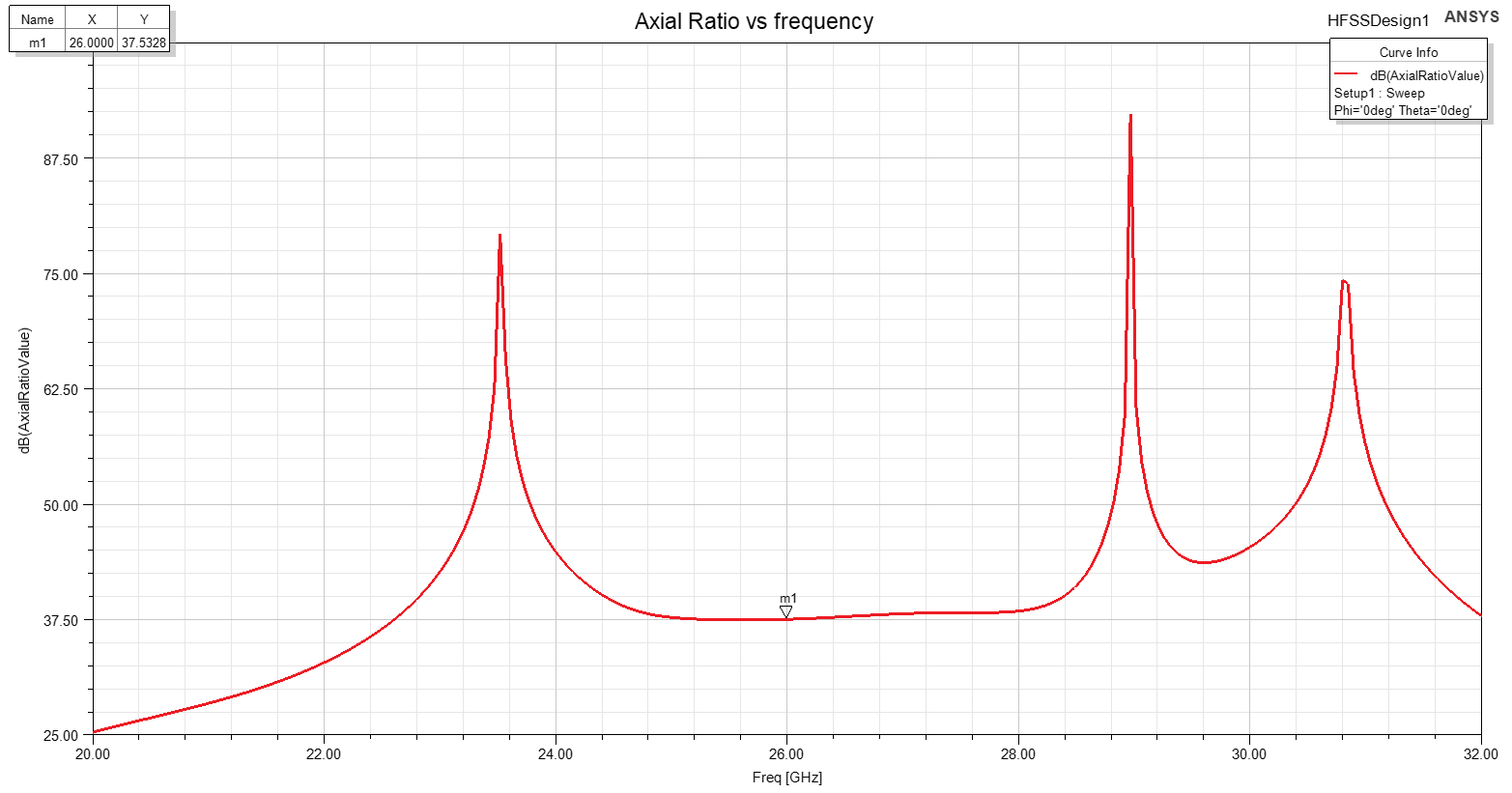


Figure 27: Second design Axial ratio vs frequency

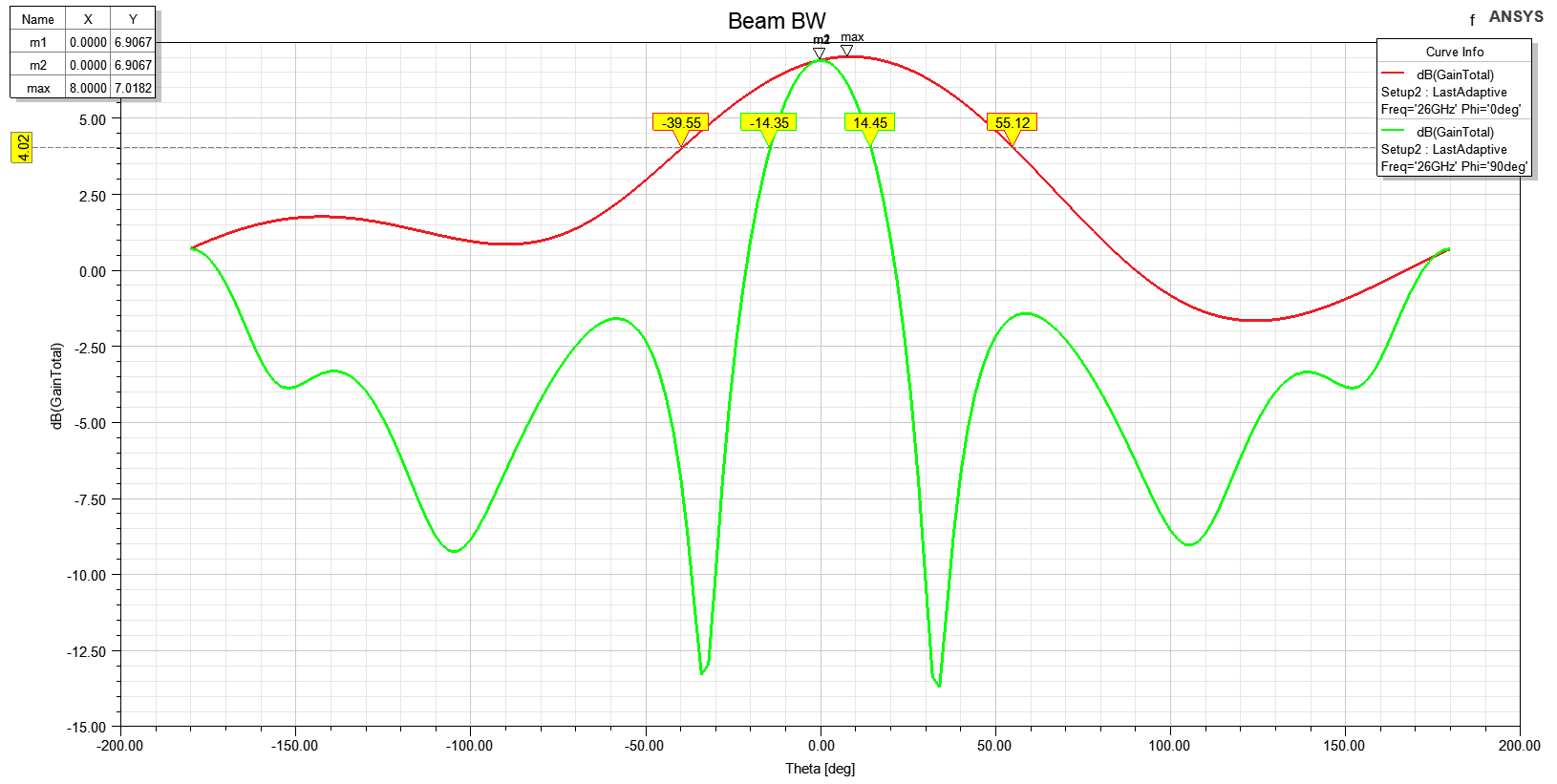


Figure 28: Second design Bram Bandwidth

## The gain and radiation efficiency of the antenna vs frequency.

### First design:

### A graph with a red line Description automatically generated

Figure 29: First design Gain vs frequency

A graph with a red line

Description automatically generated

Figure 30: First design Radiation efficiency vs frequency

### Second design:

A graph with a red line

Description automatically generated

Figure 31: Second design Gain vs frequency

A graph with a red line

Description automatically generated

Figure 32: Second design Radiation efficiency vs frequency

##### Discussion:

|  |  |  |
| --- | --- | --- |
|  | **First design** | **Second design** |
| **Gain(dB)** | **7** | **9.11** |
| **S11(return loss)** | **-18** | **-35.69** |
| **S21(Mutual coupling)** |  |  |
| **Relative Matching Bandwidth** | **12%** | **30.77%** |
| **Radiation Efficiency** | **95%** | **92** |
| **Axial ratio** | **26460.7113** | **44.9580** |

* **Resonance Behavior**At resonant frequencies, the antenna achieves its peak gain. This is due to efficient impedance matching between the antenna and the feedline, minimizing reflection and maximizing the radiation of electromagnetic waves. Peaks in the plot typically correspond to these resonances.
* **Gain Stability Across Frequencies**  
  A stable gain over a wide frequency range is advantageous, particularly for broadband antennas, as it ensures consistent performance. Fluctuations or rapid drops in gain indicate inefficiencies, such as increased losses or poor impedance matching at certain frequencies.
* **Radiation Efficiency**  
  The plot typically highlights the efficiency with which the antenna radiates the input power into free space at various frequencies **focusing on the disered frequency at 26 GHz the radiation efficiency is 92% in the first design and 95% in the second design .** High radiation efficiency indicates minimal power loss to heat, material losses, or mismatched impedance. Peaks in radiation correspond to frequencies where the antenna is well-tuned and operates optimally.
* **Bandwidth**  
  The frequency range over which the radiation efficiency remains within acceptable levels defines the antenna's bandwidth. A wider bandwidth indicates better suitability for broadband applications, while narrower bandwidths are useful for single-frequency operations like radio or television broadcasting.

## 6. The more specific characteristic to the antenna in your statement.

## Design 1:

**1. Design Specifications**

* **Frequency of Operation**: **26 GHz** .
* **Substrate Material**: **Rogers RO4350**

1.between ground and microstrip line:

(Relative Permittivity ϵr=3.66, Loss Tangent (tanδ)=0.02, Thickness=0.508 mm ,Length =6mm ,Width=35mm).

2.between ground and patch antenna:

(Relative Permittivity ϵr=3.66, Loss Tangent (tanδ)=0.02, Thickness=0.78 mm ,Length =6mm ,Width=35mm).

* **Antenna Type**: **Slot-fed microstrip patch antenna array**.
* **Array Configuration**: **2-element linear array**.
* **Impedance Matching**: **50 ohms** .

**2. Single Element Patch Antenna Design**

* **Patch Dimensions**:

**Width**:3.9mm

**Length:**1.96mm

**3. Feed Slot Dimensions**:

**Slot Length (L\_s)**: 0.3mm

**Slot Width (W\_s)**:2.4mm

**4. Element Antenna Array Design**

* **Array Type**:

**planar array** (elements placed in a row, The inter-element spacing is optimized to lie within the range **λ/2 <d< λ** , ensuring a balance between mutual coupling and directivity).

**Element Spacing**: **S= 7mm**

* **Array Feed Structure**:

**Slot-fed configuration**: The feed uses a slot in the ground plane beneath each patch element, ensuring efficient power transfer.

**Feeding Network**: For a 2-element array, a quarter wave transformer is used to feed the antennas with equal power.

**Design** ensure proper impedance matching and minimization of signal loss in form of reflected power.

* **Radiation Pattern**:

The array is designed to improve directivity by combining the radiations from both patches. It will create a **broadside radiation pattern**, with the main beam directed perpendicular to the array.

The total gain of the array will be higher than that of a single patch due to the constructive interference of the radiated waves.

### 5. **Quarter-Wave Transformer**

A **quarter-wave transformer** is used as the feeding network. This is a classic method to match the impedance between the patch antenna and the transmission line. A quarter-wave transformer is a section of transmission line that is electrically quarter wavelength long and provides impedance matching between different impedance values.

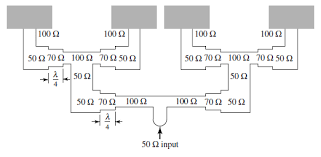


Fig. Quarter Wave Transformer

The transformer helps to **match** the impedance between the antenna and the feedline at the operating frequency by ensuring the signal travels through the transmission line without reflection. The design ensures a **minimum return loss** (S11 < -10 dB).

**6. Simulation and Optimization**

**Simulation Tool**: Use tools like **HFSS** to simulate the antenna design.

**Impedance Matching**: Ensure that the input impedance at the feed is 50 ohms to match with the transmission line.

**Return loss bandwidth**: Relative Bandwidth = 12%

(where S11 is less than -10db across that certain range of frequency to ensure 99% of the incident power is radiated)

**Return Loss**: S11= -18 db

A graph with a red line

Description automatically generated

Fig. S11 vs frequency

**Gain**: The array gain can be estimated using the formula: G=N =7 db

where:

* N is the number of elements (2 in this case),
* ​ is the gain of a single patch element.

**7. Performance Metrics**

**S-parameters**:

**S11** (return loss) =-18db

**S21** (coupling) =

to ensure good impedance matching and minimal interference between elements.

**Radiation Pattern**: Simulation of the 2D and 3D radiation patterns to evaluate the beam direction, directivity, and side lobes.

**Max Gain**: 7db

**Note**: side lobes are of relatively low power compared to main beam ( high SLL).

A colorful cactus with white text

Description automatically generated with medium confidence

Fig. radiation pattern

**Return loss bandwidth**: Relative Bandwidth = 12%

**8. Fabrication and Testing**

* **Substrate Material**: Use **Rogers RO4350** for the substrate, with careful consideration of its thickness and permittivity.

Our Consideration regarding the thickness was to minimize thickness of microstrip line as much as possible to make sure it will not radiate and to maximize the thickness of the patch layer as much as possible to violate conditions which prohibit it from radiating.

* **Antenna Fabrication**: The antenna will be fabricated using standard PCB techniques, involving etching the patch and the slot feed on the substrate.
* **Measurement**: After fabrication, the antenna's performance will be tested using a vector network analyzer (VNA) to measure the return loss, bandwidth, and radiation pattern.

**VNA** will be used to ensure that the impedance is well-matched and that the antenna operates efficiently at the desired frequency.

## Design 2:

**1. Design Specifications**

* **Frequency of Operation**: **26 GHz** .
* **Substrate Material**: **Rogers RO4350**

1.between ground and microstrip line:

(Relative Permittivity ϵr=3.66, Loss Tangent (tanδ)=0.02, Thickness=0.1 mm ,Length =9mm ,Width=20mm).

2.between ground and patch antenna:

(Relative Permittivity ϵr=3.66, Loss Tangent (tanδ)=0.02, Thickness=0.8 mm ,Length =9mm ,Width=20mm).

* **Antenna Type**: **Slot-fed microstrip patch antenna array**.
* **Array Configuration**: **2-element planar array**.
* **Impedance Matching**: **50 ohms** .

**2. Single Element Patch Antenna Design**

* **Patch Dimensions**:

**Width**:2.133mm

**Length:**2.133mm

**3. Feed Slot Dimensions**:

**Slot Length (L\_s)**: 0.15mm

**Slot Width (W\_s)**:2.091mm

**4. Element Antenna Array Design**

* **Array Type**:

**Linear array** (elements placed in a row, The inter-element spacing is optimized to lie within the range **λ/2 >d**, ensuring a balance between mutual coupling and directivity).

* **Element Spacing**: **S= 4.77mm**

For maximum radiation (broadside direction), the element spacing is typically equal to half the wavelength.

* **Array Feed Structure**:

**Slot-fed configuration**: The feed uses a slot in the ground plane beneath each patch element, ensuring efficient power transfer.

**Feeding Network**: For a 2-element array, a series fed network is used to feed the antennas with equal power.

**Design** ensure proper impedance matching and minimization of signal loss in form of reflected power.

* **Radiation Pattern**:

The array is designed to improve directivity by combining the radiations from both patches. It will create a **broadside radiation pattern**, with the main beam directed perpendicular to the array.

The total gain of the array will be higher than that of a single patch due to the constructive interference of the radiated waves.

### 5. **Series Feeding**

In **series feeding**, both patch elements (or antennas) are connected through a single transmission line in sequence. The feedline is directly connected to the first antenna, and the output of the first antenna is then connected to the second antenna. This arrangement effectively splits the power from the transmitter between the two antennas.

A diagram of a diagram

Description automatically generated

Fig. series feeding network

In a series-fed configuration, the power from the transmitter is split between the two antennas. The feedline carries the same current across both antennas, so they will radiate based on the shared current.

This configuration requires careful impedance matching to ensure that both antennas receive the correct amount of power and radiate effectively . It was hard to implement and will be even harder for N greater than 2. But it results in a more directive beam.

**6. Simulation and Optimization**

**Simulation Tool**: Use tools like **HFSS** to simulate the antenna design.

**Impedance Matching**: Ensure that the input impedance at the feed is 50 ohms to match with the transmission line.

**Return loss Bandwidth**: Relative Bandwidth = 30.77%

(where S11 is less than -10db across that certain range of frequency to ensure 99% of the incident power is radiated)

**Return Loss**: S11= -35.69 db

A graph with red lines and numbers

Description automatically generated

Fig. S11 vs frequency

**Gain**: The array gain can be estimated using the formula: G=N =9.11 db

where:

* N is the number of elements (2 in this case),
* ​is the gain of a single patch element.

**7. Performance Metrics**

**S-parameters**:

**S11** (return loss) =-35.69db

**S21** (coupling) =

to ensure good impedance matching and minimal interference between elements.

**Radiation Pattern**: Simulation of the 2D and 3D radiation patterns to evaluate the beam direction, directivity, and side lobes.

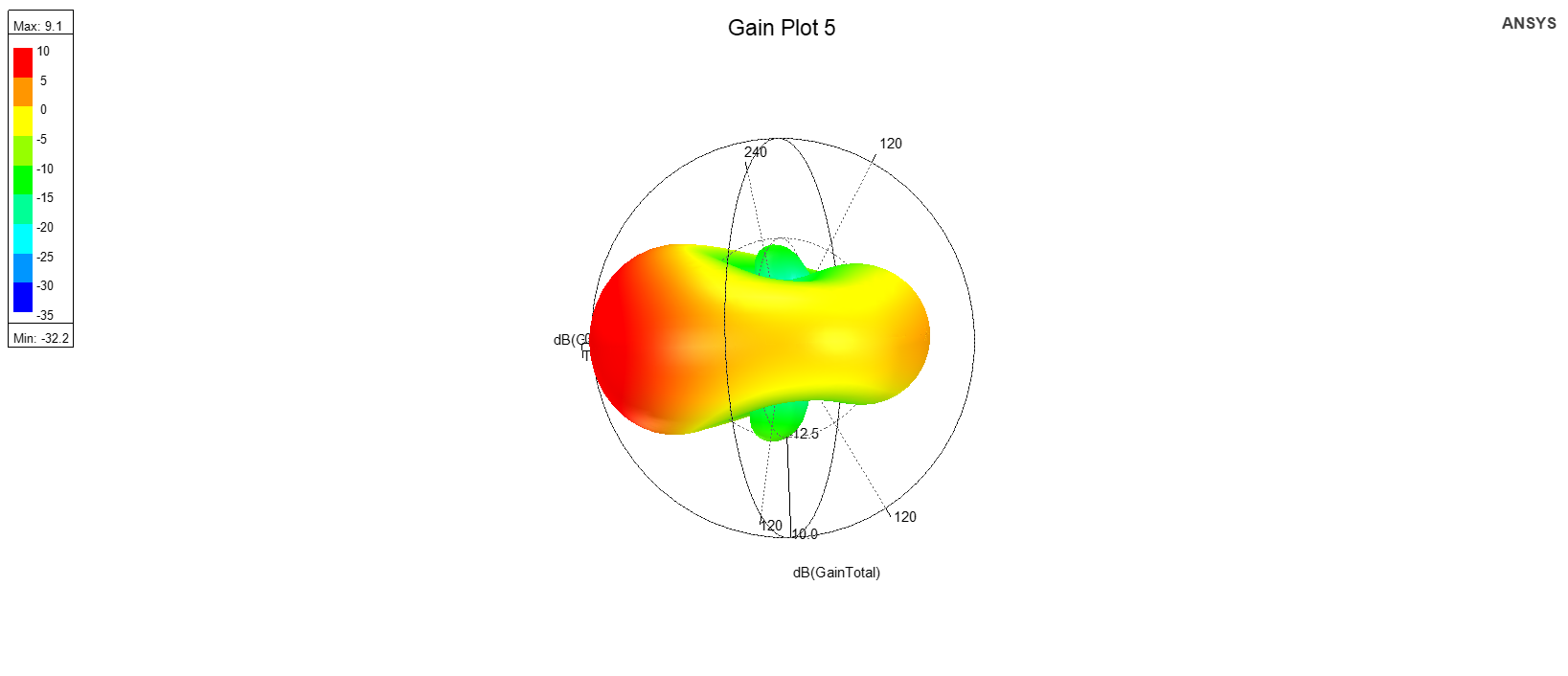
**Max Gain**: 9.11db

**Note**: side lobes are of relatively low power compared to main beam ( higher SLL and directivity compared to first design).

A diagram of a planet

Description automatically generated

Fig. radiation pattern

Fig. radiation pattern in dB

**Return loss bandwidth**: Relative Bandwidth = 30.77%

**8. Fabrication and Testing**

* **Substrate Material**: Use **Rogers RO4350** for the substrate, with careful consideration of its thickness and permittivity. Our Consideration regarding the thickness was to minimize thickness of microstrip line as much as possible to make sure it will not radiate and to maximize the thickness of the patch layer as much as possible to violate conditions which prohibit it from radiating.
* **Antenna Fabrication**: The antenna will be fabricated using standard PCB techniques, involving etching the patch and the slot feed on the substrate.
* **Measurement**: After fabrication, the antenna's performance will be tested using a vector network analyzer (VNA) to measure the return loss, bandwidth, and radiation pattern.

**VNA** will be used to ensure that the impedance is well-matched and that the antenna operates efficiently at the desired frequency.

## Conclusion

This 2-element slot-fed microstrip patch antenna array design is optimized for operation at **26 GHz** and targets efficient impedance matching, broadside radiation, and improved gain. The array configuration is designed to meet the requirements of the specific application it is intended for. Design 2 has higher gain , bandwidth ,SSL and less reflections.

# Final Design Layout

# Conclusion

# References

1. [E. Setijadi, "Gain Enhanced 26 GHz Antenna for 5G Communication Technology," *Progress In Electromagnetics Research C*, vol. 139, pp. 187-195, Dec. 2023.](https://www.jpier.org/issues/volume.html?paper=23102602)
2. [C. Seker and M. T. Güneşer, "Design and simulation of 26 GHz patch antenna for 5G mobile handset," *2019 11th International Conference on Electrical and Electronics Engineering (ELECO)*, Bursa, Turkey, 2019, pp. 1060-1064.](https://www.researchgate.net/publication/339256389_Design_and_simulation_o)
3. [Rogers Corporation, *RO4000 Series High Frequency Circuit Materials*. Advanced Connectivity Solutions, Chandler, AZ, USA, 2018.](https://www.bing.com/ck/a?!&&p=9432b18362b983a49c280a245b0b328aaccbd68ccc3eb9e1262388d704c7aadeJmltdHM9MTczNDgyNTYwMA&ptn=3&ver=2&hsh=4&fclid=34a66137-39f0-6990-3f67-758638496870&psq=Rogers-ro4000-laminates-ro4003c-and-ro4350b-data-sheet&u=a1aHR0cHM6Ly9yb2dlcnNjb3JwLmNvbS8tL21lZGlhL3Byb2plY3Qvcm9nZXJzY29ycC9kb2N1bWVudHMvYWR2YW5jZWQtZWxlY3Ryb25pY3Mtc29sdXRpb25zL2VuZ2xpc2gvZGF0YS1zaGVldHMvcm80MDAwLWxhbWluYXRlcy1ybzQwMDNjLWFuZC1ybzQzNTBiLS0tZGF0YS1zaGVldC5wZGY&ntb=1)
4. [E. A. Soliman, A. Vasylchenko, V. Volski, G. A. E. Vandenbosch, and W. De Raedt, "Series-Fed Microstrip Antenna Arrays Operating at 26 GHz," presented at the IEEE Antennas and Propagation Society International Symposium (APS), 2010.](https://www.researchgate.net/publication/224171519_Series-fed_microstrip_antenna_arrays_operating_at_26_GHz)