

**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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# 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

## Benchmark Description

A green and red line

Description automatically generated

Figure 1: dipole antenna designed for verification

* 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.
   * Feed point impedance: Typically designed for 73 Ω in free space.
   * 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. **Radiation Resistance**:
2. **Directivity**:
3. **Radiation Pattern**:
   * E-plane pattern: for .
   * H-plane pattern: for
4. **Input Impedance**:
5. **Gain**:

where is the efficiency of the antenna.

**Results Comparison**

A graph with a red line

Description automatically generated simulated results of the dipole antenna matches theoretical expectations (S11 plot, radiation pattern, and gain).

Figure 2: S11 for dipole antenna for verification

A green and white graph

Description automatically generated

Figure 3: Gain 2D for dipole antenna for verification

A graph with lines and numbers

Description automatically generatedA red and yellow sphere with lines and points

Description automatically generated

Figure 4: Zin for dipole antenna for verification

Figure 5: Gain 3D for dipole antenna for verification

**Conclusion**

* The dipole antenna serves as a reliable reference for verifying the EM simulation tool.

# 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.

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

where:

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

Effective Length:

where:

Effective dielectric constant:

where:

* : Relative permittivity of the substrate

A screenshot of a computer

Description automatically generatedWe used RO4003C dielectric with

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

**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:

​​

A diagram of a rectangular patch

Description automatically generatedDesign of single patch

Figure 6: antenna with probe feeding model

A green rectangle with orange and green rectangles on graph paper

Description automatically generated

Figure 7: 3D patch antenna design

A screenshot of a game

Description automatically generated

Figure 8: bottom view of patch antenna

A line with a green and blue line

Description automatically generated with medium confidence

Figure 9: side view of patch antenna

For designing single patch antenna, we tuned parameters to get reflection coefficient S11 achieving specs

A graph of a graph

Description automatically generated

Figure 10: S11 for single Patch antenna

From the above figure we succeeded to tuned parameters and achieve minimum s11 at operating frequency 20 GHz and we have bandwidth (range of frequency where S11<-10 dB) as shown

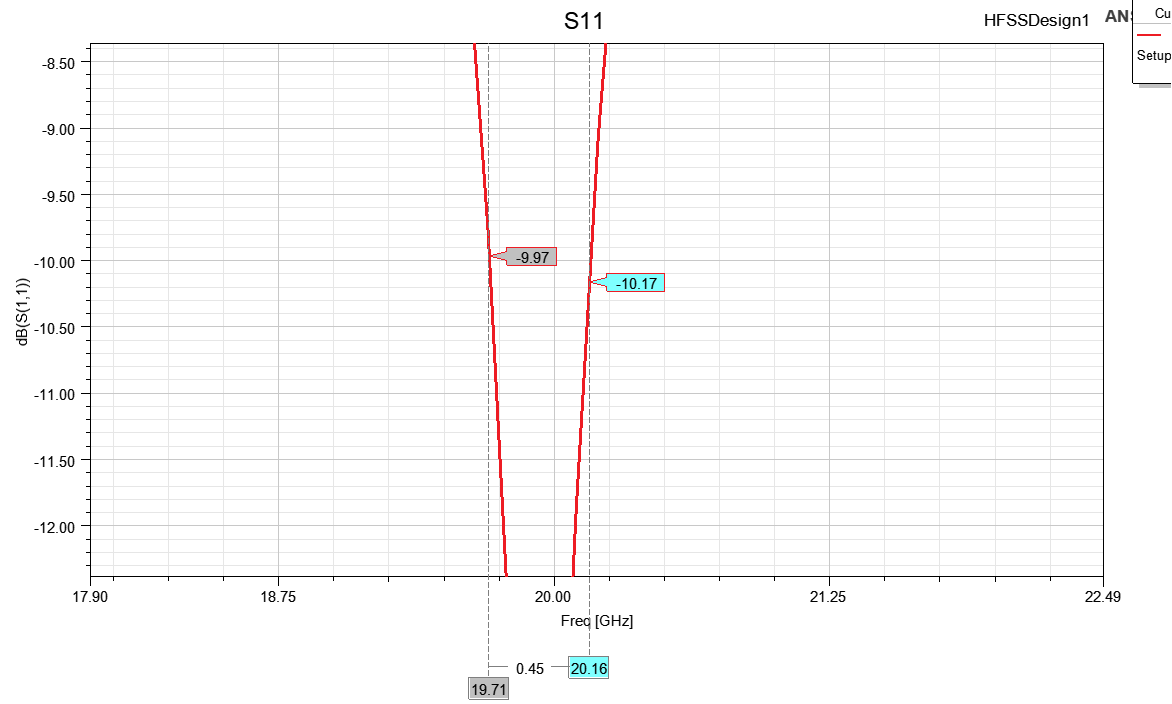


Figure 11: Bandwidth where S11<-10 dB

A diagram of a circle with a smiley face drawn on it

Description automatically generatedA graph with a red line

Description automatically generated

Figure 12: smith chart for single Patch

Figure 13: VSWR = 1.421 at 20 GHz for single patch antenna

Bandwidth achieved for VSWR=1.421

A graph with a red line

Description automatically generatedFor proper feeding from the above figure9, we found that is matching impedance required at 20GHz.A graph of a graph

Description automatically generated

Figure 14: Xfeed for single patch antenna

Figure 15: Zin for single Patch antenna at 20GHz

A graph with a red line

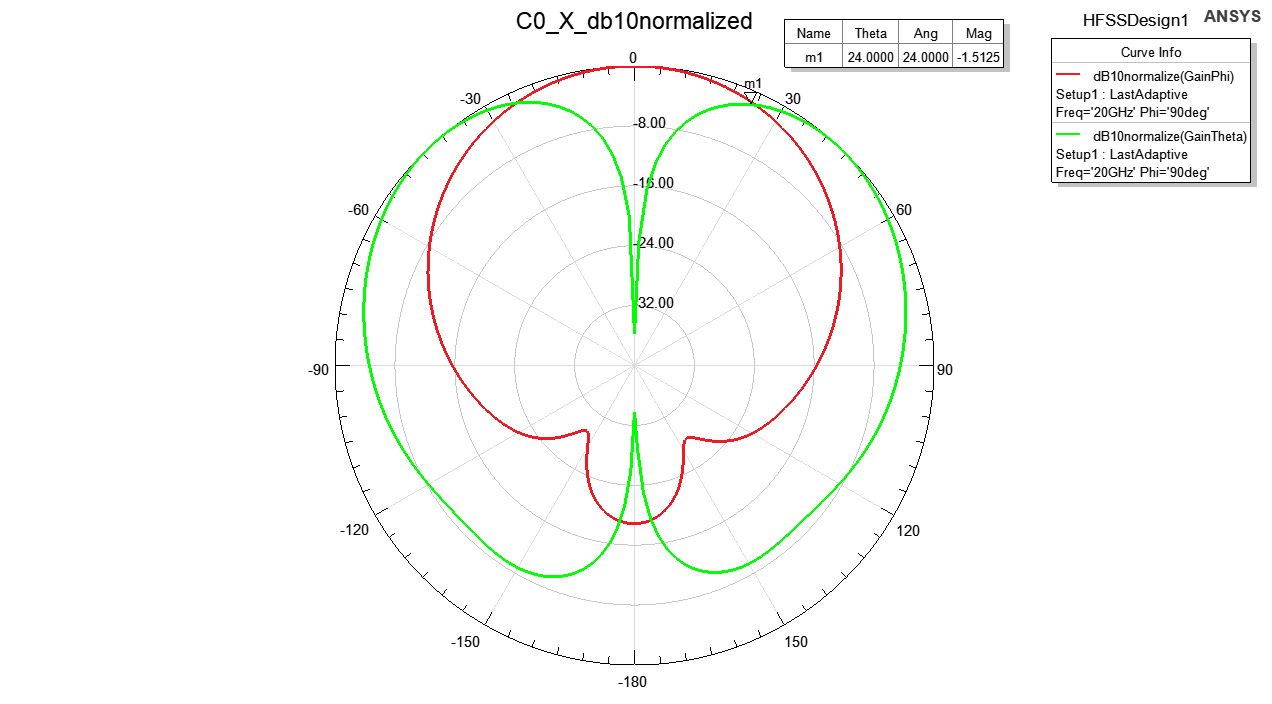
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Figure 16: Yfeed for single patch antenna

A graph with a red circle

Description automatically generatedRadiation patterns

Figure 17: Electric Field Radiation for single patch antenna



A circular pattern with red lines

Description automatically generatedA graph of a graph

Description automatically generated

Figure 18: magnetic field radiation for single patch antenna

Figure 19: Co-polarization and cross-polarization patterns in the E- and H-planes.

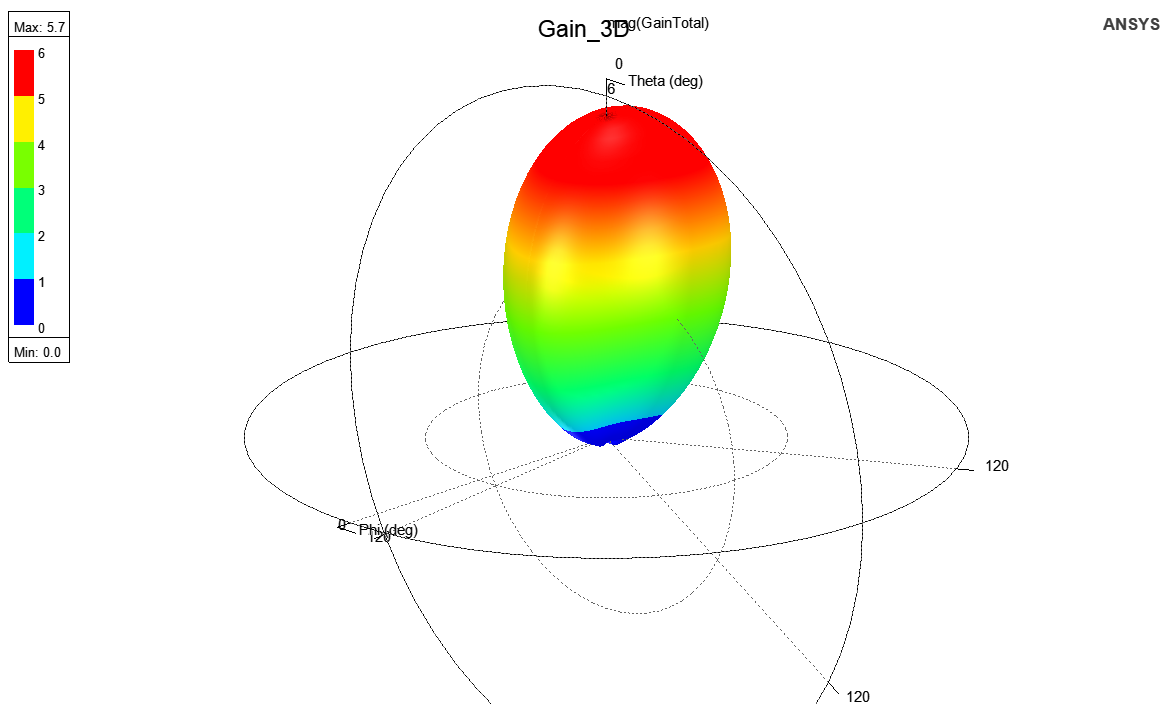
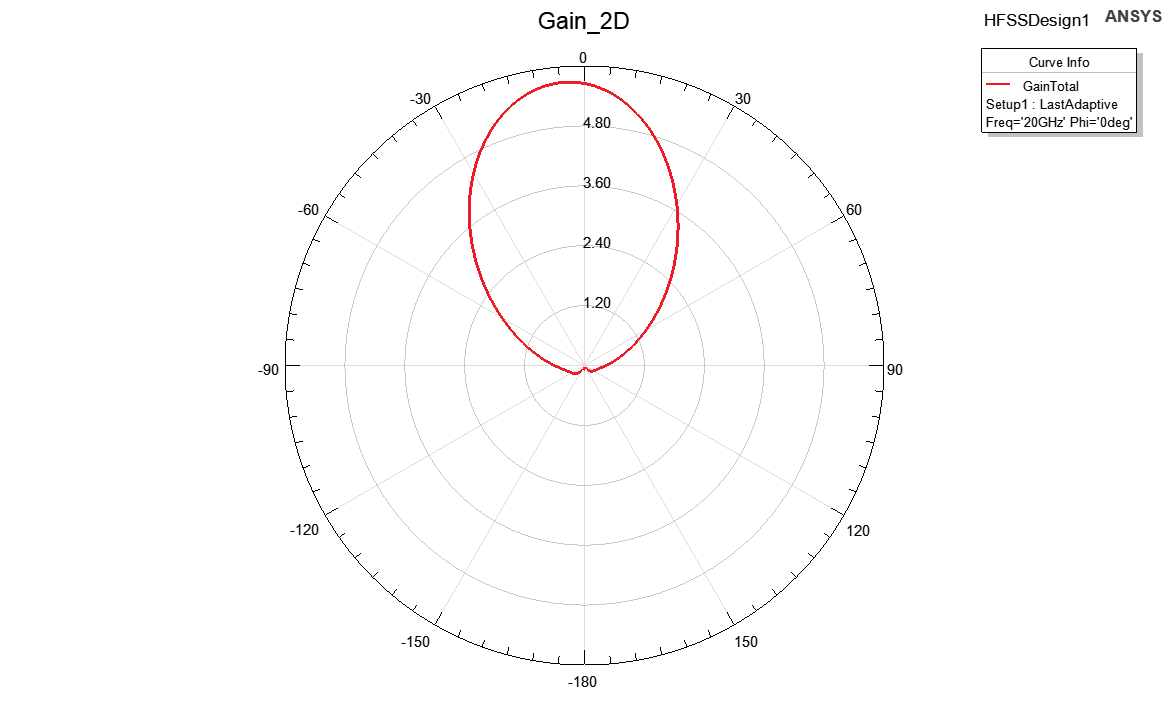


Figure 20: Gain 2D for single patch antenna

Figure 21: Gain 3D for single 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 | 7.609mm | Ground plane width |
| Ls | Mm | 6.475mm | Ground plane length |
| xsub | Mm | -3.2375mm | Substrate center x-offset |
| ysub | Mm | -3.8045mm | Substrate center y-offset |
| 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 |
| Lair | Mm | 16.475mm | Airbox length |
| Wair | Mm | 17.609mm | Airbox width |
| xair | Mm | 8.2375mm | Airbox x-center offset |
| yair | Mm | 8.8045mm | Airbox y-center offset |
| hair | Mm | 5mm | Airbox height |
| Yfeed | Mm | 0mm | Feed point y-offset |
| Xp | Mm | -1.8165mm | Patch x-origin |
| Yp | Mm | -2.5865mm | Patch y-origin |
| Hgnd | Mm | -0.032mm | Ground plane height |

Figure 22: Results for one patch antenna

A computer generated image of a rectangular object

Description automatically generatedBut we 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 23: Two Patch antenna array

A green leaf on a line

Description automatically generated

Figure 24: Two Patch side view

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

A graph with red lines and numbers

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

Figure 25: S11 for Two patches

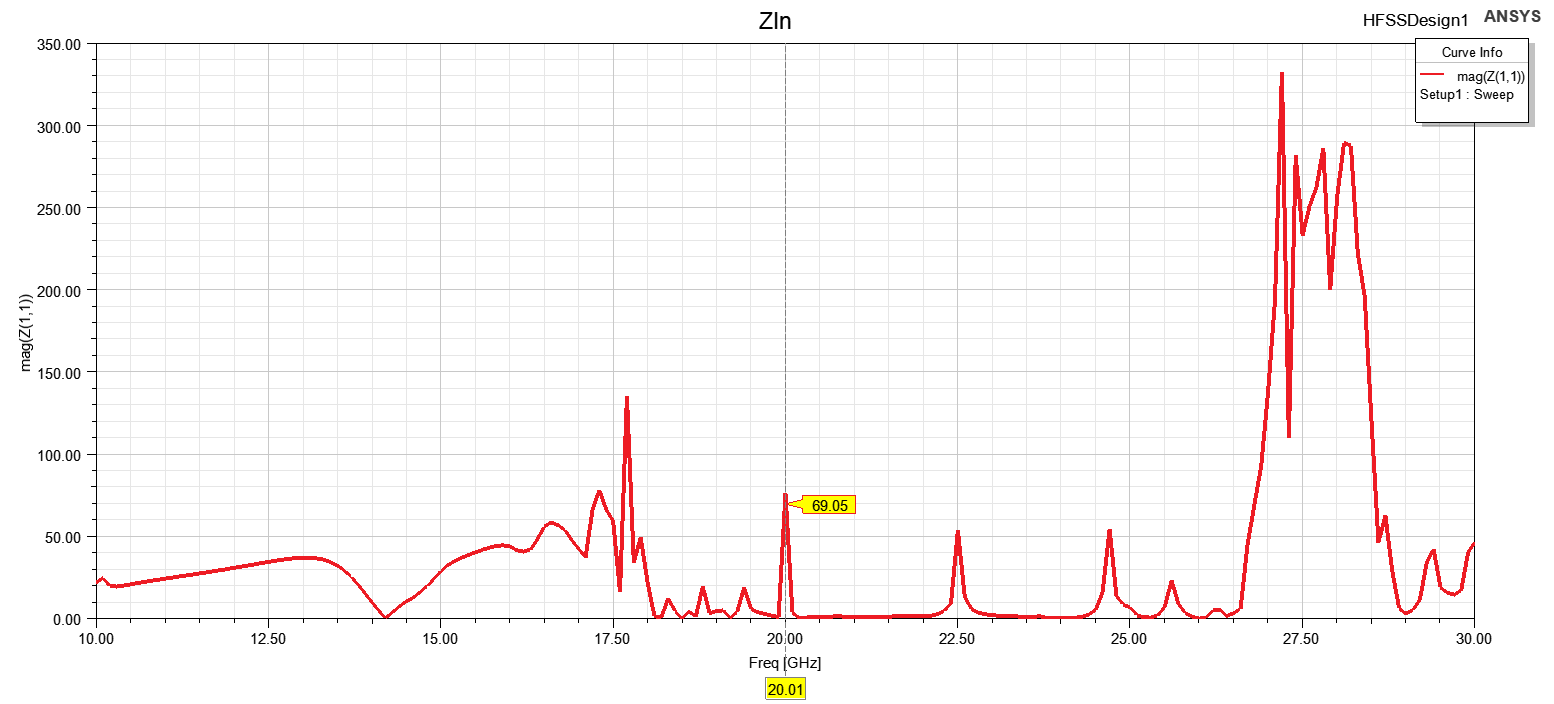


Figure 26: Zin for two Patches at 20 GHz

A graph with red lines

Description automatically generated

Figure 27: VSWR for first Patch

A graph of a heart rate

Description automatically generated

Figure 28: VSWR for second Patch

A graph of a graph

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 it

Figure 29: S21 Vs Frequency

A graph with different colored lines

Description automatically generated

Figure 30: S21 sweep Vs frequency by changing dp

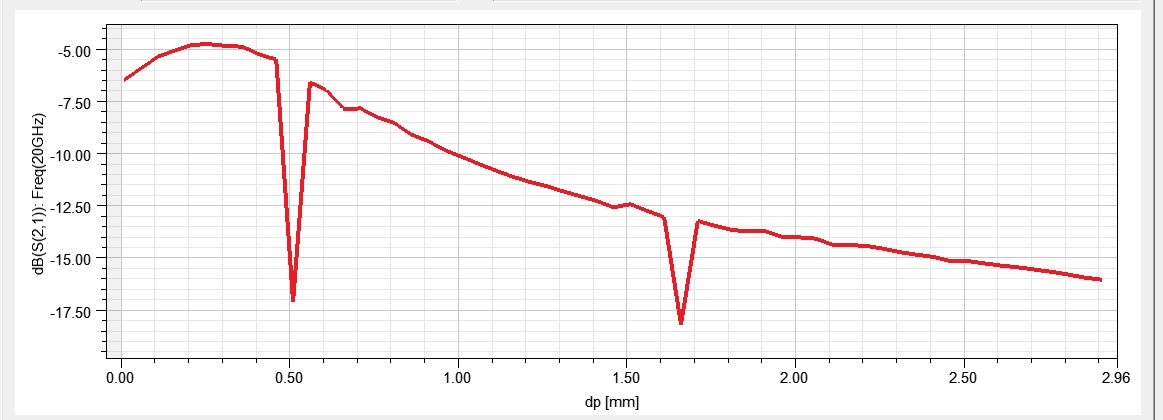
we found that distance between two patches (dp=0.306 mm) to keep S11< -11 dB.

Figure 31: S21 Vs Distance between two patches

A red circle with a number on it

Description automatically generated with medium confidence

Figure 32: Electric field radiation of two patches

A red circle with numbers

Description automatically generated

Figure 33: magnetic pattern for two patches

A graph of a circular graph

Description automatically generated with medium confidence

Figure 34: Co-polarization and cross-polarization patterns in the E- and H-planes.

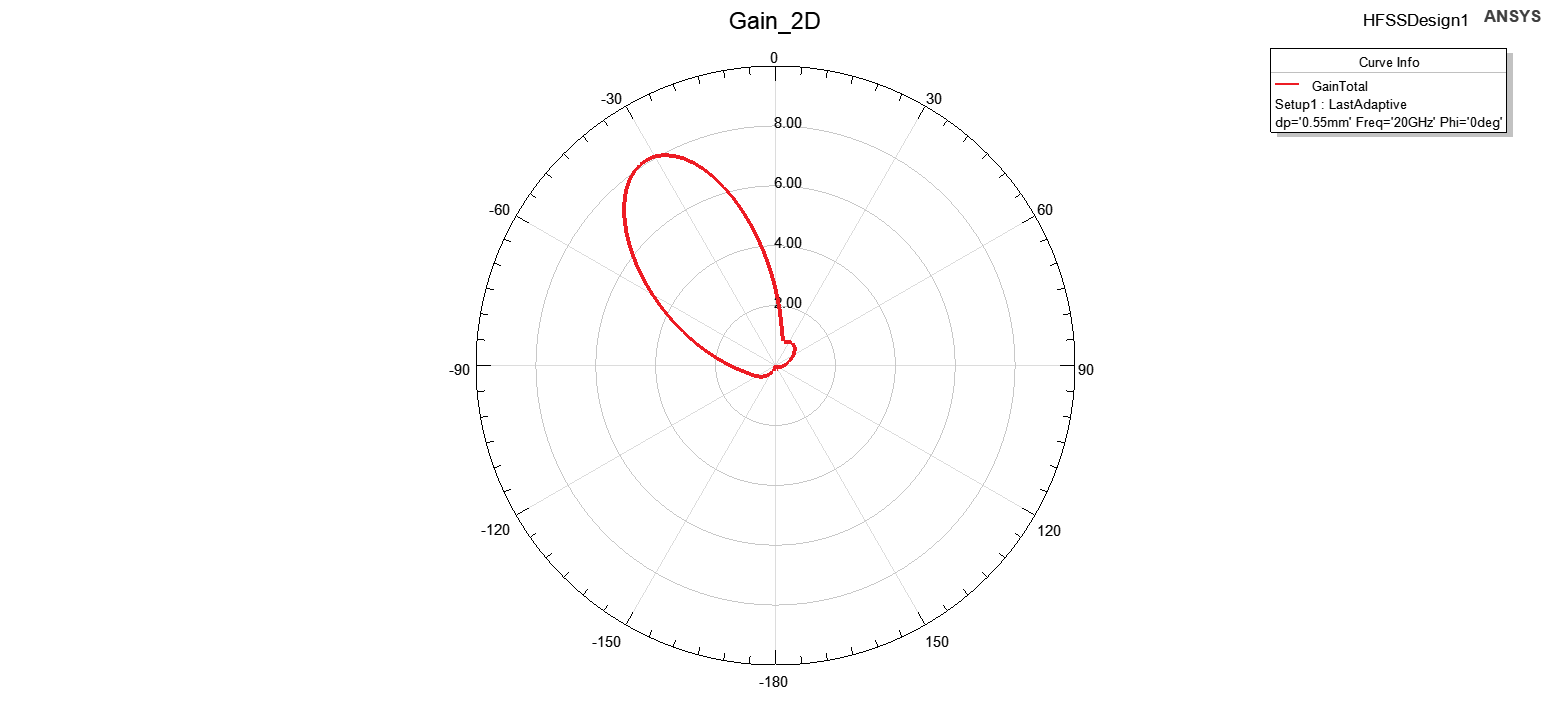


Figure 35: Gain 2D for two patches

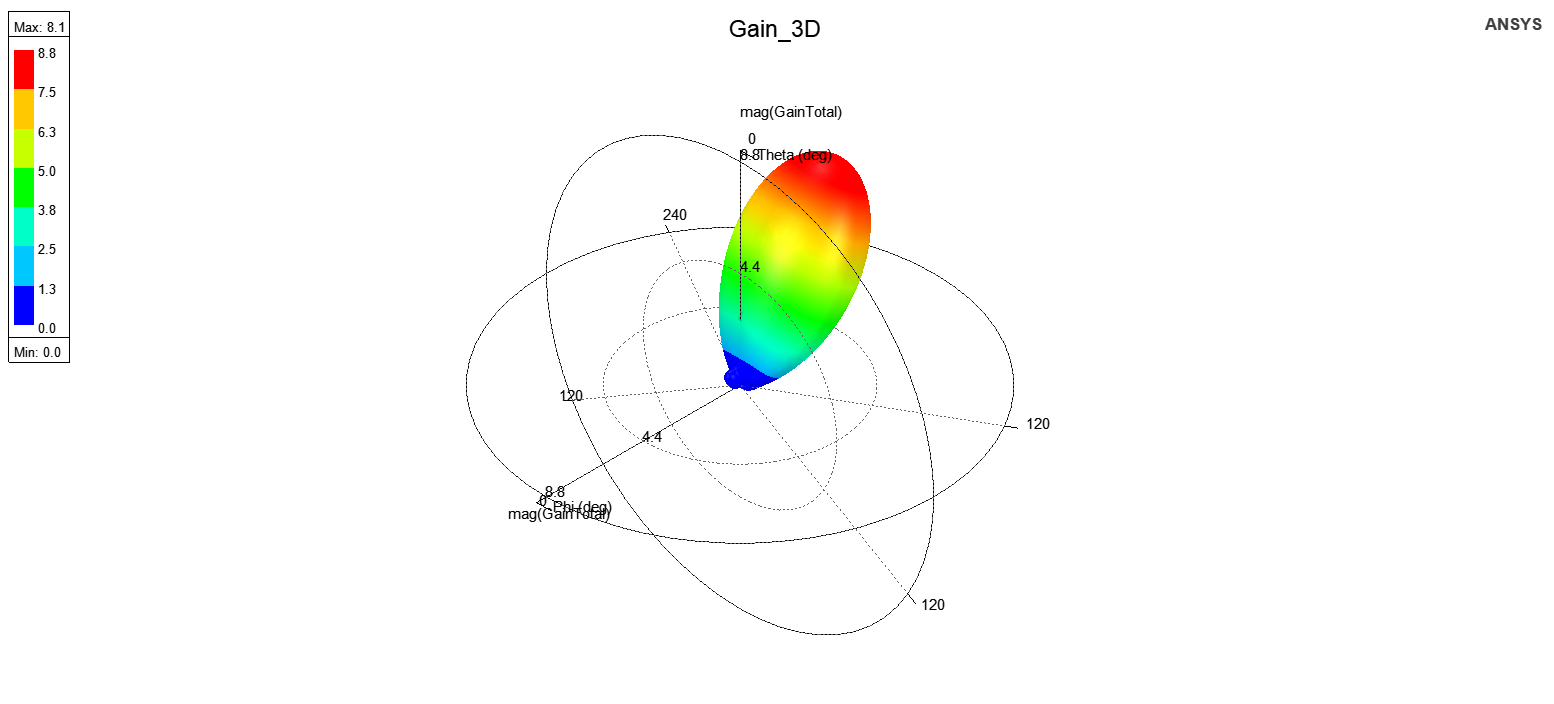
as shown we noticed that gain of two patch antennas is larger than single patch antenna however it is inclined due interference (mutual coupling between two patches)

Figure 36: Gain 3D for two patches

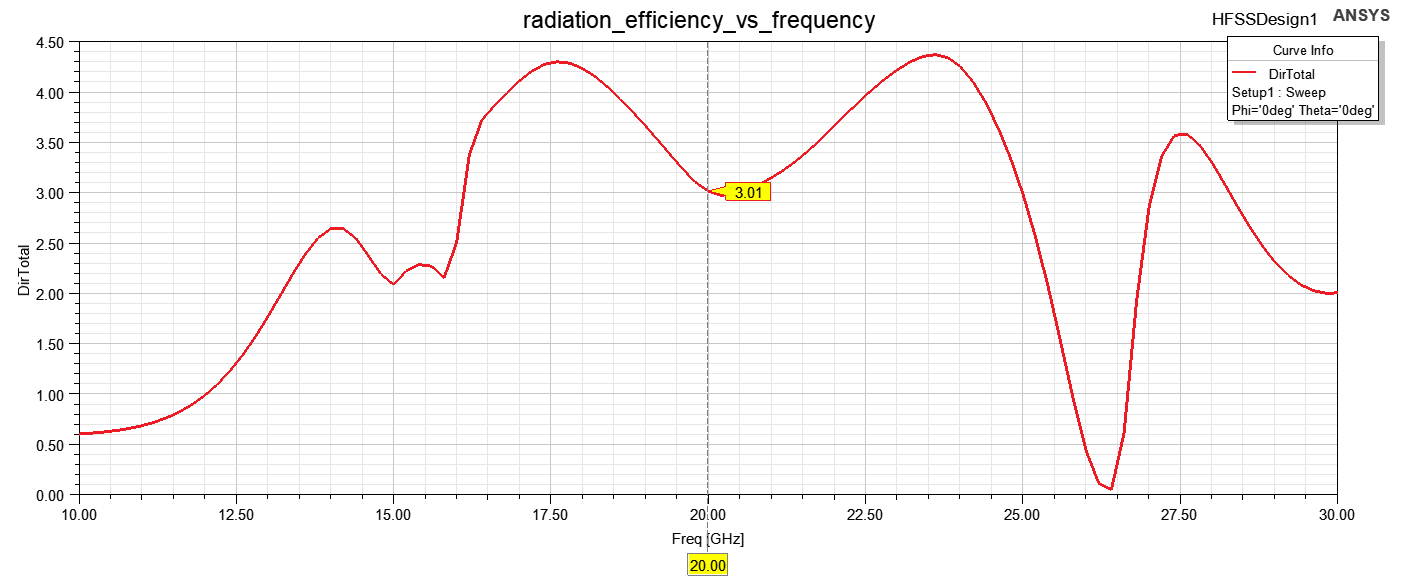
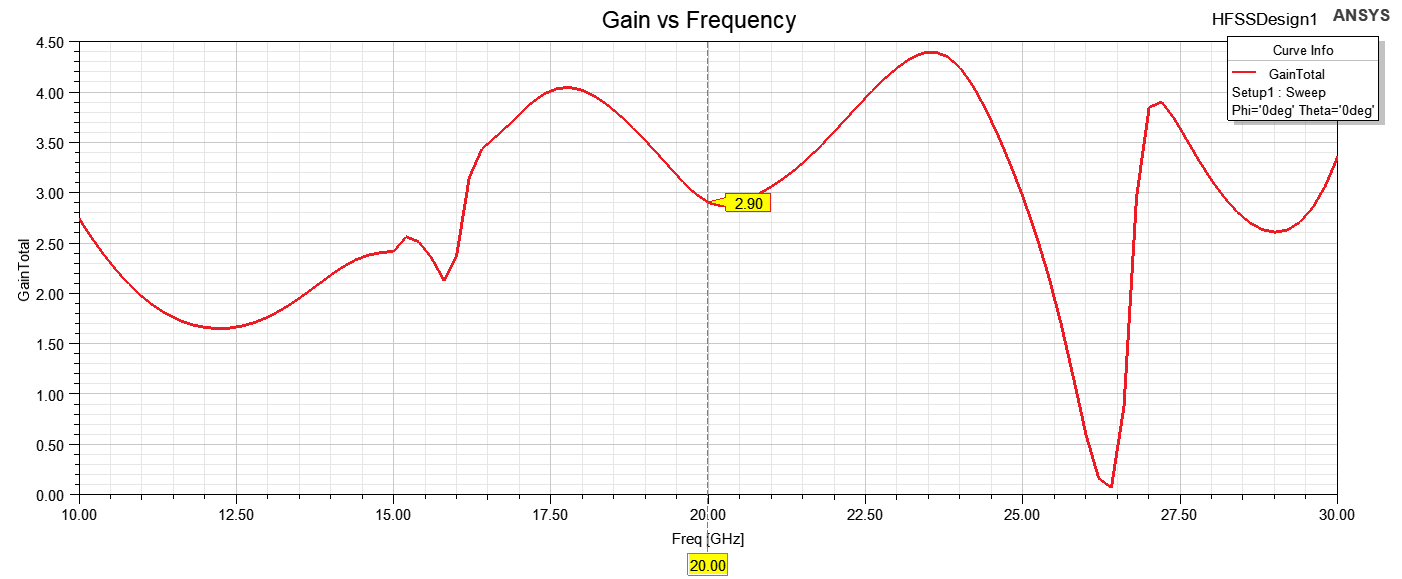


Figure 37: Gain Vs Frequency

Figure 38: Radiation Efficiency Vs Frequency

## Bandwidth Enhancement Techniques:

* + **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.

Adding Feeding Network for Two Patch antennas

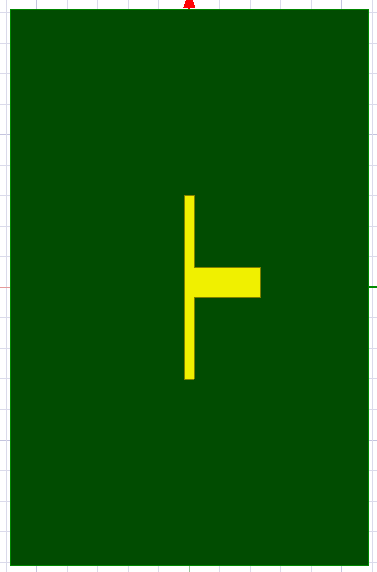
We got Zin=69.05 so for proper feeding and enhancing bandwidth we designed a transmission line T-section as shown below and we sweept on it’s dimensions till we achieved requirement.

Figure 39: T-Section transmission line

A graph of a graph

Description automatically generatedA graph with red lines

Description automatically generated

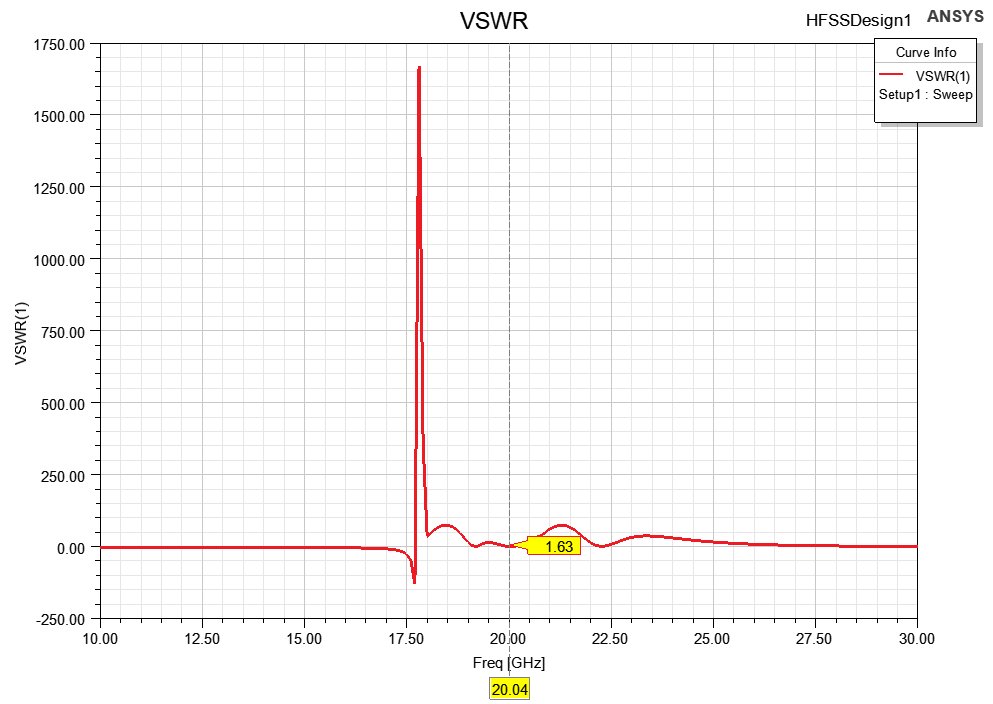
Figure 40: S11 after adding T-section TL showing enhancement in BW

Figure 41: Zin after adding T-section transmission line

From the previous figure we enhanced bandwidth to be more wide from 19.23 GHz to 20.11 GHz

Where S11 is smaller than -10 dB.

Figure 42: VSWR after adding feeding network



A graph with a red line in the shape of a flower

Description automatically generatedA graph with a red circle

Description automatically generated

Figure 43: magnetic Field Radiation of 2 antenna design probe feed

Figure 44: Electric Field Radiation of 2 antenna design probe feed

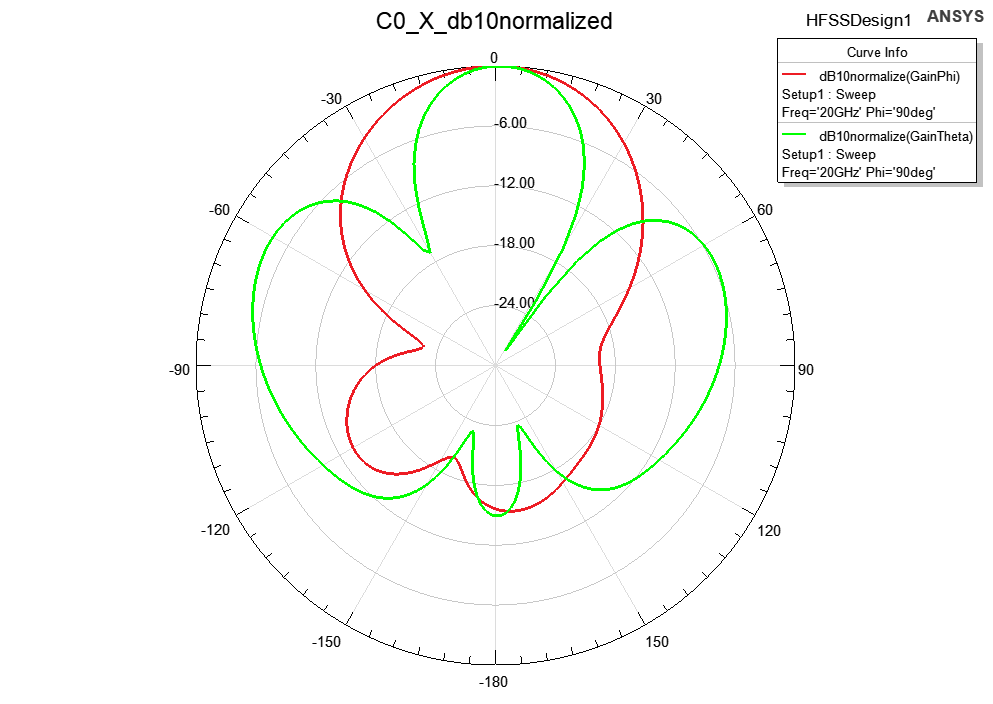


Figure 45: Co-polarization and cross-polarization patterns in the E- and H-planes for 2 antenna array probe feed

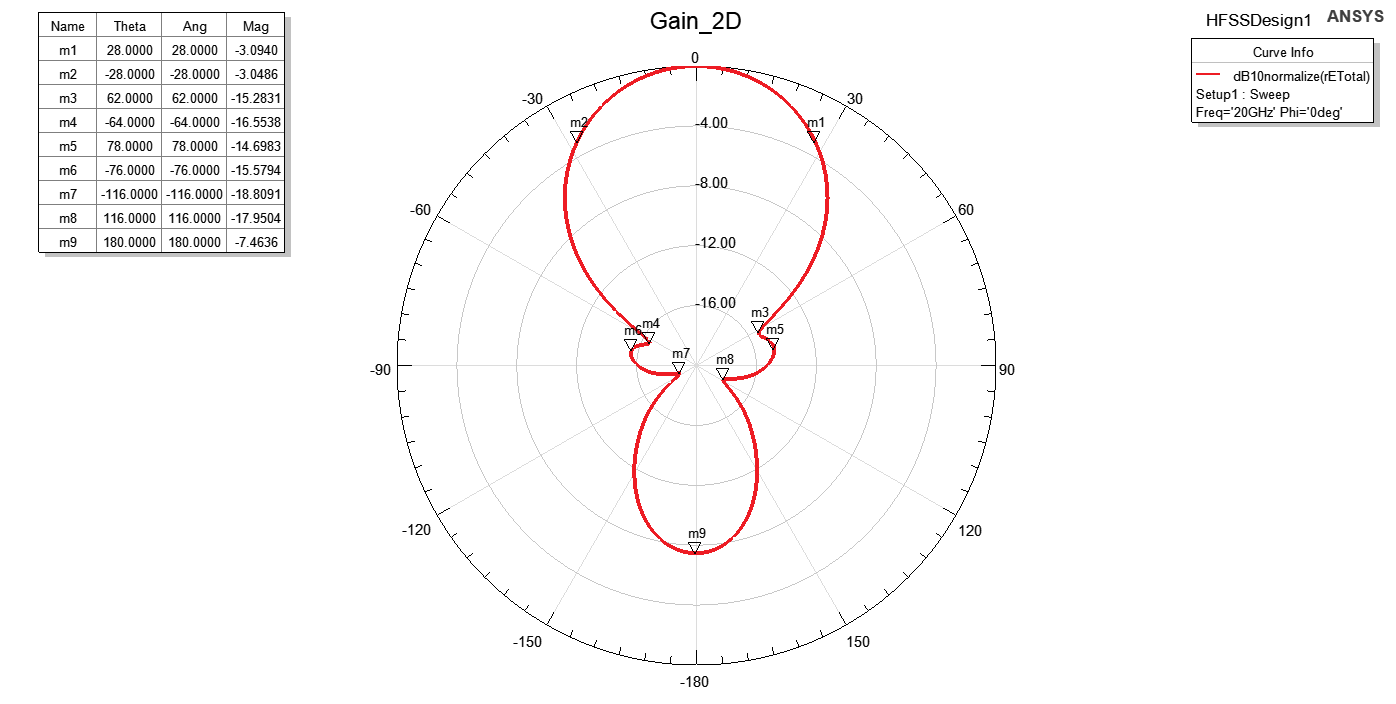


Figure 46: gain 2D for 2 antenna array probe feed

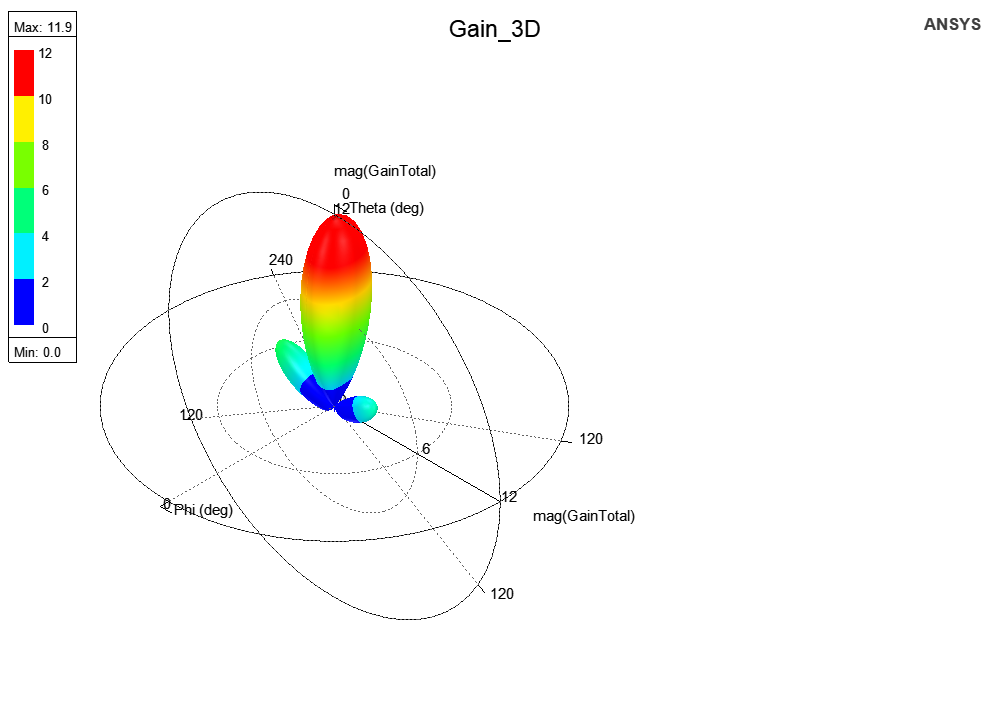


Figure 47: Gain 3D for 2 antenna array probe feed

|  |  |  |  |
| --- | --- | --- | --- |
| Name | Unit | "Evaluated Value" | Description |
| Lp | mm | 5.78mm | Patch length |
| Wp | mm | 7.54mm | Patch width |
| hs | mm | 0.406mm | Substrate height |
| Ws | mm | 11.736mm | Ground plane width |
| Ls | mm | 18.206mm | Ground plane length |
| xsub | mm | -9.103mm | Substrate center x-offset |
| ysub | mm | -5.868mm | Substrate center y-offset |
| xfeed | mm | 1.1mm | Feed point x-offset |
| dp | mm | 3.5mm | Patch offset parameter |
| rcoax | mm | 0.16mm | Coaxial feed radius |
| hcoax | mm | 0.203mm | Coaxial feed height |
| rprope | mm | 0.07mm | Probe radius |
| Lair | mm | 28.206mm | Airbox length |
| Wair | mm | 21.736mm | Airbox width |
| xair | mm | 14.103mm | Airbox x-center offset |
| yair | mm | 10.868mm | Airbox y-center offset |
| hair | mm | 5mm | Airbox height |
| yfeed | mm | 0mm | Feed point y-offset |
| xp | mm | 1.75mm | Patch x-origin |
| yp | mm | -3.77mm | Patch y-origin |
| 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 |

Figure 48: table of final results

# 3. Results and 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.

## 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.

# 4. Final Design Layout

The final layout of the antenna, including the matching network and array configuration, is shown below:

# 5. 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.