

**Cairo University**

**Faculty of Engineering**

**Electronics & Communication Department**

**ELC3050 Project**

**Design and Analysis of a 2-Element Probe-Fed Microstrip Patch Antenna Operating at 20 GHz**

**Under supervision of Dr Islam Eshra**

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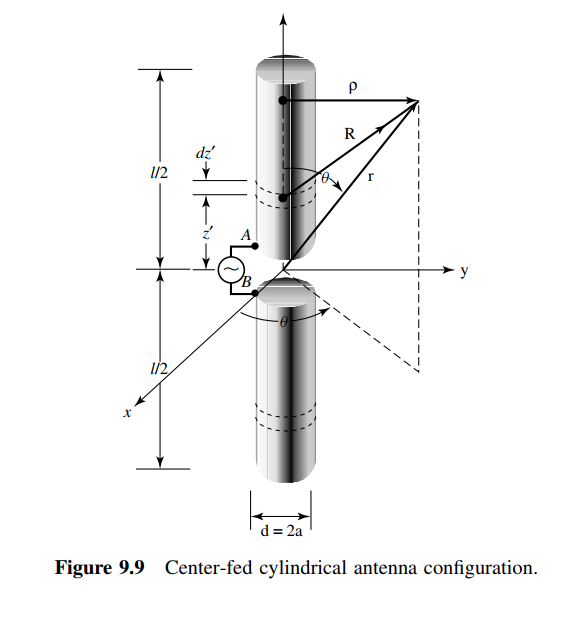
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# 1. Introduction and Problem Description

This project involves the design of a 2-element probe-fed microstrip patch antenna operating at 20 GHz. The goal is to achieve an S11 less than -10 dB at the operating frequency while optimizing performance in terms of bandwidth, gain, and radiation efficiency. A comprehensive analysis of the antenna's mutual coupling and gain vs. element spacing is also included.

# Verification Against Another Source

We’re going to simulate a dipole with the design in figure 9.9 in refrence [1] with HFSS.



|  |  |  |  |
| --- | --- | --- | --- |
| Name | Unit | "Evaluated Value" | Description |
| dl | mm | 139.5mm | Antenna length |
| rdi | mm | 0.2625mm | Antenna radius |
| gap\_L | mm | 1mm | Gap length |

With values that’s applied in Table 1:

Table 1 Diploe Antenna Dimensions

A green and red line

Description automatically generated

Figure 1: dipole antenna designed for verification

## Benchmark Description

* A dipole antenna is a standard reference in antenna theory, with well-documented characteristics such as impedance, radiation pattern, and gain.
* It is widely used as a baseline for verifying simulation accuracy and comparing performance metrics.

**Simulation Setup**

1. **Design Parameters**:
   * Length of the dipole: L= is the wavelength at the operating frequency.
   * Material: Mention the conductor used (copper or PEC).
2. **Simulation Environment**:
   * Define the simulation parameters, such as mesh size, boundary conditions, and excitation type (e.g., lumped port or wave port).
3. **Performance Metrics Evaluated**:
   * Return Loss (S11).
   * Radiation patterns in E-plane and H-plane.
   * Gain and efficiency.

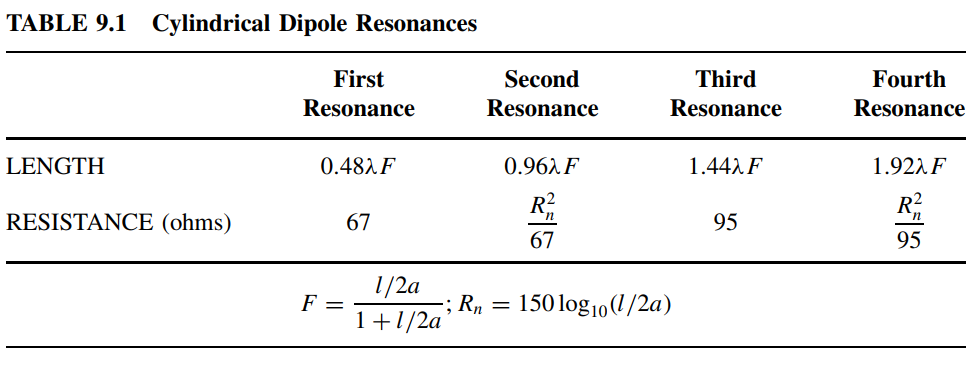
**Equations Controlling Dipole Antenna**

1. **Directivity**:
2. **Radiation Pattern**:
   * E-plane pattern: for .
   * H-plane pattern: for
3. **Input Impedance**:
4. **Gain**:

where is the efficiency of the antenna.

**Results Comparison**

We are going to use Table 9.1 in refrence [1] to verfy. According to it I’m expecting Rin=67Ω



A graph with a red line

Description automatically generated

Figure 2: S11 for dipole antenna for verification

A green and white graph

Description automatically generatedA graph with lines and numbers

Description automatically generated

Figure 3: Zin for dipole antenna for verification

Figure 4: Gain 2D for dipole antenna for verification

A red and yellow sphere with lines and points

Description automatically generated

Figure 5: Gain 3D for dipole antenna for verification

**Conclusion**

* The dipole antenna serves as a reliable reference for verifying the EM simulation tool.
* imulated results of the dipole antenna matches theoretical expectations (S11 plot, radiation pattern, and gain).
* The Rin is 68.63 which is approximately equal to the theotical value in Table 9.1.

***So the EM tool HFSS is verified***

# 2. Design Procedure

The design started with the selection of the substrate material R04003C with a dielectric constant of 3.55. Initial dimensions were calculated using standard formulas for microstrip patch antennas, considering a substrate thickness of 0.406 mm. An online calculator was used to determine the initial patch dimensions, which were fine-tuned through simulation sweeps for optimal S11 performance.

A single patch antenna was first designed and analyzed to establish baseline performance metrics. Subsequently, a 2-element array was constructed with varying patch separation distances (dp) to study mutual coupling. A matching network was designed for probe feeding to further optimize the design.

At first, we started with the following mathematical modelling for our design then we tuned and swept parameters to achieve required specs.

## Patch:

The resonant frequency of a rectangular microstrip patch antenna can be calculated using:[5]

where:

* : Speed of light in free space (  )
* : Effective length of the patch
* : Effective dielectric constant of the substrate.

Effective Length:

where:

## Substrate:

Effective dielectric constant:

where:

* : Relative permittivity of the substrate

We used RO4003C in Table 2 dielectric with [4]

* : Height of the substrate
* : Width of the patch.

A screenshot of a computer

Description automatically generated

Table 2 RT-duroid 5870 - 5880 Data Sheet

**2. Bandwidth Enhancement Analysis**

Bandwidth () is related to the quality factor () by:

Technique used to improve bandwidth:

* **Impedance Matching**: Adding a matching network to reduce reflections.
  + Use Zin and Z0 to compute matching network:

**3. Input Impedance**

The input impedance at the feed point is given by:

​

where ​ and ​ are resistance and reactance components derived from field distributions.

**4. Radiation Pattern**

The far-field electric field components can be approximated as:

where:

* ​: Wave number
* : Distance to observation point
* : Intrinsic impedance of the medium.

**5. Gain and Efficiency**

Gain () and radiation efficiency ( ​) are related:

where is the directivity.

Efficiency:

​​

# EM calculator:

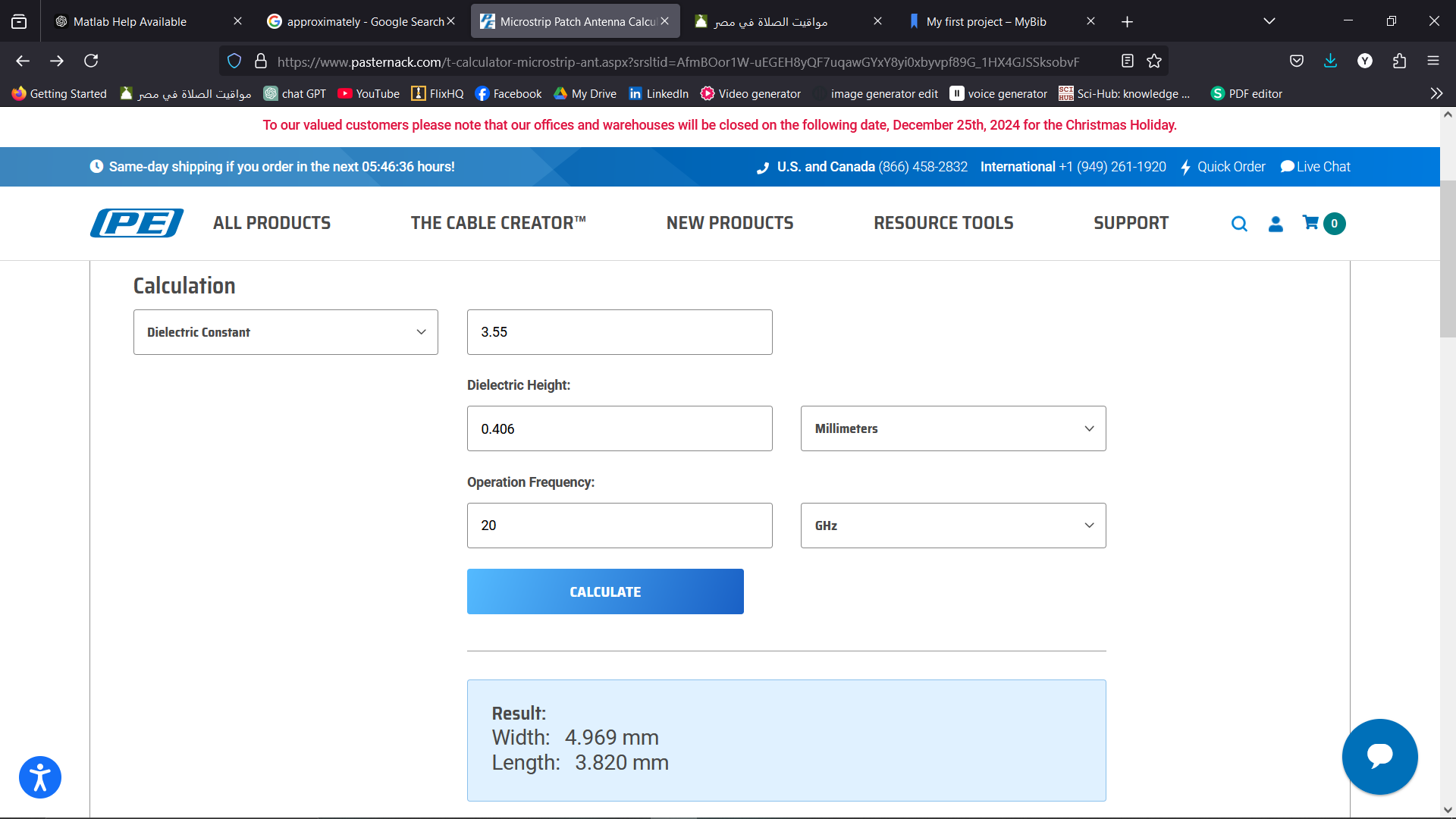
We Initialized our design using Pasternack's **Microstrip Patch Antenna Calculator[2]**

Figure 6 EM calculator results

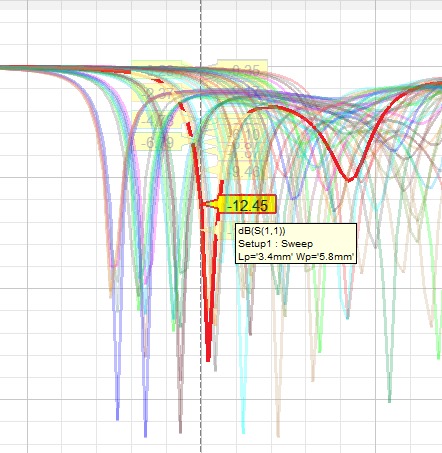
In figure 7, we can see that we started with W = 4.969 mm and L = 3.82 mm then we sweapt them to get the specs in figure 8.

Figure 7 L,W S11 sweaping

# Design of single patch

A diagram of a rectangular patch

Description automatically generated

Figure 8: antenna with probe feeding model

Figure 9: 3D patch antenna design

A green rectangle with orange and green rectangles on graph paper

Description automatically generated

A screenshot of a game

Description automatically generated

Figure 10: bottom view of patch antenna

A line with a green and blue line

Description automatically generated with medium confidence

Figure 11: side view of patch antenna

|  |  |  |  |
| --- | --- | --- | --- |
| Name | Unit | "Evaluated Value" | Description |
| Lp | Mm | 3.633mm | Patch length |
| Wp | Mm | 5.173mm | Patch width |
| hs | Mm | 0.406mm | Substrate height |
| Ws | Mm | 6\*hs+Wp=7.609mm | Ground plane width |
| Ls | Mm | 6\*hs+Lp=6.475mm | Ground plane length |
| xfeed | Mm | 1.2mm | Feed point x-offset |
| rcoax | Mm | 0.14mm | Coaxial feed radius |
| hcoax | Mm | 0.203mm | Coaxial feed height |
| rprope | Mm | 0.07mm | Probe radius |
| Yfeed | Mm | 0mm | Feed point y-offset |
| Hgnd | Mm | -0.032mm | Ground plane height |

And we designed and evaluated the values in Table 3:  
The substrate length and width is designed so the patch has 3\*hs in each side

Table 3 Single Patch Design

### S11:

A graph of a graph

Description automatically generatedFor designing single patch antenna, we tuned parameters to get reflection coefficient S11 achieving specs

Figure 12: S11 for single Patch antenna

From figure 11, we succeeded to tuned parameters and achieve minimum s11 at operating frequency 20 GHz =-15.35dB

we have bandwidth (range of frequency where S11<-10 dB)A diagram of a circle with a smiley face drawn on it

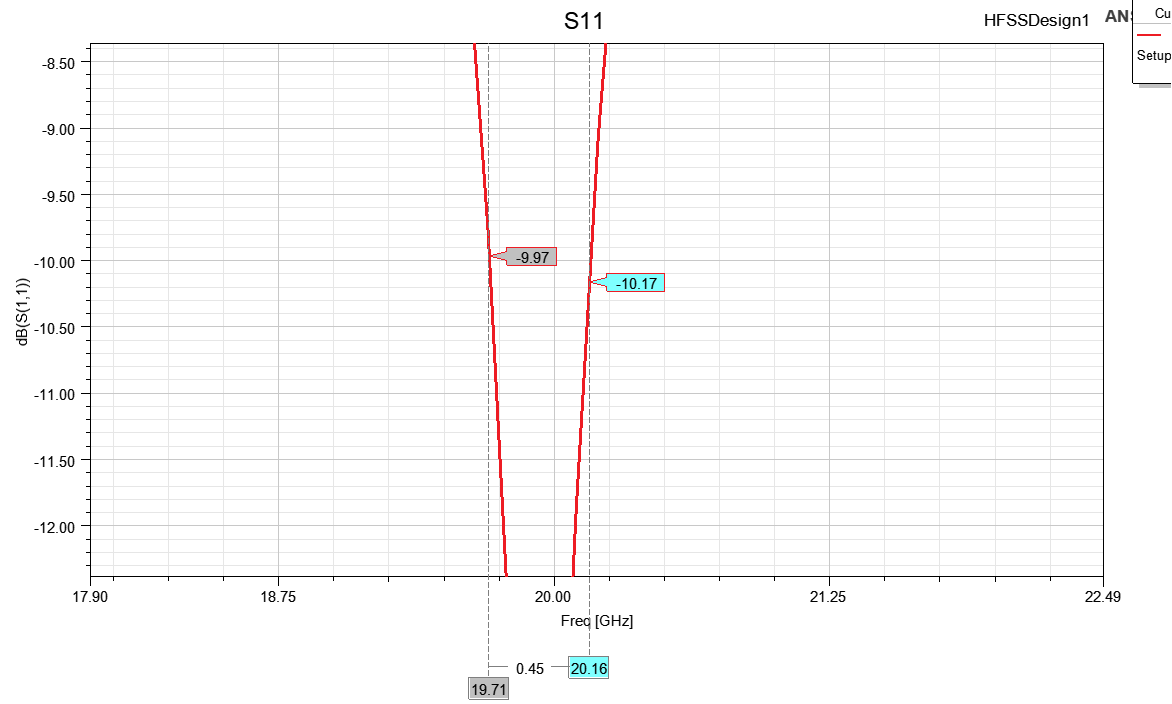
Description automatically generated,The BW = 450 MHz.

Figure 13: smith chart for single Patch

Figure 14: Bandwidth where S11<-10 dB

As shown in figure 14, Bandwidth achieved for VSWR=1.421

A graph with a red line

Description automatically generated

Figure 15: VSWR = 1.421 at 20 GHz for single patch antenna

### Zin:

A graph with a red line

Description automatically generatedFor proper feeding from the above figure 16, we found that is matching impedance required at 20GHz.

Figure 16 Xfeed for single patch antenna

Figure 17 Zin for single Patch antenna at 20GHz

A graph of a graph

Description automatically generated

A graph with a red line

Description automatically generated

Figure 18: Yfeed for single patch antenna

From figure 15 and 17, We can see that (x,y) position can change the Zin value.

So we chose (1.2,0) that matched our specs.

### Radiation patterns

Figure 19 Radiation Pattern at 20GHz in XZ Plane

Figure 20 Radiation Pattern at 20GHz in YZ Plane

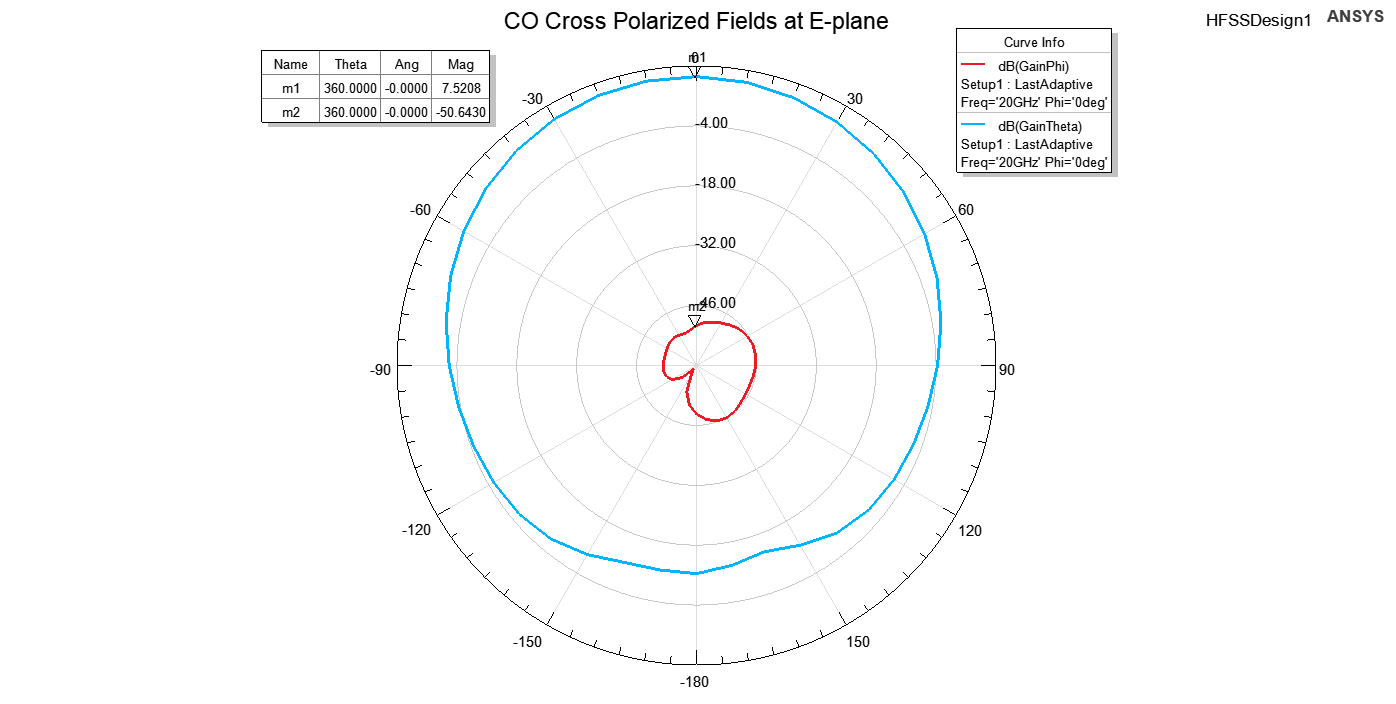
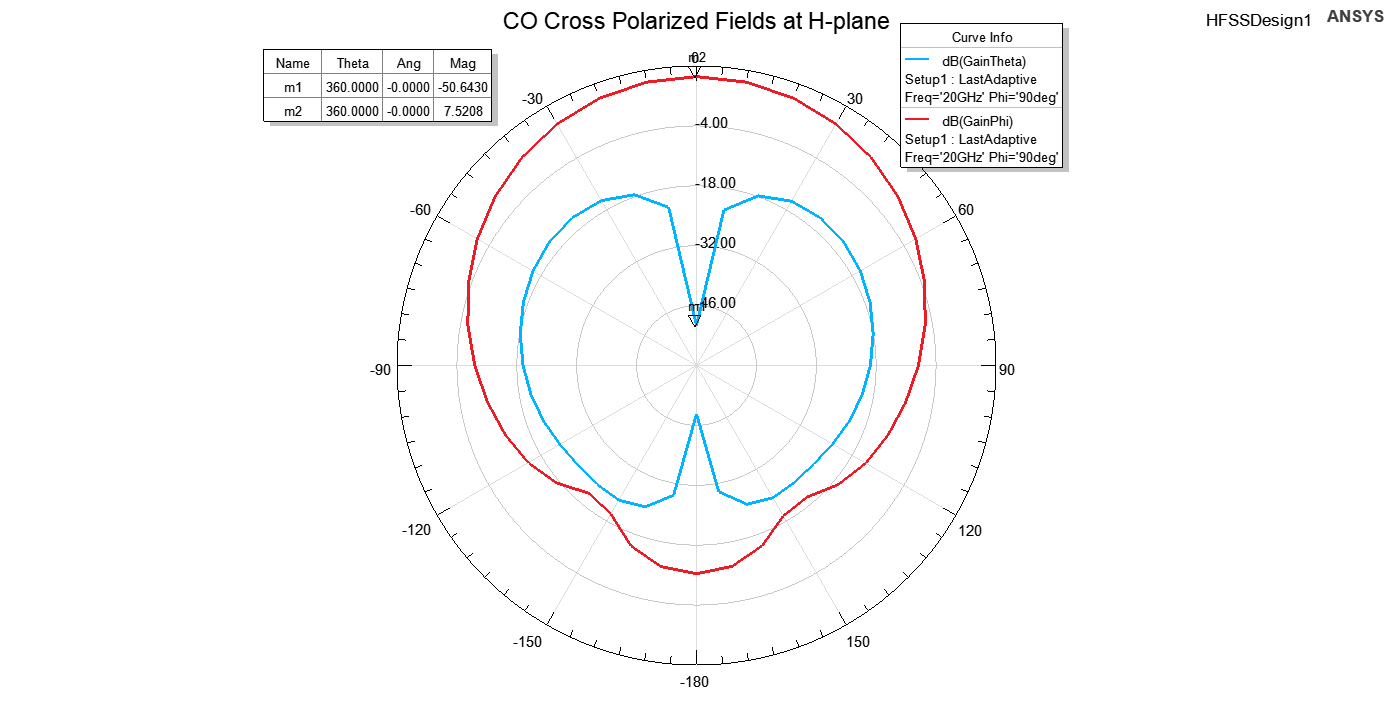


Figure 21 CO Cross Polarized Fields at E-plane

Figure 22 CO Cross Polarized Fields at H-plane

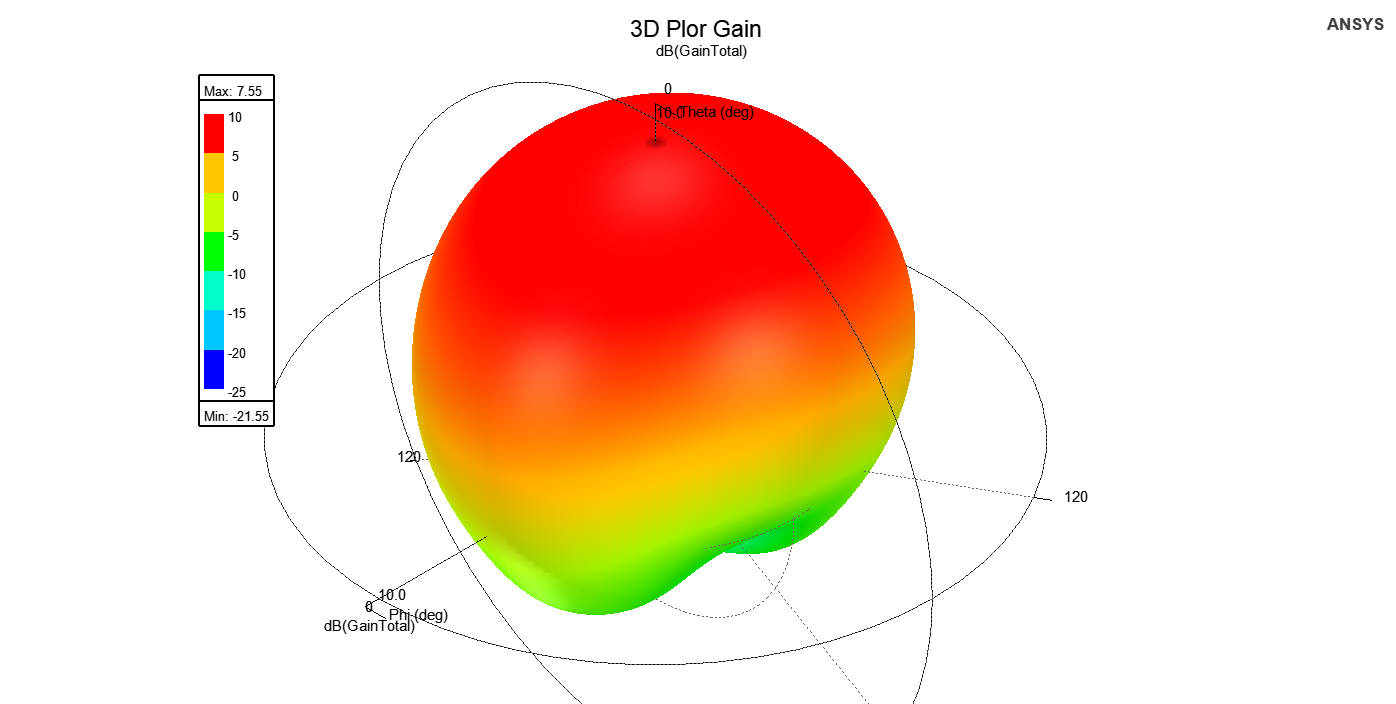
Using the figures 20, 21, 22, 23 and 24, we can calculate the variables in Table 4:

Figure 23 3D Polar Gain at 20GHz

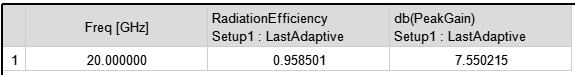
|  |  |
| --- | --- |
| Name | Evaluated Value |
| Gain | 7.52dB |
| XPD | 58.16dB |
| Front-to-BackXZ | 21.18dB |
| Front-to-BackXY | 18.87dB |

Table 4 Single Patch Radiation Pattern Results

As shown in (Figure 20) and (Figure 21), the radiation pattern of the designed single antenna is illustrated along with the co- and cross-polarized fields. The antenna achieves a gain of 7.52 dB, indicating a strong directional performance. It can be observed from the co- and cross-polarization plots that the antenna achieves a high cross-polarization discrimination (XPD) of 58.16 dB, reflecting excellent polarization purity. Furthermore, the front-to-back ratio is 21.18 dB in the XZ plane and 18.87 dB in the XY plane, demonstrating good suppression of backward radiation and indicating stable performance across planes.

### Antenna Parameters

Table 5 Single Antenna Parameters



The antenna gain is one of the key antenna characteristics as it combines radiation efficiency and directivity.

As shown in table 5, where the peak realized gain of the proposed antenna is 7.55 dB, indicating strong performance in the boresight direction. A radiation efficiency of 95.85% is achieved, showcasing the antenna's ability to efficiently convert input power into radiated energy. Note that this efficiency and gain are specific to the evaluated frequency range, as the simulation was focused on the design's target operational band.

### Gain Performance of a Single Patch Antenna

As shown in figure 23 and 24, The gain of the single patch antenna was measured, and the results showed a single main beam centered at θ=0° with a maximum gain of 7.52dB and directivity of 7.7dB

This pattern is consistent with the fundamental radiation mode of a microstrip patch antenna, which is typically a broadside radiator designed to focus energy perpendicular to the patch surface.

The observed gain value of 5.7dB is within the expected range for a single patch operating at the designed frequency, accounting for the following factors:

1. **Effective Aperture:** The size and geometry of the patch contribute to its directivity.
2. **Substrate Material:** The dielectric constant and loss tangent of the substrate slightly influence the gain.
3. **Impedance Matching:** Proper matching ensures minimal reflection and maximum radiation efficiency.

This result establishes a baseline for evaluating the performance of the 2-element patch array configuration.

# Design of Two Patches:

A computer generated image of a rectangular object

Description automatically generatedWe are targeting to design 2 antenna arrays, so we made a replica from our patch and we swept and tuned our parameter to achieve the required specs

Figure 24: Two Patch antenna array

A green leaf on a line

Description automatically generated

Figure 25: Two Patch side view

We make a sweap on distance between patches (dp) to meet the specs.

The best results was at dp=0.36mm putting in mind that it will change after designing the TL.

### S-Parameters:

Also designing two patch antenna array is expected to provide us with higher gain compared to single patch however we noticed that there is a trade off between mutual coupling S21 and achieving required gain:

At first, we tuned parameters to achieve S11 as required

Figure 26: S11 for Two patches

A graph with red lines and numbers

Description automatically generatedAs shown in Figure 27, We have S11 = -10.46 dB< -10 dB at 20 GHz however we faced problems with Bandwidth as it is a very narrow band.

A graph with red lines

Description automatically generated

Figure 27: VSWR for first Patch

A graph of a graph

Description automatically generatedA graph of a heart rate

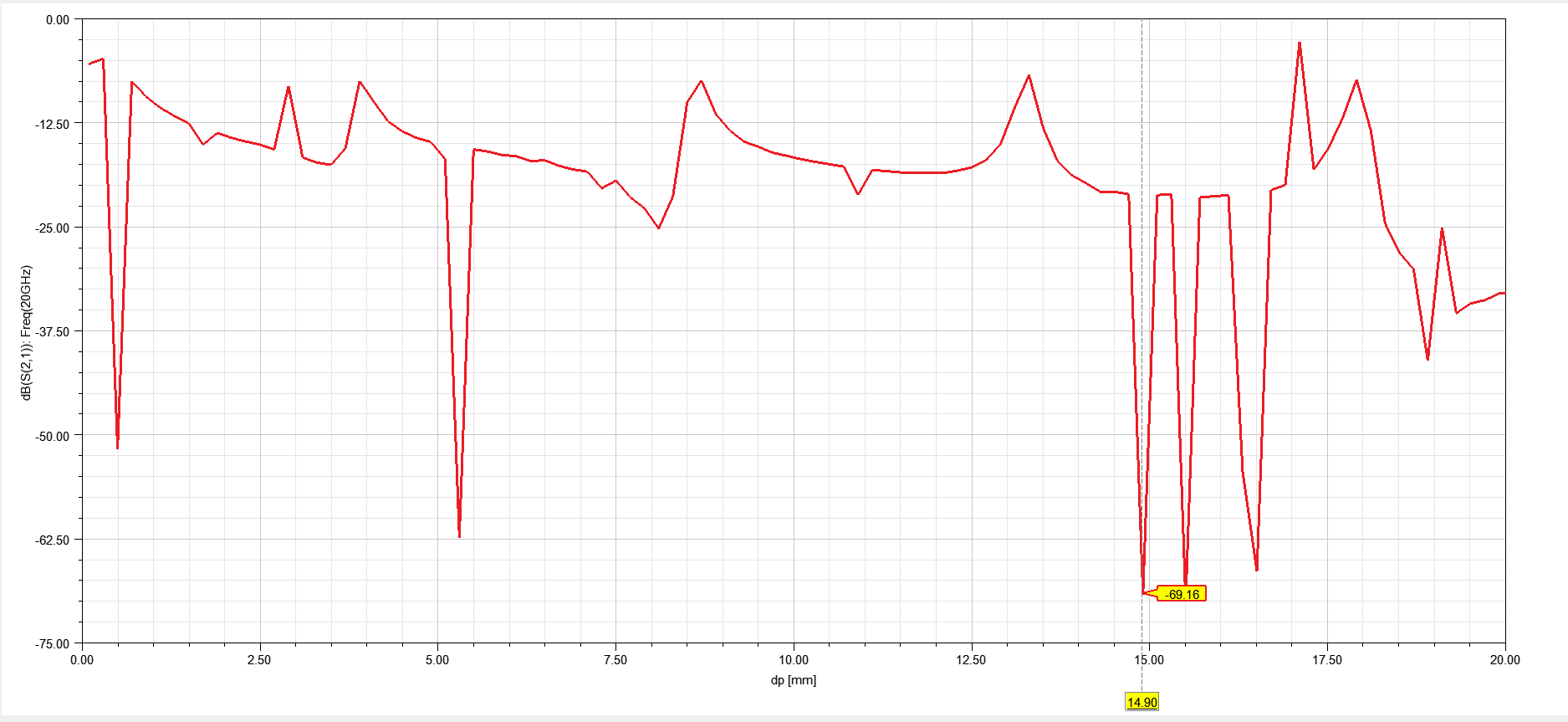
Description automatically generatedAs shown in Figure 29 and 30, The VSWR1 VSWR2 is equal to 1.63.

Figure 28: VSWR for second Patch

As shown in figure 31, The S21 value equals to -6.52 dB.

Figure 29: S21 Vs Frequency

### Mutual Coupling vs Element Spacing:

A graph with different colored lines

Description automatically generatedas we discussed mutual coupling S21 originated when we add the second patch and we noticed that it varies with distance between two patches (dp) so we made sweep on:

Figure 30: S21 Vs Distance between two patches

Figure 31: S21 sweep Vs frequency by changing dp

As shown in figure 32 and 33:

The behavior of the S21 graph versus element distance is primarily due to the constructive and destructive interference of the electromagnetic waves radiating from the two patches.

At certain distances, the waves reinforce each other, creating tops in the graph, while at others, they cancel out, resulting in bottoms. These interactions are influenced by the phase difference between the signals from the patches, which changes with element spacing.

The observed tops at 8.7 mm, 13.31 mm, and 17.11 mm correspond to distances where the phase alignment of the waves maximizes coupling. Conversely, the bottoms at 14.9 mm, 15.5 mm, and 16.5 mm represent destructive interference points where the coupling is minimized.

***We will choose for the TL design a distance of 14.9 mm because it is the nearest value to the wavelength λ, which equals 15 mm.***

### Zin:

Figure 32: Zin for two Patches at 20 GHz

As shown in figure 28, The Zin equals to 69.05 Ω

We got Zin=69.05 so for proper feeding and enhancing bandwidth.

### Radiation patterns

Figure 33 Radiation Pattern at 20GHz in YZ Plane

Figure 34 Radiation Pattern at 20GHz in XZ Plane

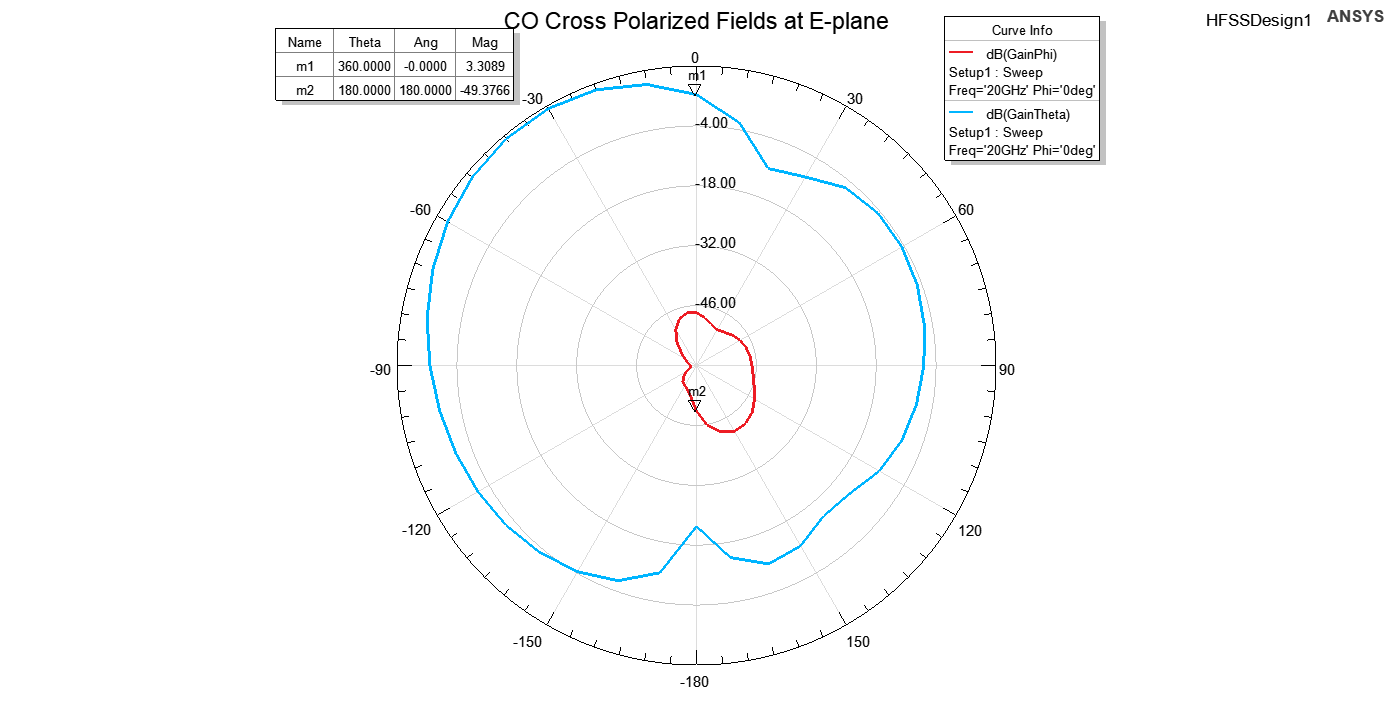
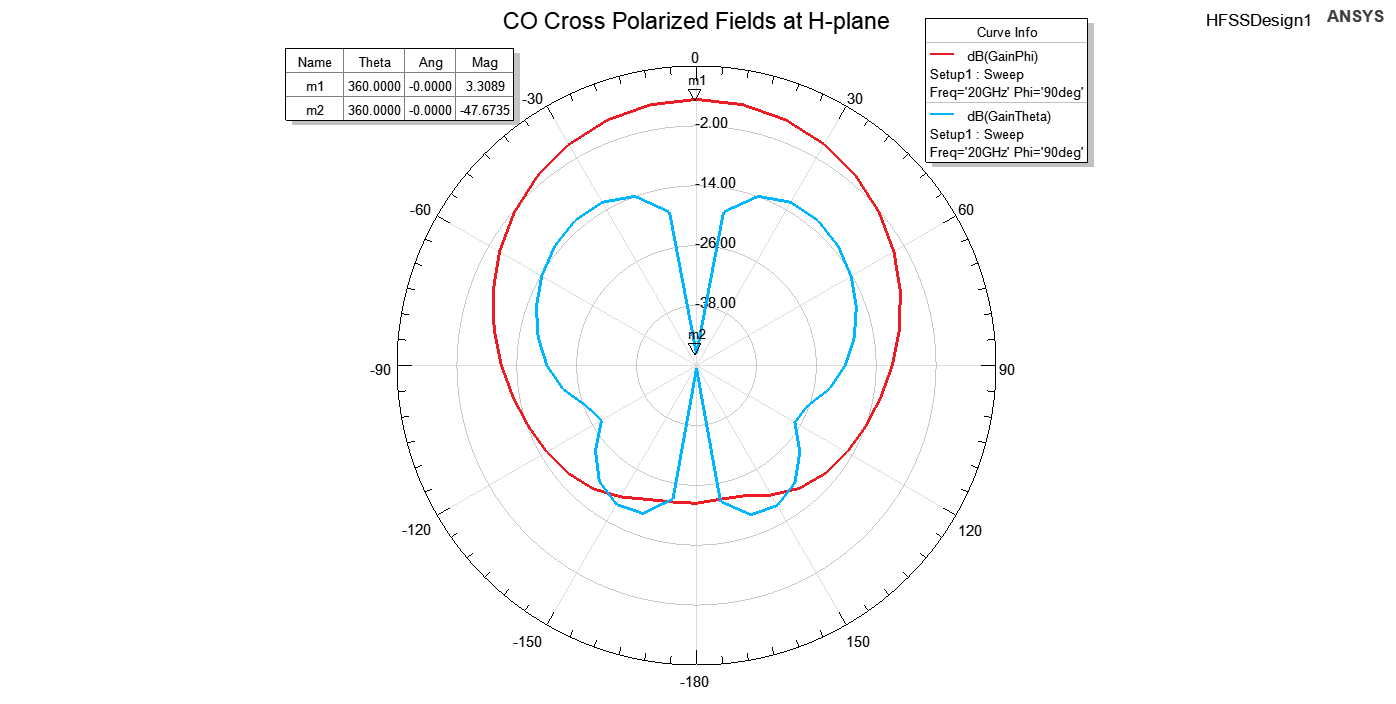


Figure 35 CO Cross Polarized Fields at E-plane

Figure 36 CO Cross Polarized Fields at H-plane

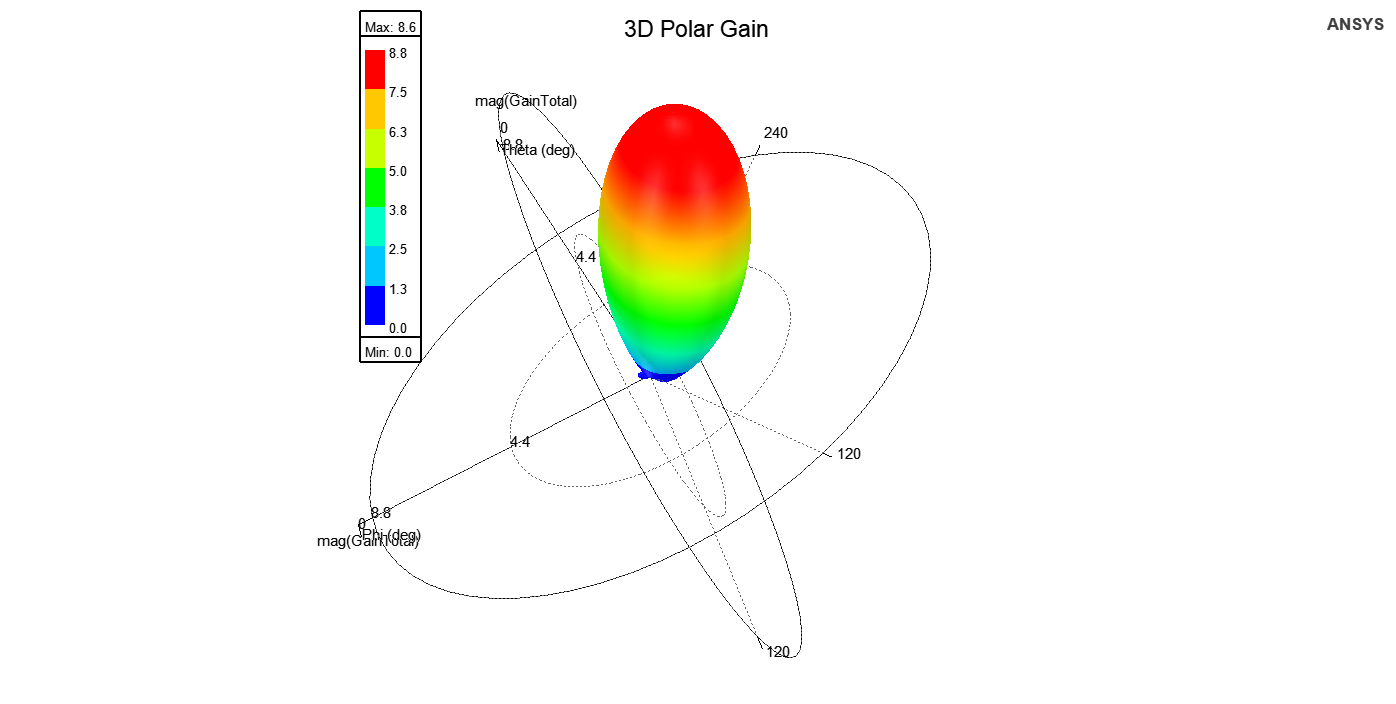
Using the figures 33, 34, 35, 36 and 37, we can calculate the variables in Table 4:

Figure 37 3D Polar Gain at 20GHz

|  |  |
| --- | --- |
| Name | Evaluated Value |
| Gain | 3.3dB |
| XPD | 52.67dB |
| Front-to-BackXZ | 25dB |
| Front-to-BackXY | 25dB |

Table 6 Two Patch Radiation Pattern Results

As shown in Table 6, when the two patches were combined into an array, the mutual coupling between the elements and the phase difference between their feeds caused the main lobe of the radiation pattern to shift, with the main beam centered at θ = -30°. This offset, typical of such interactions, arises from unequal phase distribution or asymmetry in the feed network.

The array achieved a gain of 3.3 dB and a cross-polarization discrimination (XPD) of 52.67 dB, with a front-to-back ratio of 25 dB in both the XZ and XY planes, as summarized in Table 6. However, the radiation efficiency was lower than that of the single patch due to the offset and coupling effects, highlighting the trade-off between gain improvement and efficiency in array configurations.

This behavior can be attributed to the following factors:

1. **Element Spacing and Phase Difference:**
   * The mutual coupling and spacing between the two patches likely introduced a phase difference in the radiated fields from each element. This phase offset caused constructive interference to occur at an angle rather than directly broadside (θ=0∘\theta = 0^\circθ=0∘).
2. **Feed Network Asymmetry:**
   * If the feed network introduced a phase imbalance between the two patches, it would steer the beam away from the broadside direction.
3. **Mutual Coupling Effect:**
   * The interaction between the two patches may have modified the effective radiation pattern, pushing the main beam off-center.

This result highlights the importance of ensuring symmetrical feeding and carefully managing element spacing to maintain broadside radiation. Corrective measures, such as tuning the transmission line lengths or adjusting the relative phases, can mitigate this offset.

### Antenna parameters:

Figure 39 Two Patch Gain Vs Frequency

Figure 38: Radiation Efficiency Vs Frequency

As shown in figure 38 and 39, The plots of **Gain** and **Radiation Efficiency** versus frequency for the two-patch array reveal the following observations:

1. **Maximum Gain and Efficiency:**

* The total gain reaches 9.2dB and radiation efficiency peaks at 9.57dB, but these values are not the global maxima across the frequency range.

1. **Two Distinct Peaks:**

* The gain and efficiency curves exhibit two prominent peaks at approximately **17.5 GHz** and **23.5 GHz**, indicating the frequencies where the array's performance is optimized.
* These peaks could be attributed to **resonances** of the patches, where the radiation is most efficient due to better impedance matching and minimal losses.

1. **Behavior Between Peaks:**

* Between these peaks, the gain and efficiency slightly drop, likely due to suboptimal matching or increased losses in the antenna system.

To maximize performance at a specific operational frequency, the design could be further tuned, such as by adjusting the element spacing, feed network, or patch dimensions. Including this analysis in the report emphasizes the importance of frequency optimization in array design.

# Adding Feeding Network for Two Patch antennas:

Figure 40 Serial TL

## Serial Transmission Line:

As shown in figure 41, We first tried to use the Serial TL with the Two patches with dimensions:

|  |  |  |  |
| --- | --- | --- | --- |
| Name | Unit | "Evaluated Value" | Description |
| LTL\_feed | mm | Ls=10.72mm | Feed transmission line length |
| WTL\_feed | mm | 0.3mm | Feed transmission line width |

Table 7 Serial TL Dimensions

### Results:

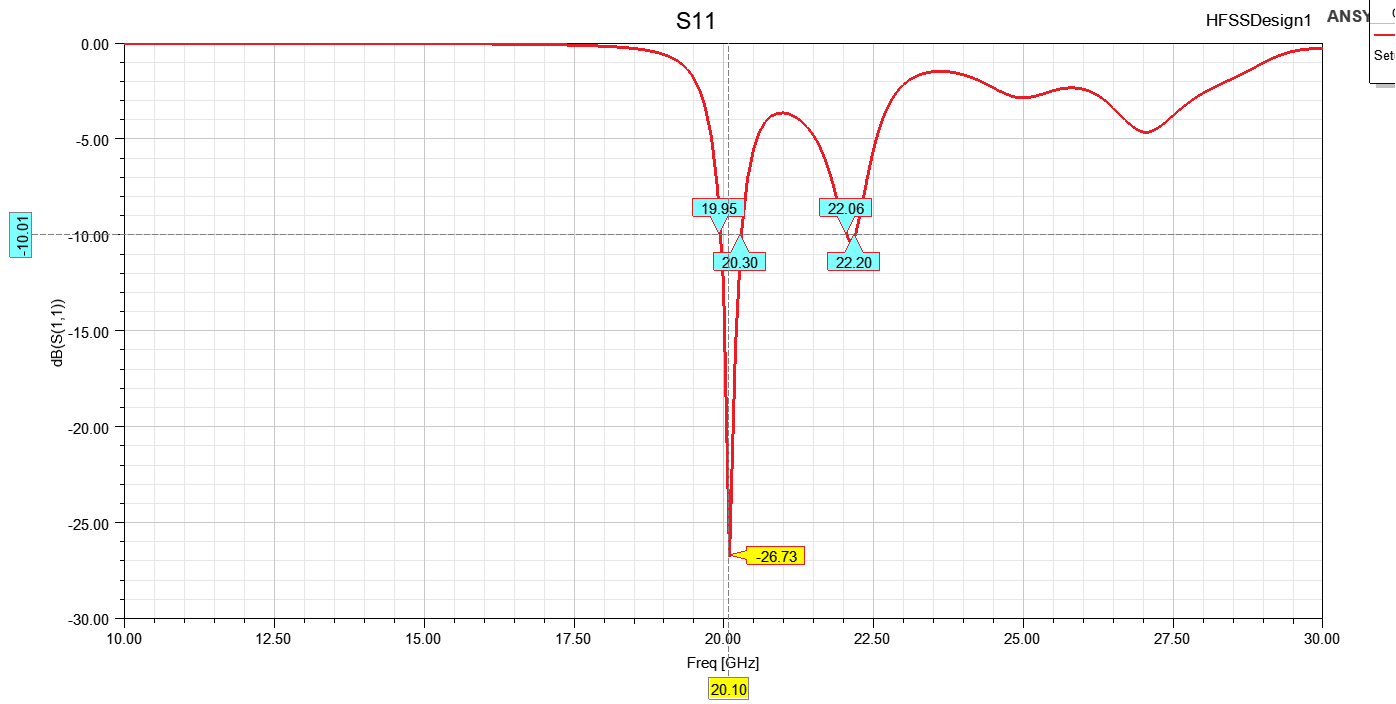


Figure 41 S11 with Serial TL

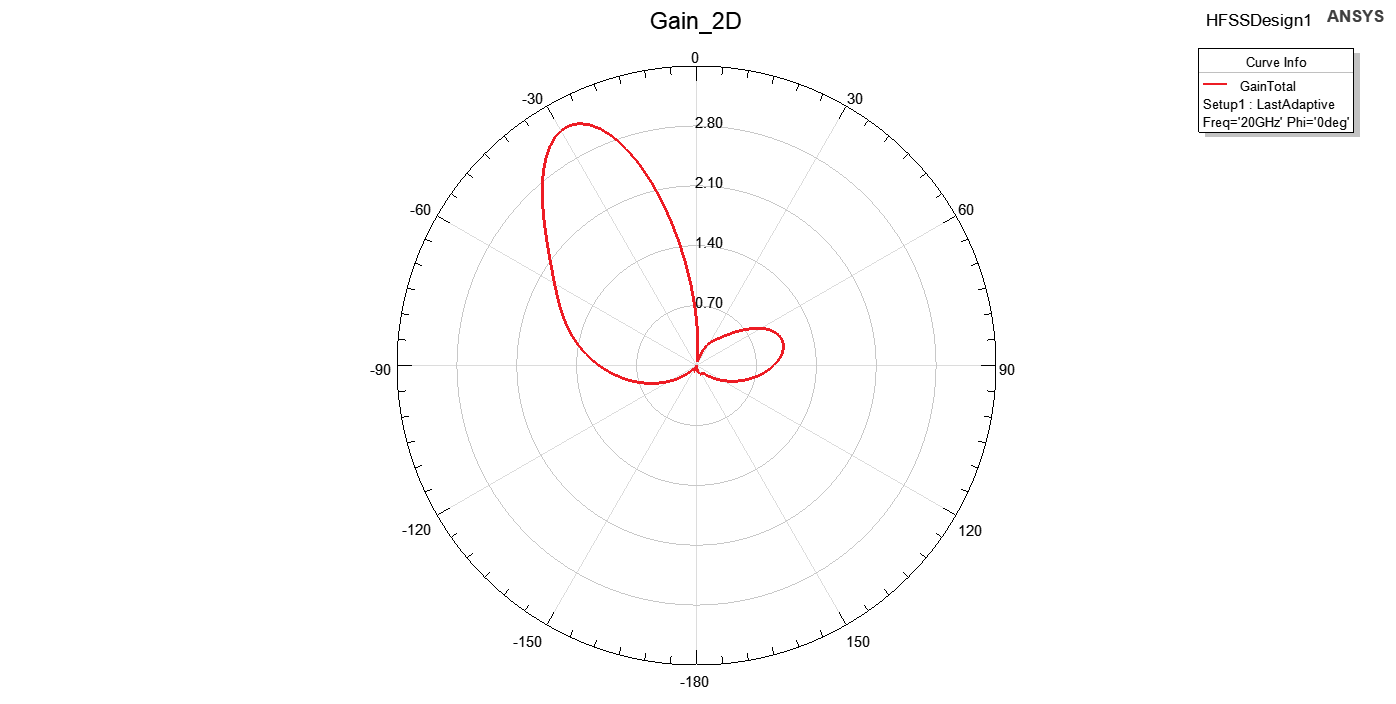
As shown in figure 42, The S11 achieved the specs

Figure 42 Gain with Serial TL

As shown in figure 43, The gain was centered at θ =−30°.

The serial transmission line improved impedance matching (S11), but the radiation pattern remained centered at θ = -30° due to phase imbalance between the two patches, caused by unequal path lengths. This imbalance led to constructive interference in the offset direction.

***So we shifted to T-section design***

## Final Design with T-Section Transmission Line:

Figure 43: T-Section transmission line

As shown in figure 44, We designed a transmission line T-section as shown below and we swept on its dimensions till we achieved requirement.

And to have maximum gain we make distance equal to **λ = 15mm**

After Sweaping Here’s the final dimensions:

|  |  |  |  |
| --- | --- | --- | --- |
| Name | Unit | Evaluated Value | Description |
| Lp | mm | 5.78mm | Patch length |
| Wp | mm | 7.54mm | Patch width |
| hs | mm | 0.406mm | Substrate height |
| Ws | - | 11.736mm | Ground plane width |
| Ls | - | 18.206mm | Ground plane length |
| xfeed | mm | 1.1mm | Feed point x-offset |
| dp | mm | **λ** = 15mm | Patch offset parameter |
| rcoax | mm | 0.16mm | Coaxial feed radius |
| hcoax | mm | 0.203mm | Coaxial feed height |
| rprope | mm | 0.07mm | Probe radius |
| yfeed | mm | 0mm | Feed point y-offset |
| hgnd | mm | -0.032mm | Ground plane height |
| Xcoax | - | 2 | Coaxial feed x-offset |
| WTL\_In | mm | 0.673367mm | Input transmission line width |
| LTL\_feed | mm | 2.179292mm | Feed transmission line length |
| WTL\_feed | mm | 0.976256mm | Feed transmission line width |
| LTL\_Slot | mm | 0.25mm | Slot length |

### S11:

Figure 44: S11 after adding T-section

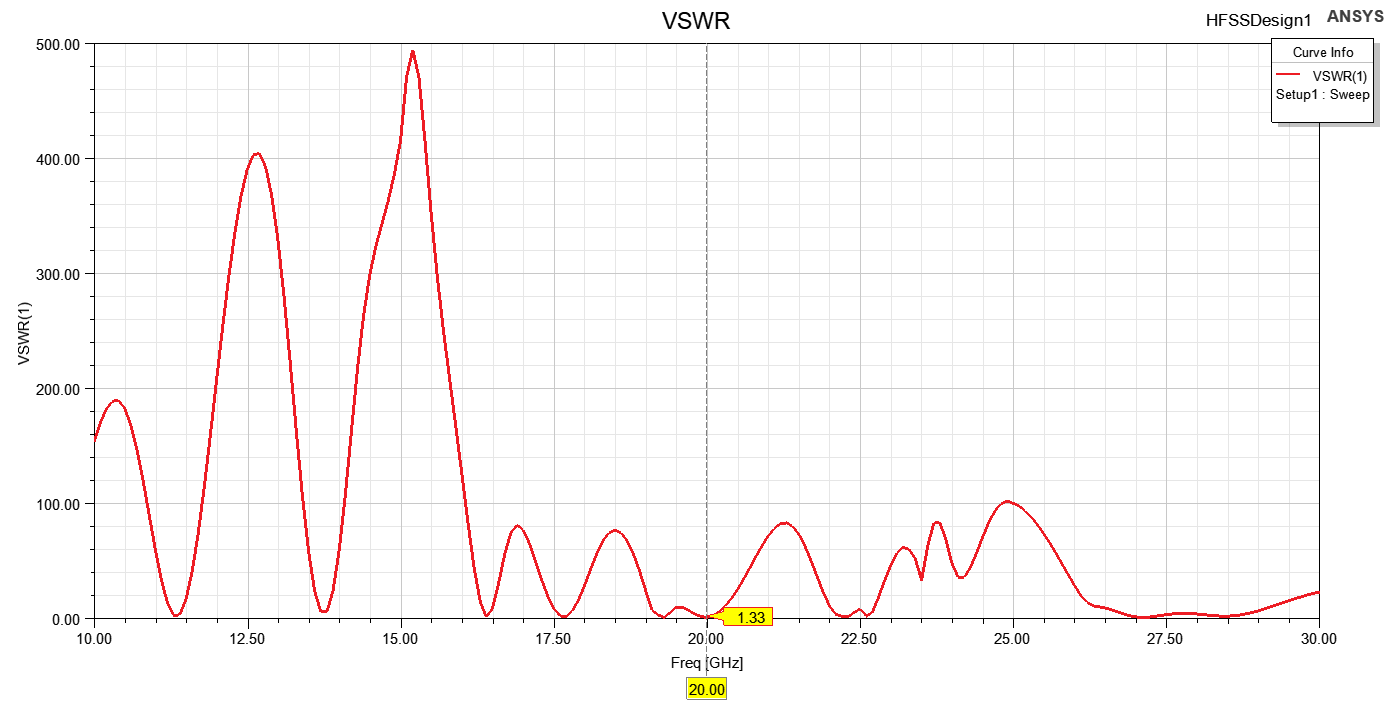
From figure 45, we enhanced bandwidth to be more wide from 19.91 GHz to 20.06 GHz with BW= 150MHz.

Figure 45: VSWR after adding feeding network

As shown in figure 47, The VSWR at frequency 20Ghz equals to 1.33.

### Zin:

Figure 46: Zin after adding T-section transmission line

As shown in Figure 46, The Zin equals to 56.53Ω.

### Radiation Pattern:

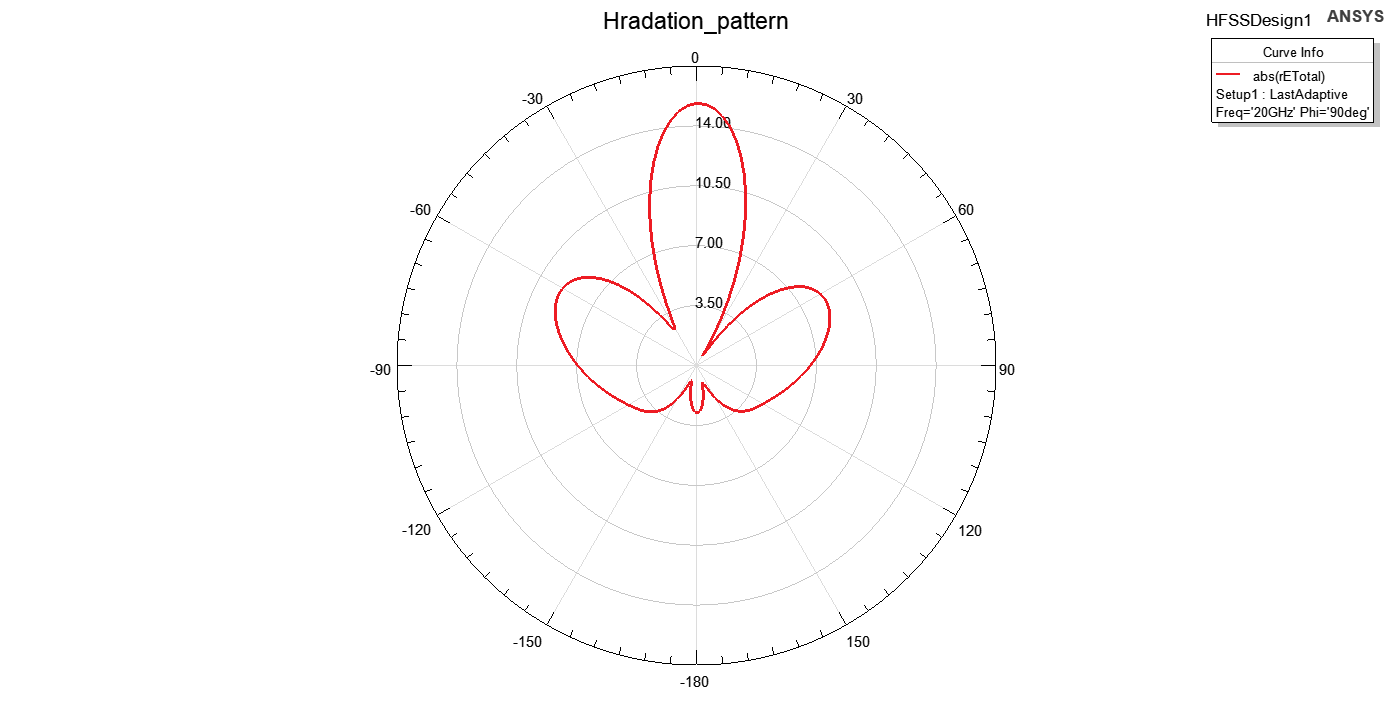


Figure 47: magnetic Field Radiation with T-Section TL

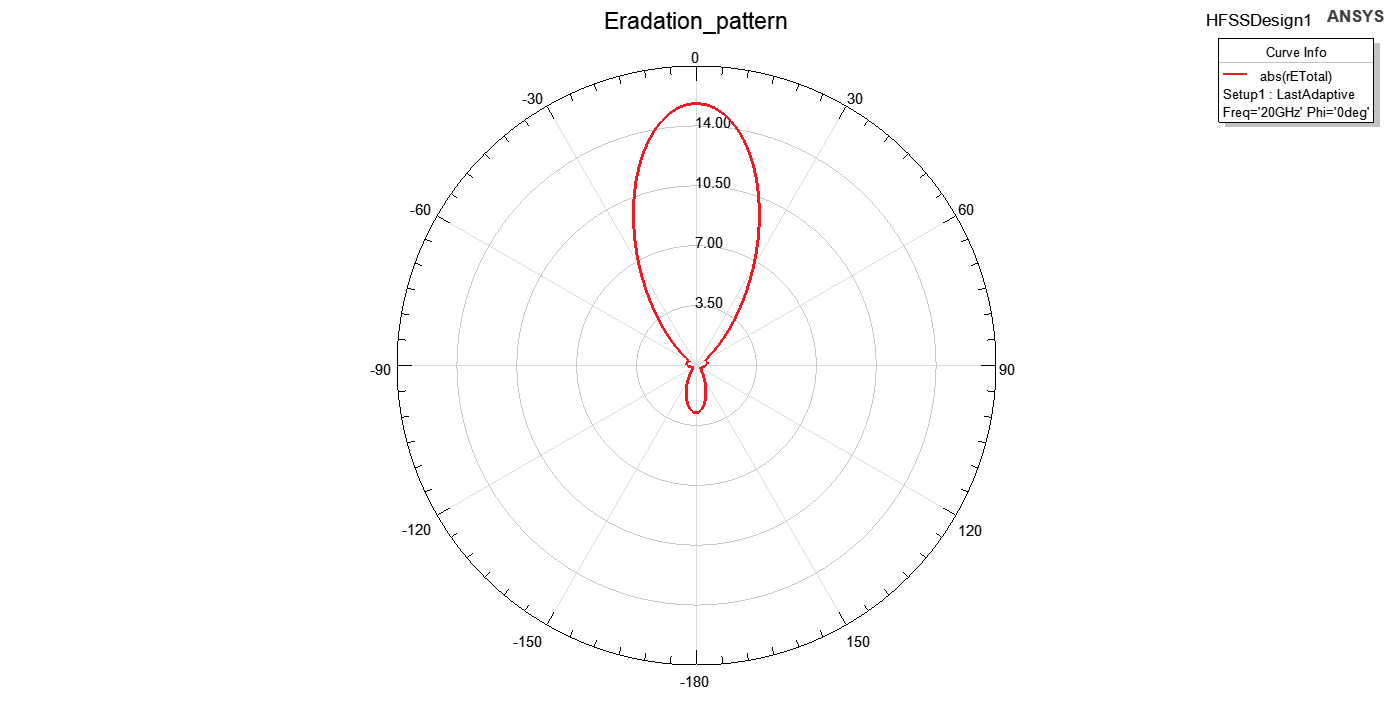


Figure 48: Electric Field Radiation with T-Section TL

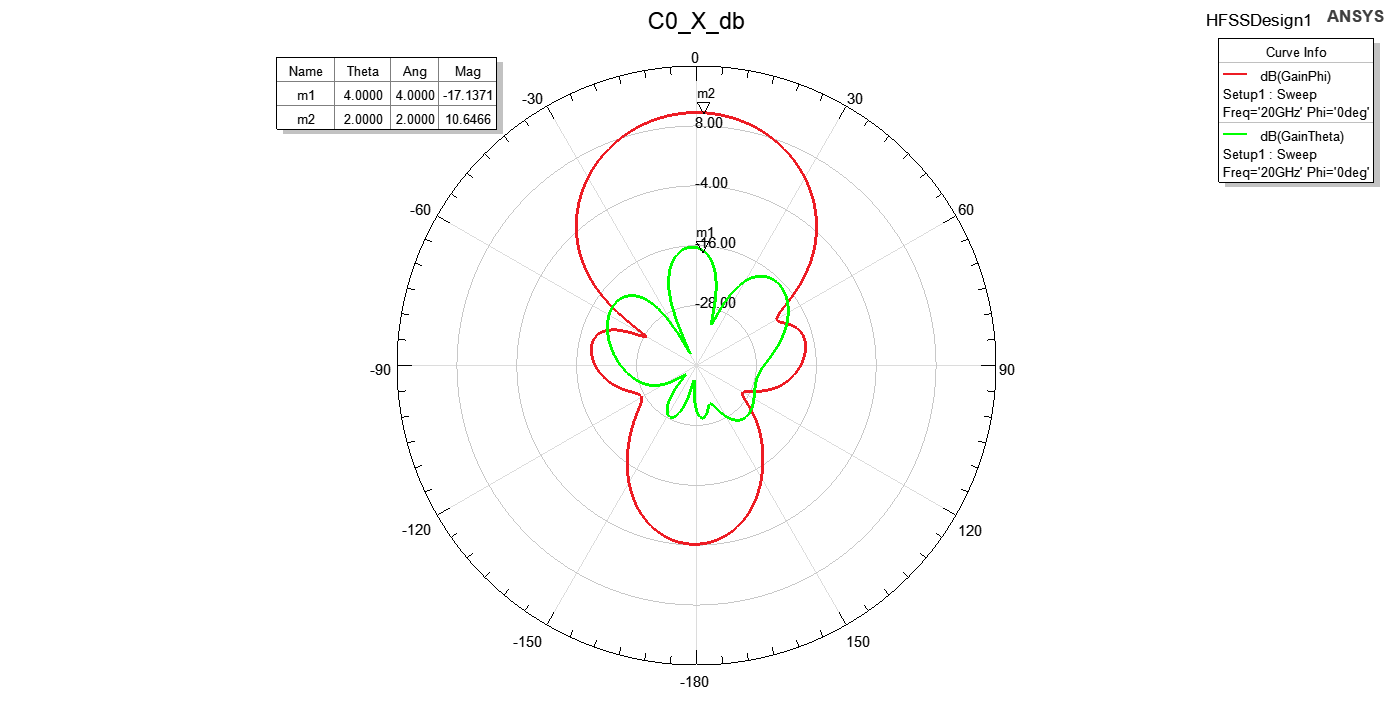


Figure 49: Co-polarization and cross-polarization patterns in the E- and H-planes

As shown in the figures 48,49 and 50, the addition of the T-section transmission line effectively corrected the radiation pattern alignment. This adjustment centered the pattern at theta equal to zero, addressing the previous deviation observed at -30 degrees. The T-section design improved the impedance matching, ensuring proper energy distribution and pattern symmetry.

### Gain:

Figure 50: gain 2D for 2 antenna array probe feed

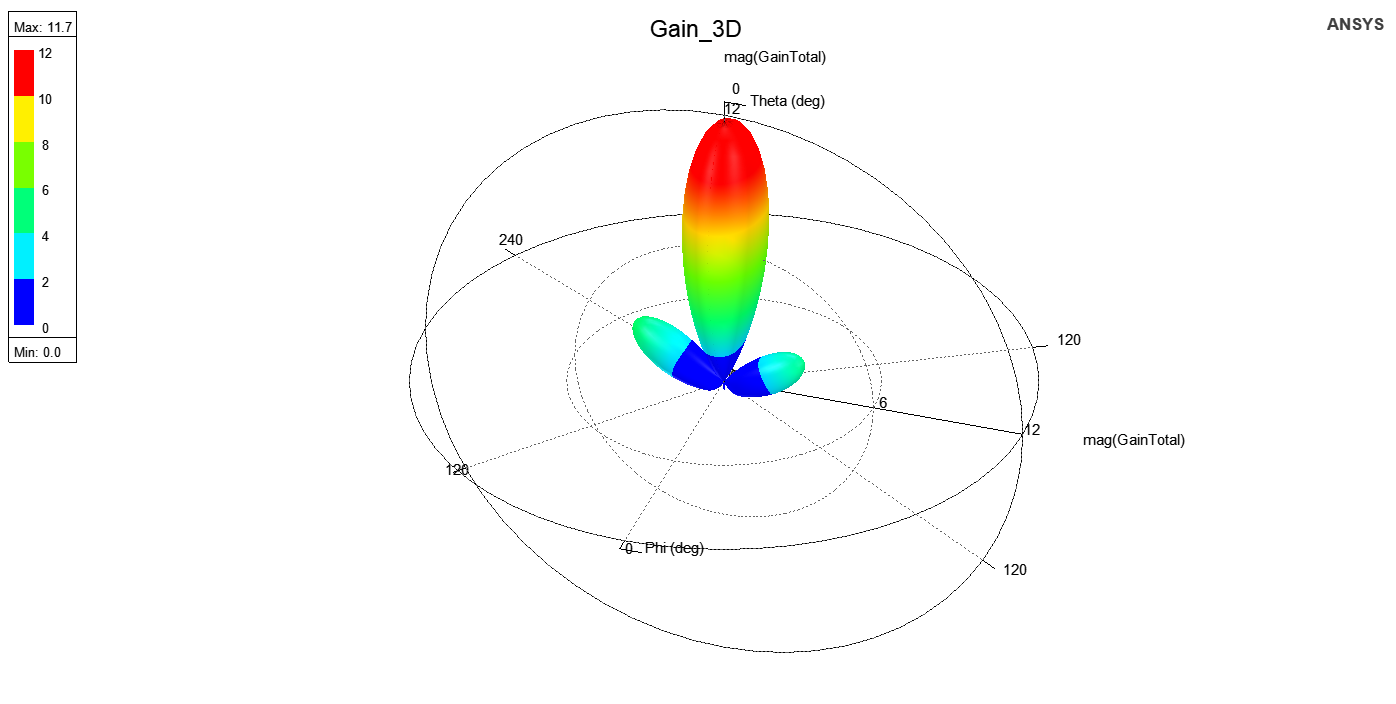


Figure 51: Gain 3D for 2 antenna array probe feed

As shown in figure 51 and 52, We calculated the following:

|  |  |
| --- | --- |
| Name | Evaluated Value |
| Gain | 11.7 dB |
| 3dB beamwidth | 56° |
| Fisrt Null beamwidth | 124° |
| First Null | 62° |
| Side Lobe beamwidth | 54° |
| Side Lobe | 78° |
| Front-to-Back ratio | -7.4315 dB |

We can say that the gain has increased but with slightly larger front-to-back ratio is attributed to transmission line leakage, which affects the back radiation performance.

### Gain vs Element Spacing:

### Antenna Parameters:

# 3. Results’ Discussion:

## 3.1 Return Loss (S11)

* The S11 parameter was evaluated for both the single patch and the 2-element array configurations. The single patch exhibited an S11 below -10 dB at the target frequency of 20 GHz, confirming adequate impedance matching. The 2-element array maintained a similar performance with an optimal patch separation distance of 0.36 mm.
* **Importance of S11 < -10 dB**: Achieving a return loss below -10 dB indicates that at least 90% of the input power is radiated, signifying efficient impedance matching and minimal reflections.

## 3.2 Mutual Coupling (S21)

* Mutual coupling between the patches was studied by sweeping the separation distance (dp). At dp = 0.36 mm, the coupling (S21) was minimized without significantly impacting the radiation characteristics.
* **Element Spacing**: Optimal spacing between array elements is vital to minimize mutual coupling, which can adversely affect radiation patterns and impedance matching. Studies suggest that a separation of approximately half a wavelength is effective in reducing coupling effects.

## 3.3 Smith Chart Analysis

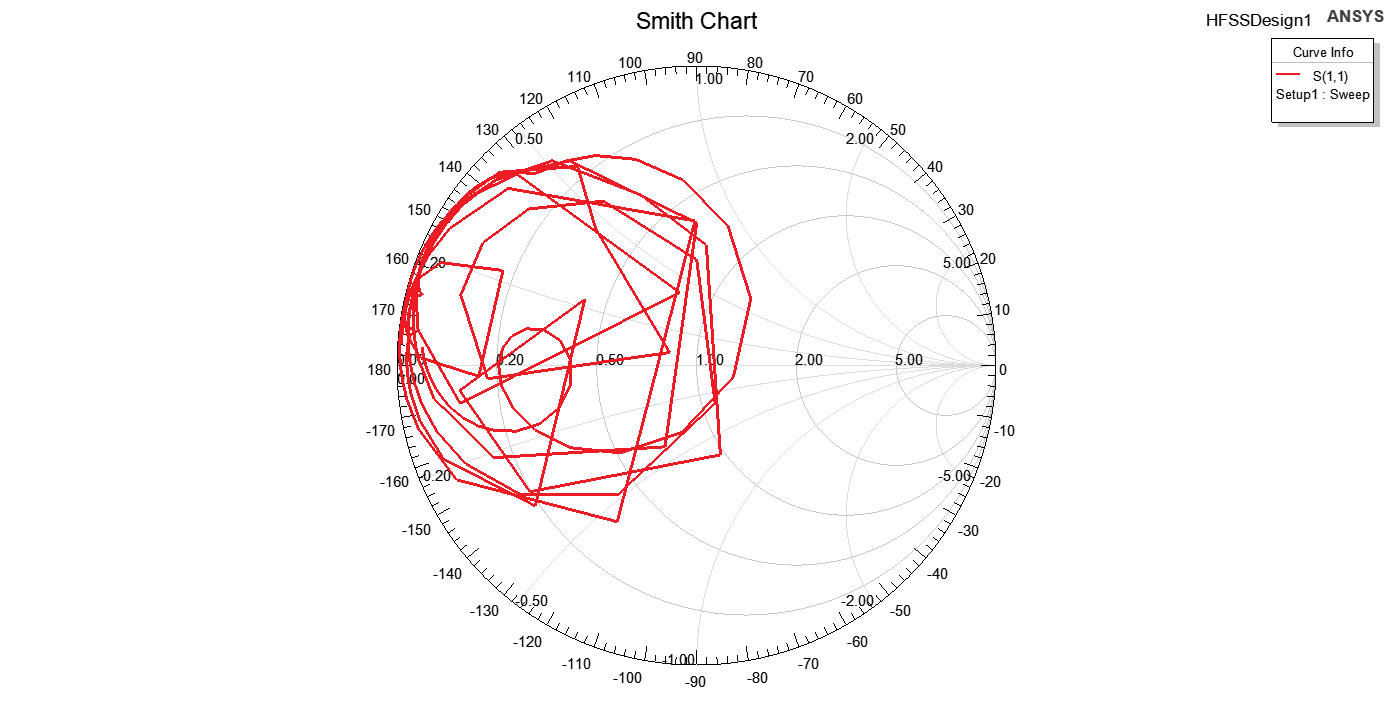
* **Impedance Matching**: The Smith chart provides a visual representation of the antenna's impedance across frequencies. A locus close to the center of the chart at 20 GHz confirms effective matching, which is crucial for maximizing power transfer and minimizing signal reflections as shown in figure 53.

Figure 52 Smith Chart with T-Section

## 3.4 Radiation Patterns

* The co-polarization and cross-polarization patterns were analyzed in the E and H planes. The results demonstrated a directive radiation pattern with minimal cross-polarization, aligning with design expectations.
* **E-plane and H-plane Patterns**: Analyzing the radiation patterns in both planes reveals the antenna's directivity and beamwidth. A well-designed antenna should exhibit symmetrical patterns with minimal sidelobes, indicating efficient radiation and reduced interference.
* **Cross-Polarization Levels**: Low cross-polarization levels are essential for maintaining signal purity and reducing polarization mismatches, which is particularly important in communication systems to ensure signal integrity.

## 3.5 Gain and Efficiency

* **Impact of Array Configuration**: Transitioning from a single patch to a 2-element array can enhance gain due to constructive interference, but it's essential to manage mutual coupling to prevent efficiency degradation. Proper element spacing and feeding techniques are critical in this regard.

## 3.6 Bandwidth Enhancement Techniques:[3]

* + **Impedance Matching**: Adding a matching network to minimize reflections.
  + **Stacked Patches**: Introducing a second resonant patch above the main patch.
  + **Capacitive Coupling**: Modifying the feed structure to include a capacitive element.
  + **Slotted Patch**: Adding slots to the patch to create additional resonances.

To achieve bandwidth enhancement, we found that the previous techniques are used we started to design our antenna at given resonance frequency 20GHz and we got result for S11, VSWR, Radiation pattern, Gain and directivity, then we found that feeding network is not matched with designed antenna, so we decided to enhance bandwidth using Impedance Matching technique.

We also found out that

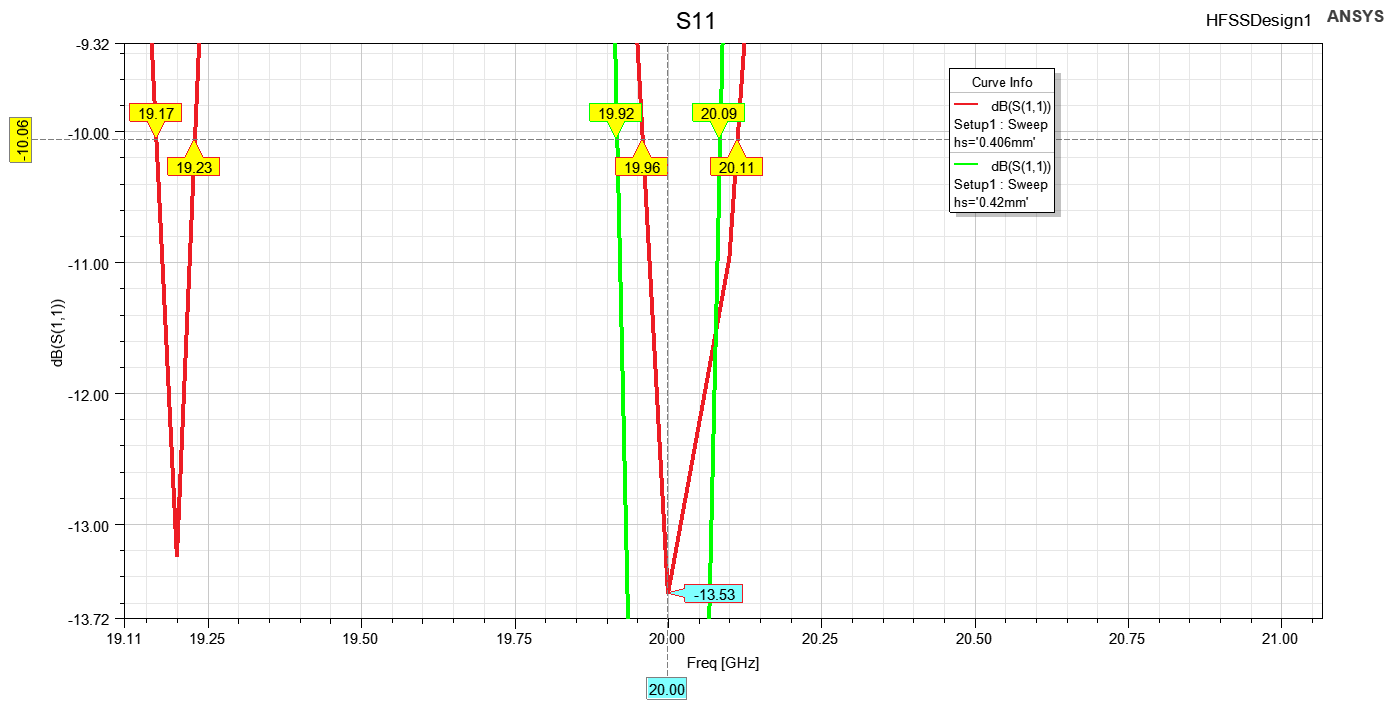
1. **Increasing the substrate height (hs) increases the BW:**

Figure 53 hs increase

|  |  |
| --- | --- |
| hs | BW |
|  |  |
| 0.406 mm | 150MHz |
| 0.42 mm | 170MHz |

As shown in figure 54:

So the BW increased

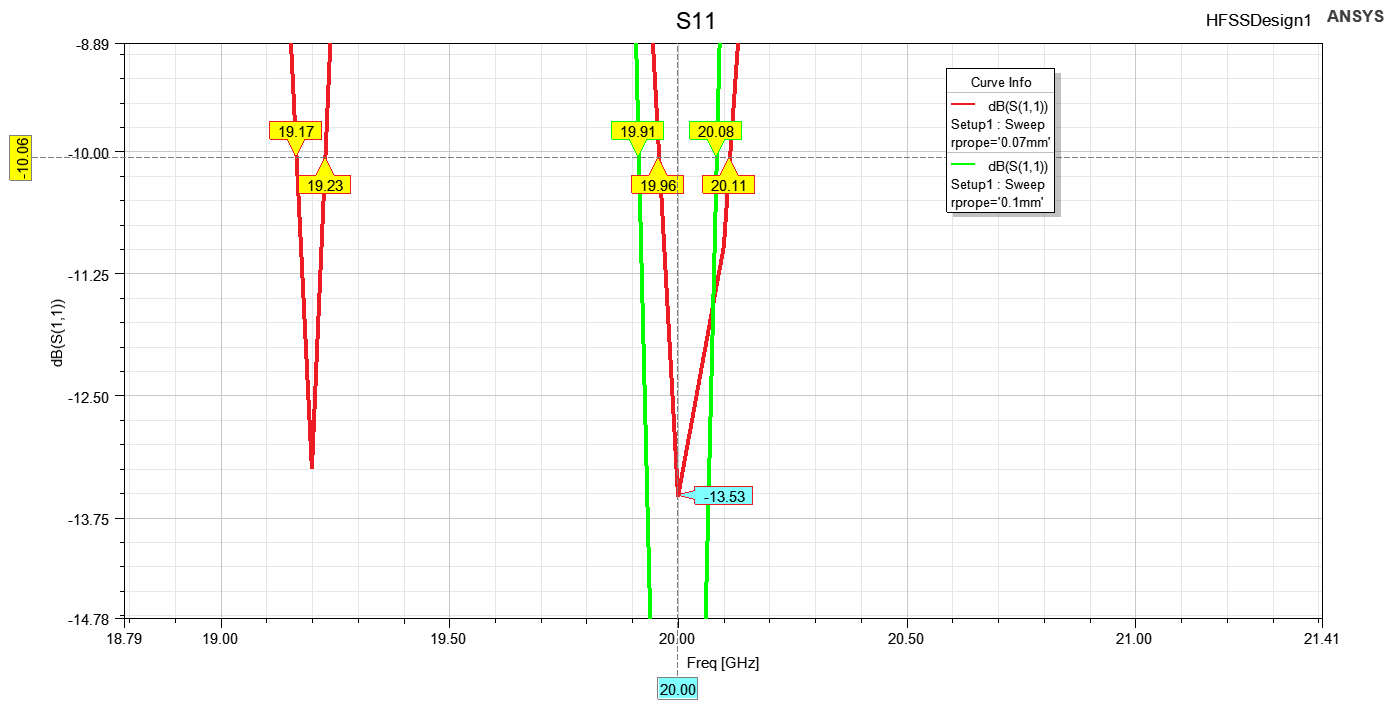
1. **Increasing the probe radius increases the BW:**

Figure 54 rprope increase

As showm in figure 55:

|  |  |
| --- | --- |
| rprope | BW |
| 0.07 mm | 150MHz |
| 0.1 mm | 170MHz |

So the BW increased.

# 4. Conclusion

The project successfully designed and analyzed a 2-element probe-fed microstrip patch antenna operating at 20 GHz. The design achieved the desired specifications with S11 below -10 dB, high gain, and radiation efficiency. Mutual coupling and gain vs. element spacing were thoroughly evaluated, and the results provide valuable insights for future antenna designs.

BW%

# 6. Refrences:

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[5] R. Garg, P. Bhartia, I. Bahl, and A. Ittipiboon, Microstrip Antenna Design Handbook. Norwood, MA, USA: Artech House, 2001, Sec. 9.2.