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**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, mutual coupling or side lobes.
4. **Impedance Matching**: Ensuring that the antenna’s impedance is matched to the transmission line and the input source 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, array configuration, and the feeding network 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. Substrates 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

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Figure : Slot-fed microstrip patch antenna structure[5]

### 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 material and thickness

For the substrates material we used **Rogers RO4350B** with dielectric constant **3.66** and loss tangent in the first design, and **Rogers RO4003C** with dielectric constant **3.44** and loss tangent in 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 [4], and.

### Slots dimensions

For the slot dimensions, in the first design we got its dimensions from [1] matched with 50 as a starting point before tuning. and .

For the second design we got its dimensions from [4] matched with 50 . 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 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 [4] dimensions, and it tuned them,   
 and .

Now, after we designed a single slot-fed microstrip patch antenna operating at 26 GHz with 50 , 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 2** to equally distribute the source power.

The second design is series fed and matched using one quarter-wave section as shown in **figure 3**. The space between the two antennas centers is a multiple of the wavelength to make the two elements in phase.

We made sure that the matched terminations feeding network return loss is below -20 dB at the range of interest.

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Figure : First design feeding network6

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Figure : Second design feeding network4

### Substrates and ground dimensions

The substrate and ground dimensions (area) influence the gain and radiation pattern, the gain is directly proportional to the area. We chose the dimensions to be **6 mmx35 mm** in the first design and **9 mmx20 mm** 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 feeding network losses increases, and at spacing higher than the wavelength – in concern to the radiation pattern – two side lobes start to appear and attenuate the intended gain beam. After sweeping the spacing, we found that **10 mm** spacing is a sweet spot for the first design, while the spacing in the second design is **6.903 mm** such that the gain is optimum, no phase difference between the two elements and small side lobes in the first design while no side lobes in the second.

# 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 as shown in **figure 4** 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.

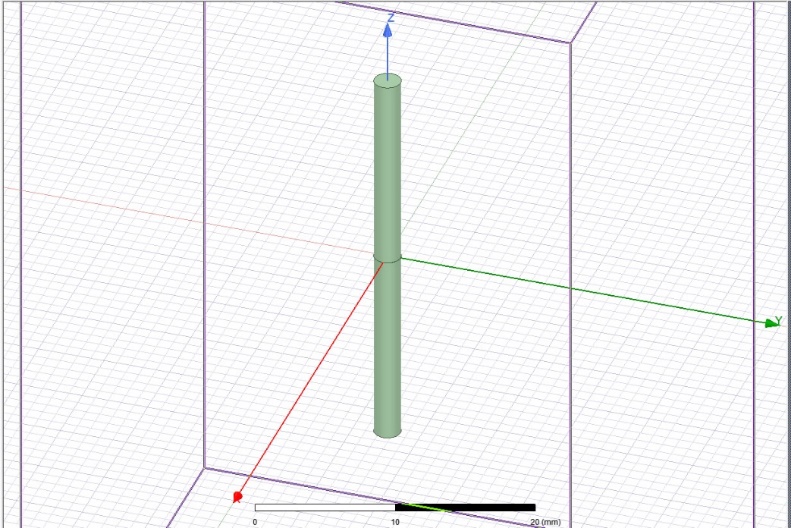


Figure : dipole structure

In the first simulation we adjusted the diameter of the dipole to 1 mm and its length to 30 mm and the gap between the two wires – due to the supposed feeding – to 1 mm.

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

60 mm, 5 GHz.

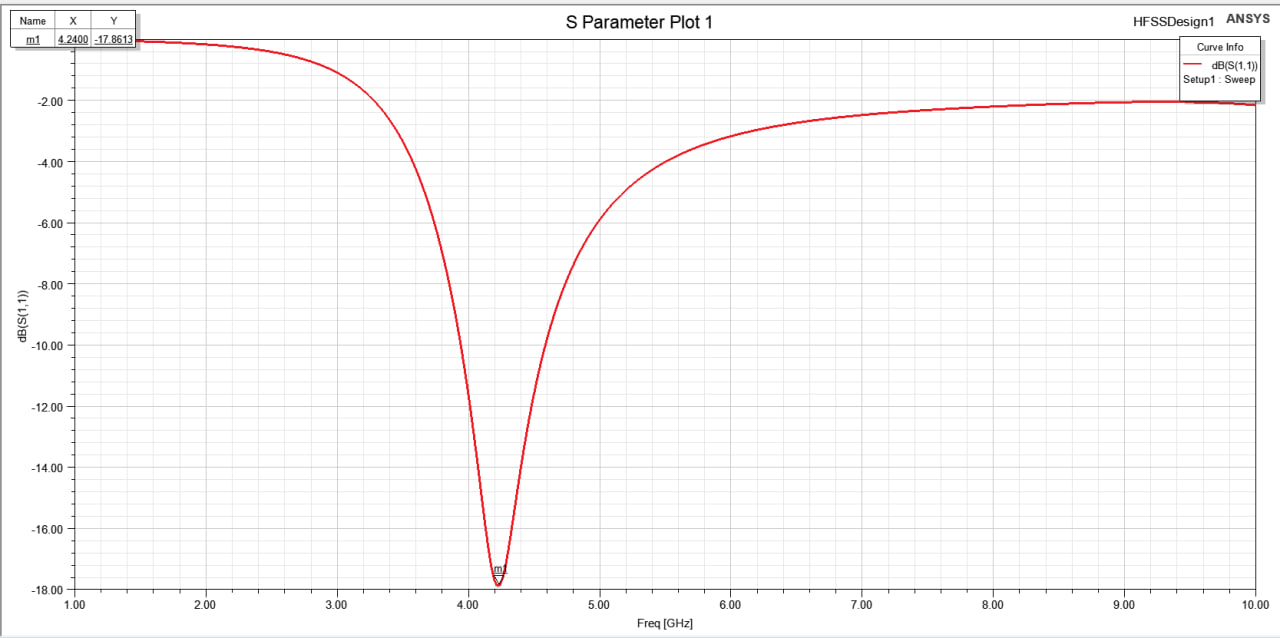


Figure : dipole return loss

As we see in **figure 5**, it is resonant at **4.24 GHz** 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 0.01 mm,30 mm and the gap0.01 mm.

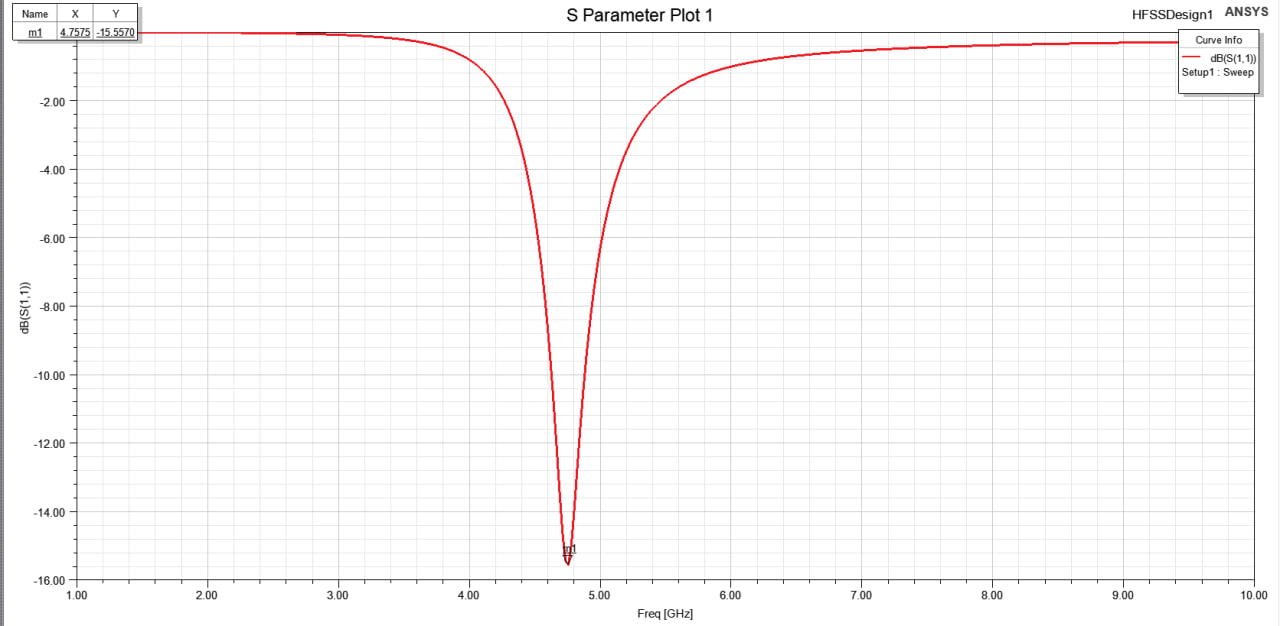


Figure : New dipole return loss

As shown in **figure 6**, the frequency became **4.76 GHz** closer to the ideal frequency.

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 **figures 7-10**. 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.

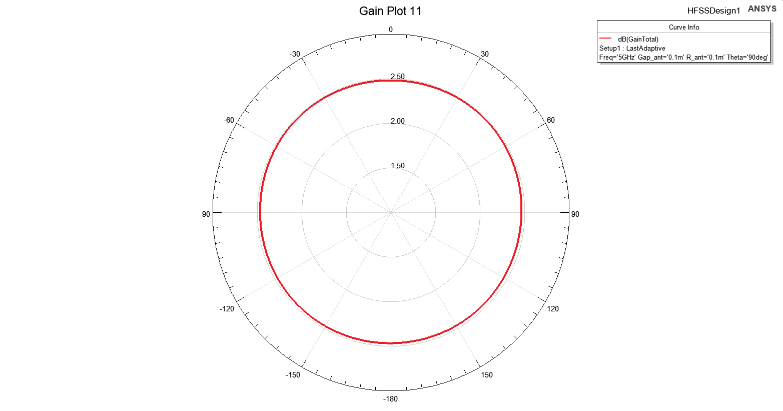
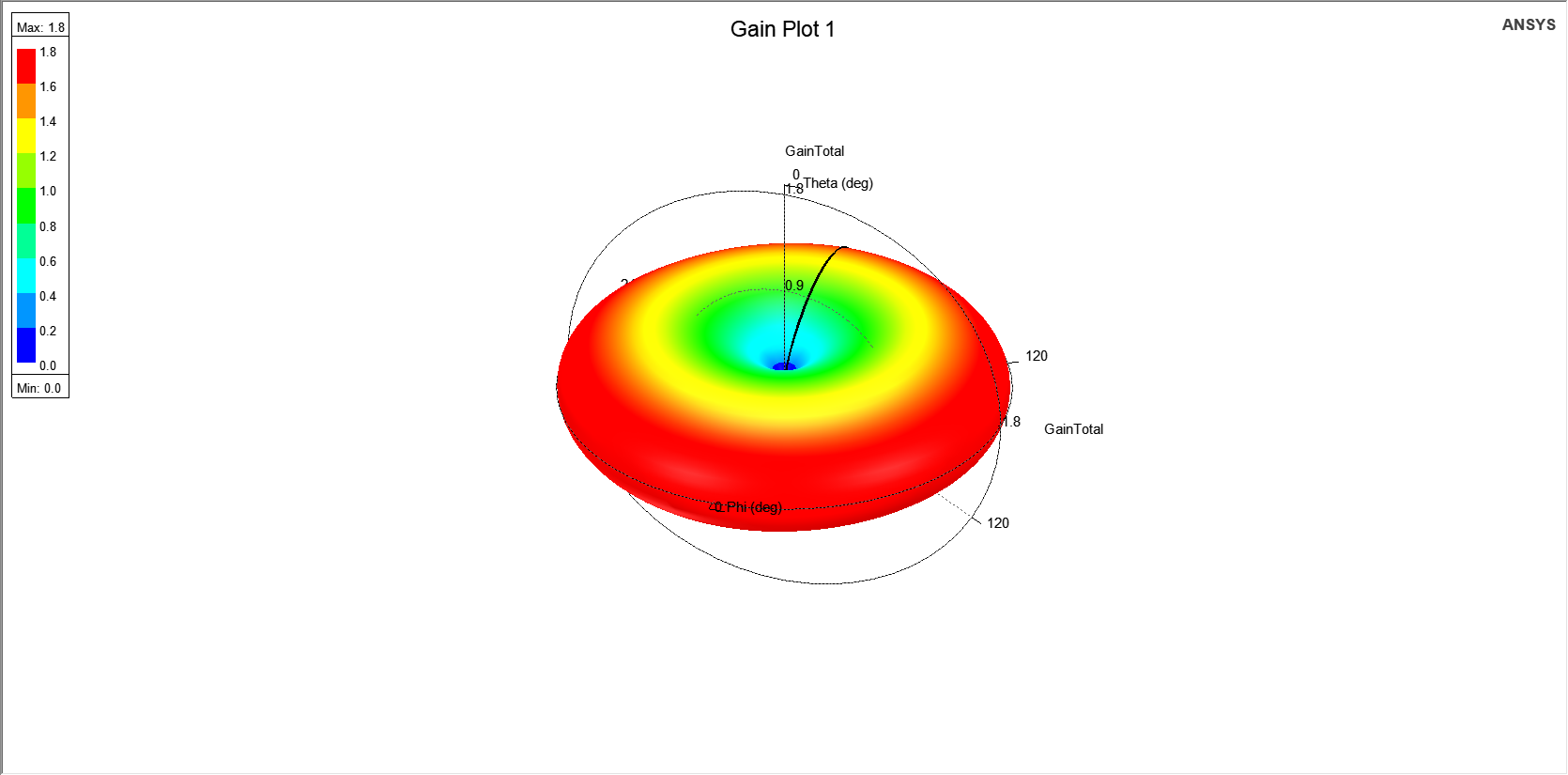
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Figure : λ/2 dipole 3D polar gain (linear)

Figure : λ/2 dipole Radiation pattern in H(xy)-plane (dB)

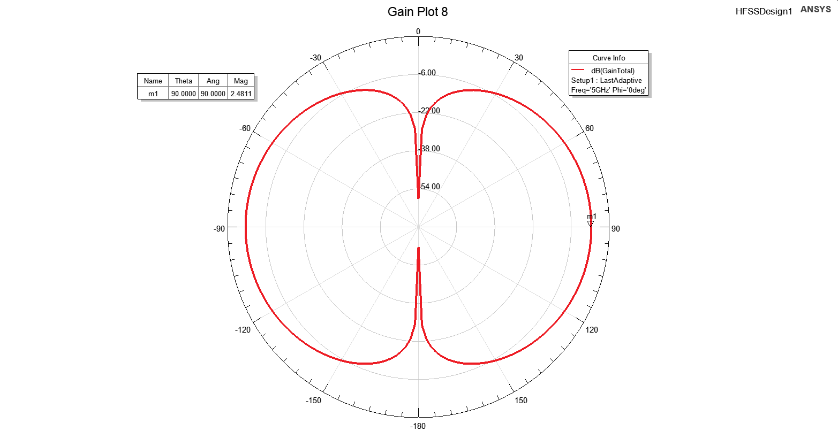
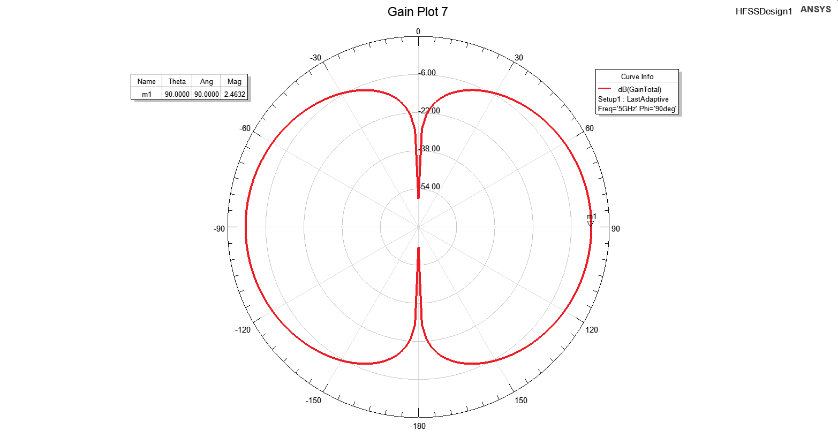


Figure : λ/2 dipole Radiation pattern in the yz-plane

Figure : λ/2 dipole Radiation pattern in the xz-plane

## Return loss

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

### First design

By examining the return loss graphs for the first design in **figure 11**, 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.

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Figure : First design return loss

### Second design

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. As shown in **figure 12.**

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.

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Figure : Second design return loss

## The input impedance of the designed antenna on the Smith chart

The input impedance of the two designs was analyzed using Ansys-HFSS Smith chart, focusing on their behavior at the target frequency of **26 GHz**. This analysis is crucial for ensuring efficient power transfer between the antenna and the feeding transmission line, minimizing reflections and achieving good impedance matching.

1. **First design:**

The Smith Chart was used to visualize the impedance behavior across the frequency range of interest. At **26 GHz**, the normalized simulated input impedance was found to be approximately **1.267 – j0.14 Ω** from **figure 13**,by which we can get the input impedance by multiplying by 50. So,  **= 63.35 – j7 Ω**, which is close to the target characteristic impedance of **50 Ω**. The input impedance's real and imaginary components indicate the antenna's resistive and reactive behavior, respectively. To minimize the reflection coefficient (S11), the reactive part was tuned to near-zero, ensuring resonance at the desired frequency. Impedance matching was verified through the calculated **reflection coefficient**, which showed a value of  **≈ 0.1259** that was calculated from the got value of S11, confirming that most of the input power is radiated by the antenna.

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Figure : Input impedance of first design on Smith chart

1. **Second design:**

The Smith Chart was used to visualize the impedance behavior across the frequency range of interest. At **26 GHz**, the normalized simulated input impedance was found to be approximately **0.969 + j0.0338 Ω** from **figure 14**,by which we can get the input impedance by multiplying by 50. So,  **= 48.445 – j1.69 Ω**, which is close to the target characteristic impedance of **50 Ω**. The input impedance's real and imaginary components indicate the antenna's resistive and reactive behavior, respectively. To minimize the reflection coefficient (S11), the reactive part was tuned to near-zero, ensuring resonance at the desired frequency. Impedance matching was verified through the calculated **reflection coefficient**, which showed a value of  **≈ 0.0259** that was calculated from the got value of S11, confirming that most of the input power is radiated by the antenna.

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Figure : Input impedance of second design on Smith chart

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

### First design:

In **figure 16**, we can see the gain of the antenna in dB in the main direction which is **6.9 dB**, and we can estimate the beamwidth from that graph about **96 degrees** in the xz-plane. The front-to-back ratio is around **6.25 dB**, that’s because the slot-fed antennas have bad front to back ratio because of the gap in the ground. And we can see the same from **figure 15** in the yz-plane graph but only the difference in beamwidth in that direction, which is quite higher than **28 degrees**, smaller beamwidth is due to the presence of 2 antennas on y-axis, and we can get also the side-lobe level (SLL) which equals **8.5 dB**. In **figure 24**, the beamwidth in both planes appears more accurate and it equals **29 degrees** in yz-plane and **95 degrees** in xz-plane.

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Description automatically generated**As shown in **figures 17 &18**, It can be observed that the first design achieves a large cross-polarization discrimination (XPD) of around **48 dB** in **figure 22**, show the axial ratio versus theta in two different planes and the mean value is about **53.69 dB**. **Figure 23** shows the axial ratio in the boresight for different frequencies, the axial ratio is above **30 dB** in the range of interest (the frequencies from 22 to 30 GHz).

Figure : First design Radiation pattern in the yz-plane

Figure : First design Radiation pattern in the xz-plane

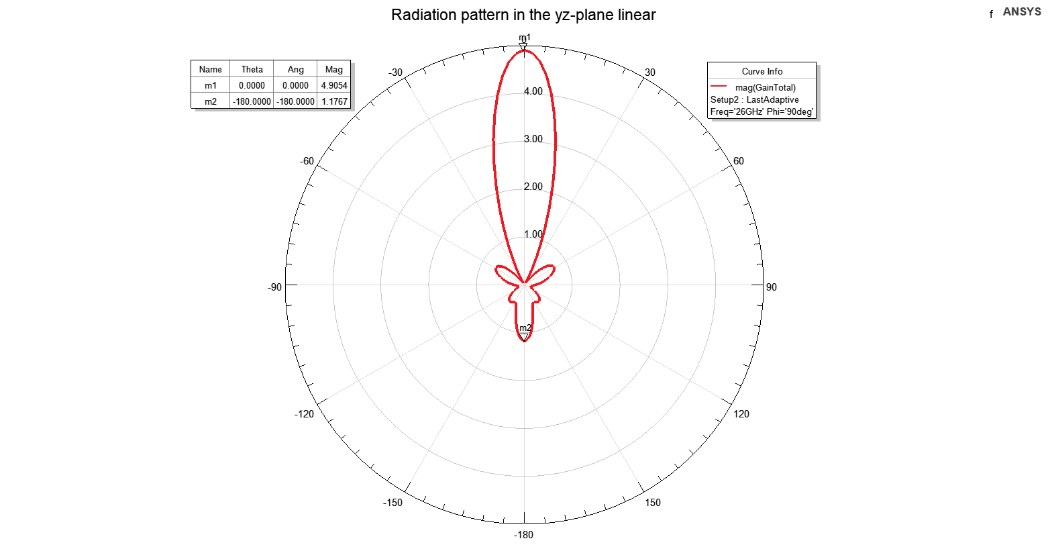
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Figure : First design Co & Cross Polarized Fields in H-Plane

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

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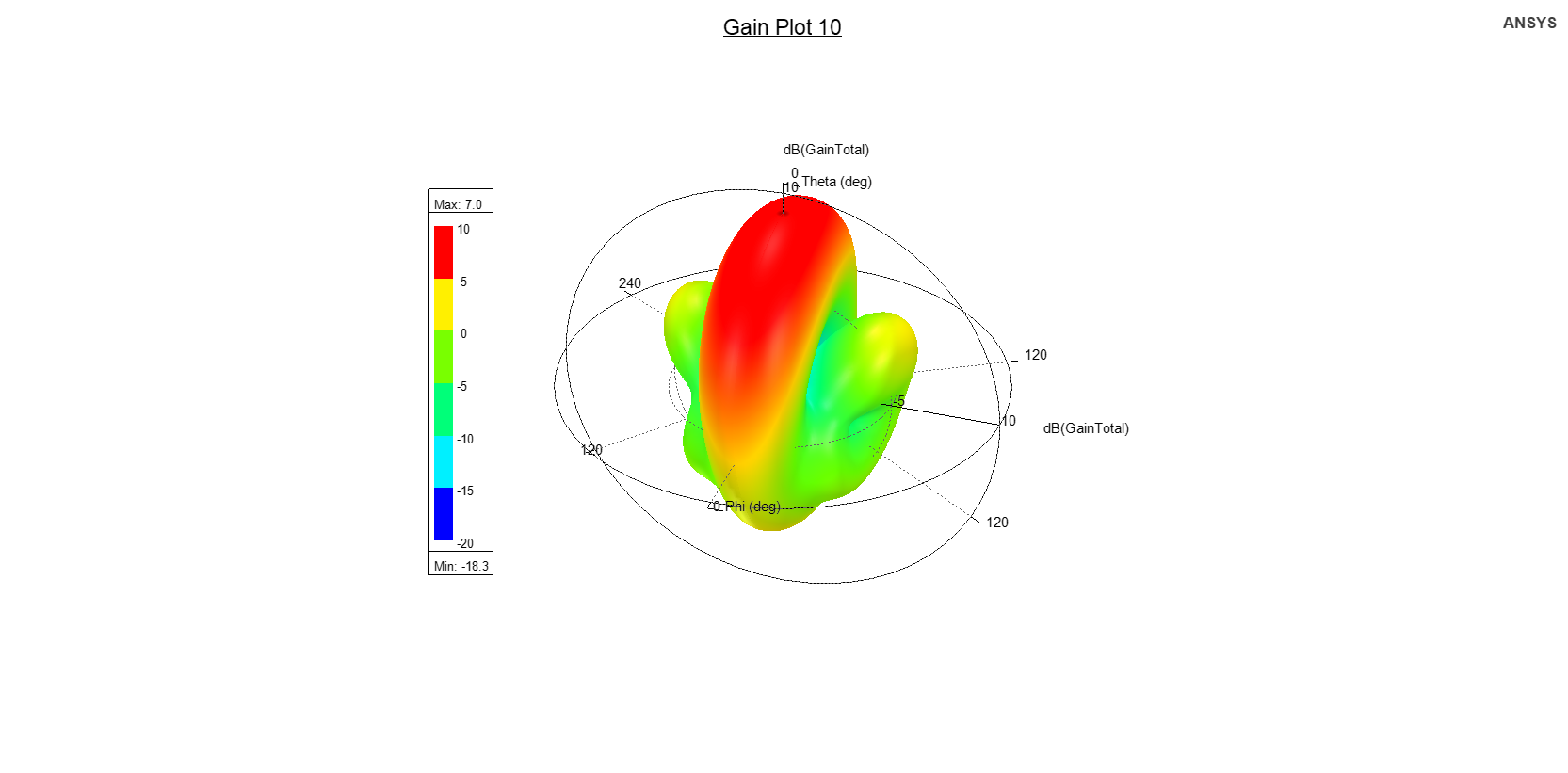


Figure 19: First design Radiation pattern in the yz-plane (linear)

Figure 20: First design Radiation pattern in the xz-plane (linear)

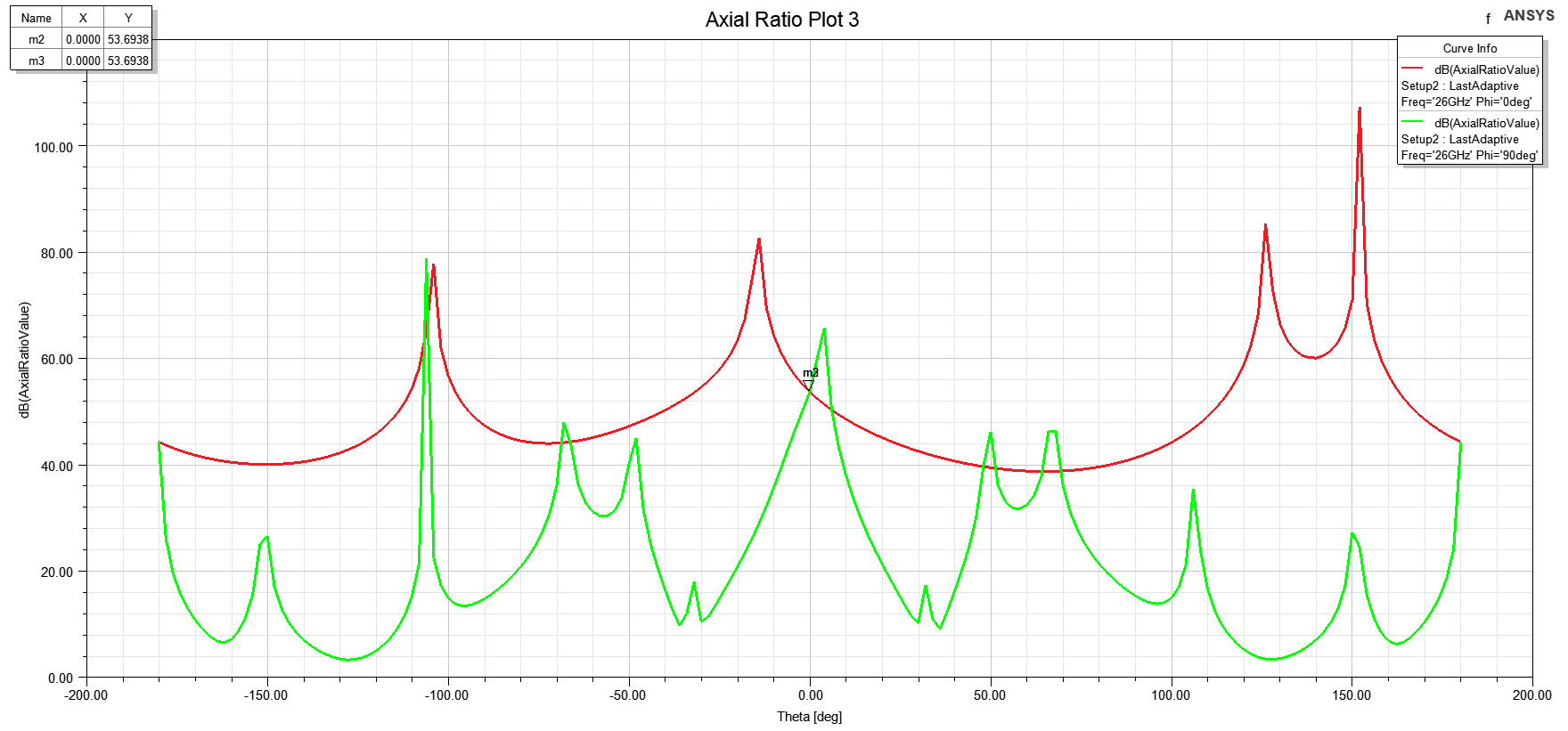


Figure 21: First design 3D Polar Plot of Gain (dB)

Figure 22: First design Axial ratio vs theta

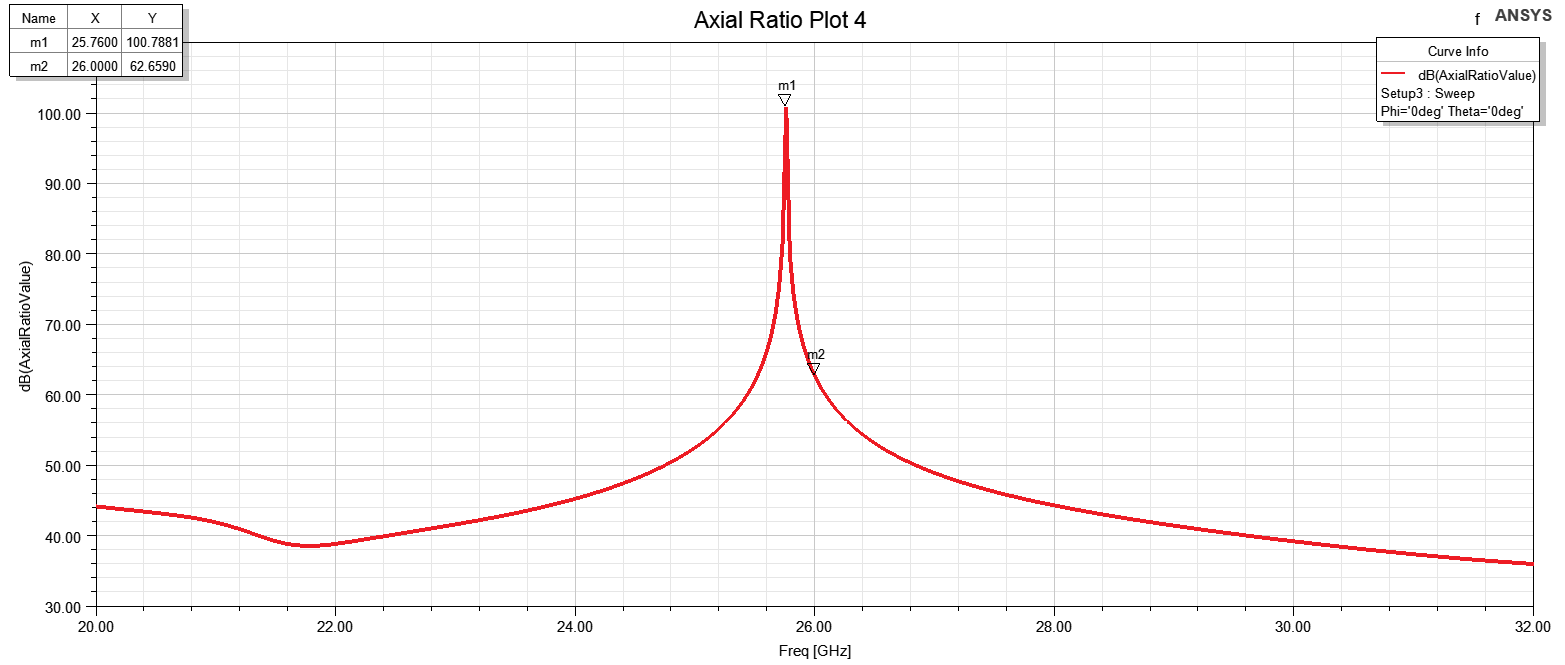


Figure 23: First design axial ratio vs frequency

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Figure 24: First design Beamwidth

### Second design:

In **figure 26**, we can see the gain of the antenna in dB in the main direction which is **9.16 dB**. The front-to-back ratio is around **10.66 dB**, that’s because the slot-fed antennas have bad front to back ratio because of the gap in the ground. In **figure 34**, the beamwidth in both planes appears more accurate and it equals **29 degrees** in yz-plane and **95 degrees** in xz-plane, smaller beamwidth in yz-plane is due to the presence of 2 antennas on y-axis, and the side-lobe level equals **22 dB**.

As shown in **figures 27 &28**, It can be observed that the second design achieves a large cross-polarization discrimination (XPD) of around **36.84 dB** in **figure 32**, show the axial ratio versus theta in two different planes and the mean value is about **38.7 dB**. **Figure 33** shows the axial ratio in the boresight for different frequencies, the axial ratio is above **25 dB** in the range of interest (the frequencies from 22 to 30 GHz).

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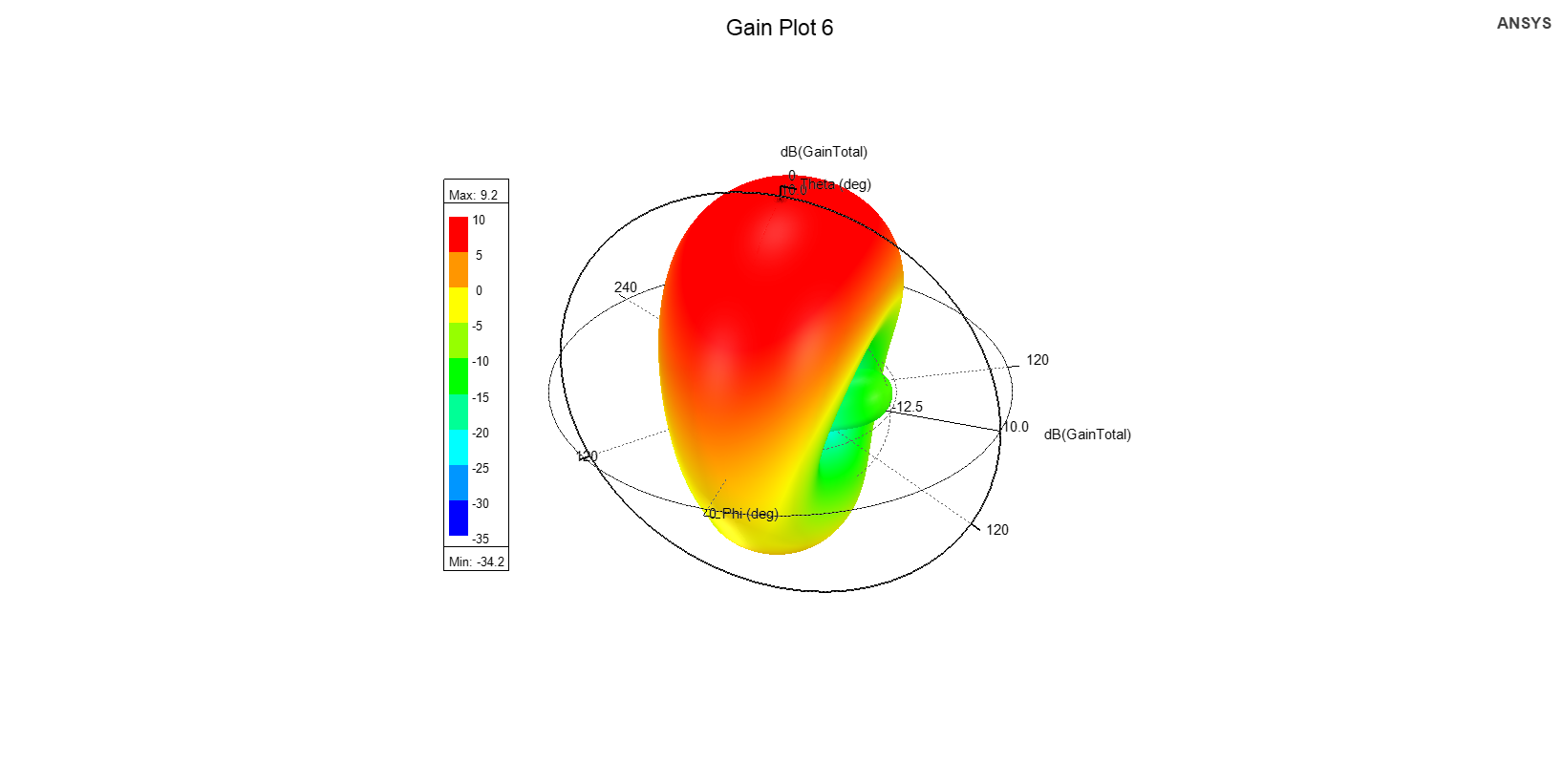
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Figure 25: Second design Co & Cross Polarized Fields in H-Plane

Figure : Second design Radiation pattern in the yz-plane

Figure : Second design Radiation pattern in the xz-plane

Figure 28: Second design Co & Cross Polarized Fields in E-Plane

Figure 29: Second design 3D Polar Plot of Gain (dB)

## 

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Figure 30: Second design Radiation pattern in the xz-plane (linear)

Figure 31: Second design Radiation pattern in the yz-plane (linear)

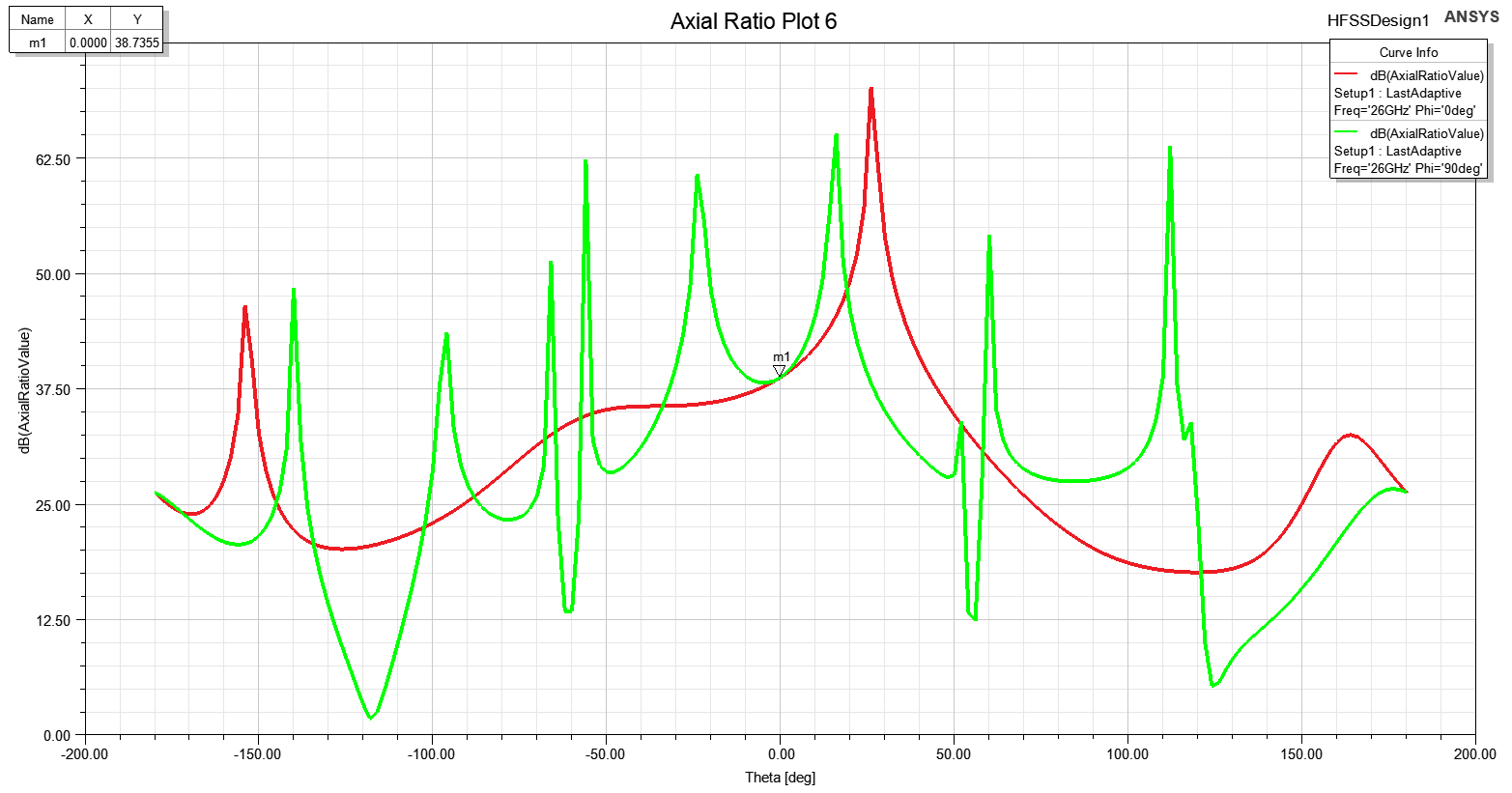
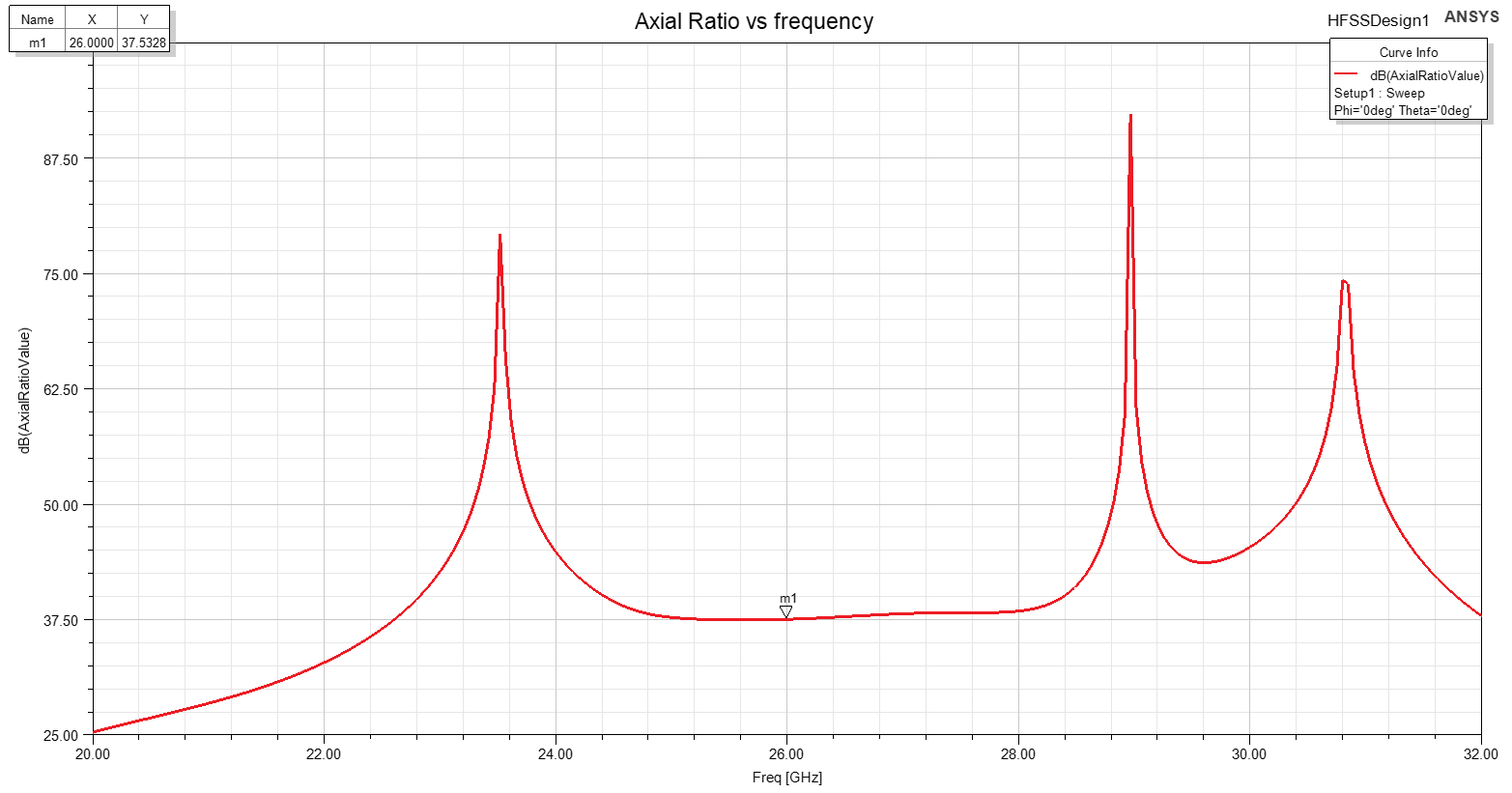


Figure 32: Second design Axial ratio vs theta



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Figure 33: Second design Axial ratio vs frequency

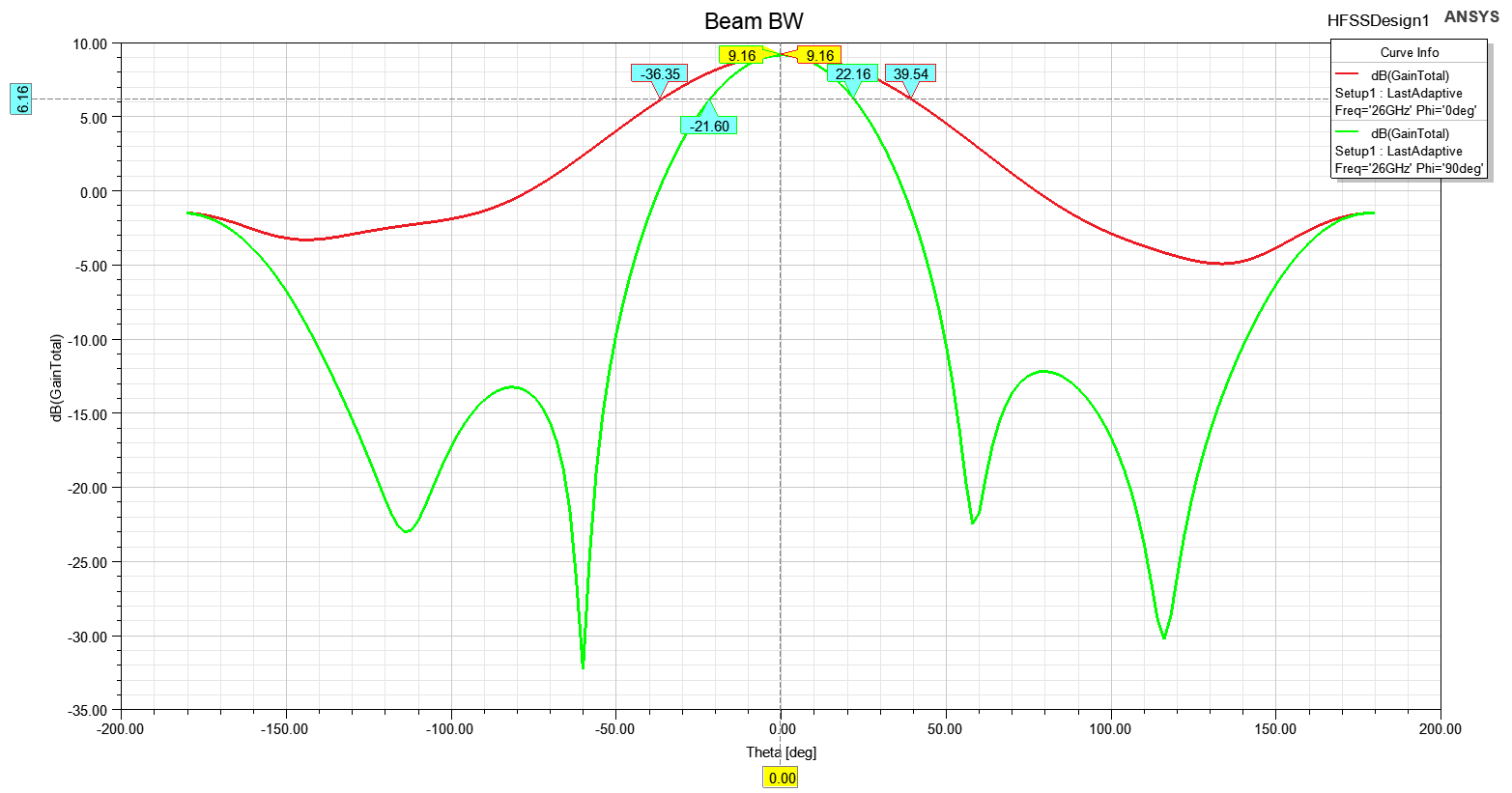


Figure 34: Second design Beamwidth

In conclusion, the first design has better axial ratio, but the second design has higher gain.

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

### First design:

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Figure : First design Gain vs frequency

A graph with a red line

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Figure : First design Radiation efficiency vs frequency

A graph with a red line

Description automatically generatedFigure 33: First design Realized gain vs frequency

### Second design:

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Figure 34: Second design Gain vs frequency

A graph with a red line

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Figure 35: Second design Radiation efficiency vs frequency

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##### Discussion:

|  |  |  |
| --- | --- | --- |
|  | **1st. design** | **2nd.design** |
| **Gain(dB)** | **7** | **9.11** |
| **Relative Matching Bandwidth** | **12%**  **(24.88GHz-28.38GHz)** | **30.77%**  **(24.81GHz-32.76GHz)** |
| **Radiation Efficiency** | **95%** | **92%** |
| **1-dB relative Gain band-width** | **11.2%**  **(24.101GHz-30.3232GHz)** | **14.81%**  **(24.4980GHz-28.3534GHz)** |
| **1-dB relative Realized Gain band-width** | **15.18%**  **(24.80GHz-28.76GHz)** | **12.34%**  **(24.97GHz-28.19GHz)** |
| **Intersected operating Bandwidth** | **13.45%**  **( 24.88GHz-28.38GHz )** | **12.38%**  **( 24.97GHz-28.19GHz )** |

* **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.

## Equivalent circuit model of the antenna

To gain a deeper understanding of the slot-fed 2-element array antenna's impedance behavior at the target frequency of **26 GHz**, an equivalent circuit model for S11 was developed using **Advanced Design System (ADS)**. This model provides a simplified yet accurate representation of the antenna’s electrical behavior and validates the EM simulation results.

The equivalent circuit was constructed in ADS using a combination of lumped elements, including resistors (**R**), inductors (**L**), and capacitors (**C**), to replicate the antenna's impedance characteristics. The built-in **optimization tool** in ADS was used to fine-tune the circuit parameters to achieve the best match with the reflection coefficient (**S11**) obtained from the EM simulations.

1. **First Design**

**A diagram of electrical circuits

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Figure 35 First design equivalent circuit model

We started the operation of getting the model by a few number of parameters but to get accurate results and easy use of the optimizer, we increased the number of parameters to get more degrees of freedom for the simulator to optimize.

The reflection coefficient (**S11**) calculated from the optimized circuit model was overlaid with the EM simulation results, showing a high degree of alignment, particularly at **26 GHz** as follows:

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Original circuit

Equivalent circuit

Figure 36: Return loss of both equivalent circuit model and original structure for first design

1. **Second Design**

A close-up of a computer

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Figure 37 Second design equivalent circuit model

We started the operation of getting the model by a few number of parameters but to get accurate results and easy use of the optimizer, we increased the number of parameters to get more degrees of freedom for the simulator to optimize. (observing three notch in design was a good indicator for 3 series filters, and knowing an approximate quality factor from graph and the operating frequency and using these 2 equations andto get a good range for L and C for the optimizer to work on.

The reflection coefficient (**S11**) calculated from the optimized circuit model was overlaid with the EM simulation results, showing a high degree of alignment, particularly at **26 GHz** as follows:

A graph with red and blue lines

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Original circuit

Equivalent circuit

Figure 38: Return loss of both equivalent circuit model and original structure for second design

## Effect of spacing between antenna array elements

1. **First Design**

This study went through three aspects:

1. Gain
2. Mutual Coupling
3. Active Return Loss
4. **Effect On Gain**

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Figure 37: Gain(dB) vs Spacing between the two elements for first design

Through the **Optimetric** tool provided by HFSS, we could define the spacing between the two elements as a parameter and perform parametric sweep in order to study this effect, which showed strange effects that weren’t clearly understandable as shown in previous figure with the knowledge that the spacing between the center of two elements in our design is **0.95.**

1. **Effect on mutual coupling**

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Figure 38: Isometric of reconstructed design to simulate mutual coupling and active return loss for first design

A red and green line

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Figure 39: Bottom side of reconstructed design showing the feeding mictostripline

We studied the effect of spacing between the the antenna array elements through changing the design structure in order to define two matched ports, one for each antenna.

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Figure 40: Mutual coupling vs Spacing between two elements for first design

Also through using **Optimetric,**  we could study the effect on the mutual coupling which really makes sense that is as increasing the spacing between the antennas, the mutual coupling decreases gradually.

1. **Effect on Active Return Loss**

Results showed almost constant active return loss in range of **0.5**to **2.5** while it starts noticeably increase starting from spacing of **2.7.**

A graph with lines and numbers

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Figure 41 :Active return loss vs spacing between the two elements for first design

1. **Second Design**

This study went through three aspects as the previous design:

1. Gain
2. Mutual Coupling

3. Active Return Loss

1. **Effect On Gain**

In this design Gain with spacing is not as the previous as the phase because of the feeding network changes so it is divided into two cases without the Feeding network and with it

1. Without the feeding network

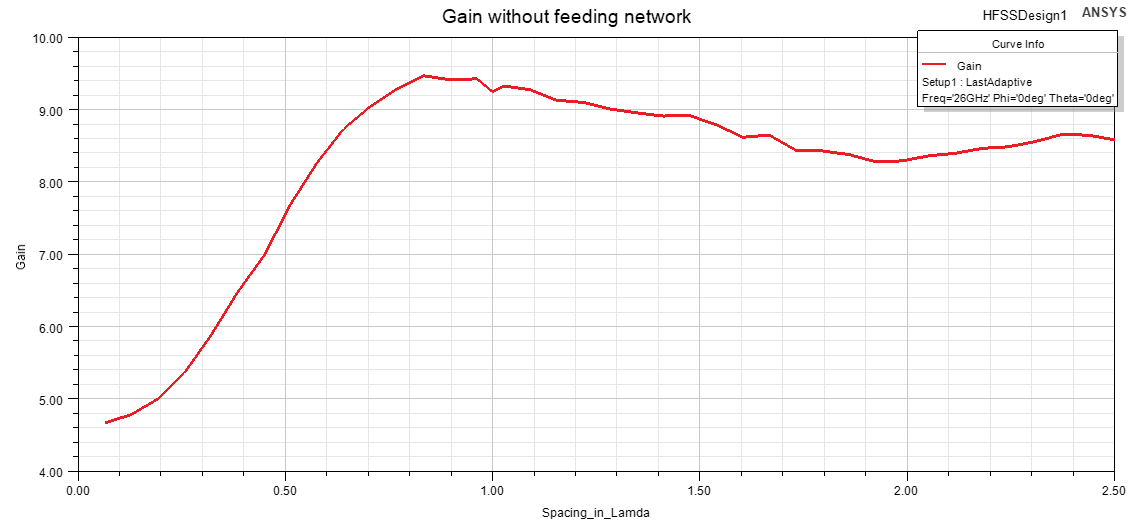


Figure 42: Gain(dB) vs Spacing between the two elements without feeding network for second design

Here as the spacing increases the area making it better gain until side loop introduced that take some power from the main loop

As seen in the following figure ??:

A screen shot of a graph

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As in the space factor

1. This time we are going to put the feeding network this time there is a phase causing two effects

We can see this effects on the following graphs

A graph with red lines

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It goes to zero at the main beam is because of the tilting because of the phase difference

As we see in the space factor equation here

We can see this results in the following figure

A graph with a heart drawn on it

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Note that original design has spacing of

1. **Effect on mutual coupling**

A diagram of a green and red line

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Figure 43: Isometric of reconstructed design to simulate mutual coupling and active return loss for second design

A graph with a green rectangular object with red lines

Description automatically generated

Figure 44: Bottom side of reconstructed design showing the feeding mictostripline

We studied the effect of spacing between the antenna array elements through changing the design structure in order to define two matched ports, one for each antenna.

A graph with a red line

Description automatically generated

Figure 45: Mutual coupling vs Spacing between two elements for Second design

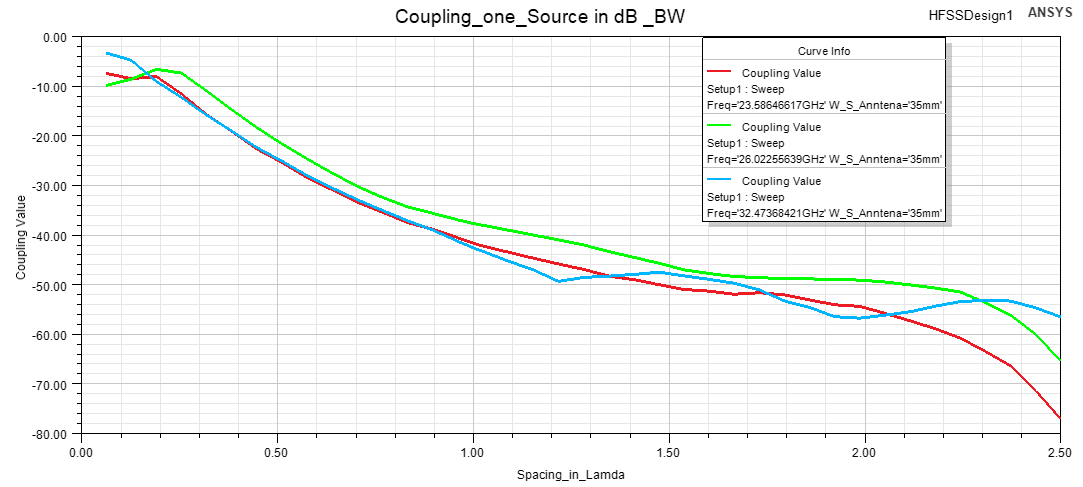
****

Figure 46: coupling around the BW

**A graph showing different colored lines

Description automatically generated**

Figure 47: around deffrient lamda Vs frequency

Note that the mutual coupling at the design is -25dB

Also through using **Optimetric,** we could study the effect on the mutual coupling which really makes sense that is as increasing the spacing between the antennas, the mutual coupling decreases gradually.

1. **Effect on Active Return Loss**

Results showed almost constant active return loss in range of **0.1**to **2.5**.

Figure 48 :Active return loss vs spacing between the two elements for first design

## 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.

|  |  |  |
| --- | --- | --- |
| **Antenna parameters** | **First design** | **Second design** |
| **Return loss at 26 GHz (dB)** |  |  |
|  |  |  |
|  |  |  |
| **Gain at 26 GHz (dB)** | 6.9 dB | 9.16 dB |
| **Gain at 26 GHz (linear)** | 4.95 | 8.24 |
| **Beamwidth xz-plane** |  |  |
| **Beamwidth yz-plane** |  |  |
| **Axial ratio (dB)** | 53.69 dB | 38.73 dB |

# Final Design Layout

# Conclusion

# References

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