1. Design and Simulate an Insertion Power Patch Antenna

1.1. Introduction and Objective

This report documents the process of designing, simulating, and analyzing a microstrip patch antenna. The primary objective of the exercise is to create an antenna with effective impedance matching using the insertion feed technique (also known as *inset feed*).

This power supply methodology was chosen for its ability to achieve optimal adaptation without the need for additional components such as a quarter-wavelength (λ/4) impedance transformer, the use of which can limit the antenna's operating bandwidth.

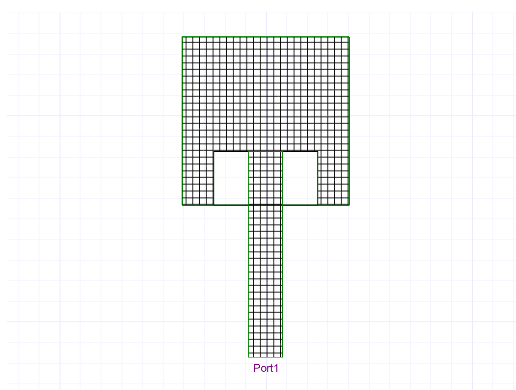
The evaluation of the project's performance is based on the analysis of the following parameters:

- **Return Loss (S_11):** To quantify impedance matching.
- Input impedance (Real Part and Imaginary Part): to check the resonance conditions.

1.2. Design methodology

1.2.1. Antenna structure

The basic structure of the antenna consists of a square-shaped radiating element (patch), positioned above a ground plane and separated from it by a dielectric substrate (not detailed in the files). Power is supplied by a microstrip line.



1.2.2. Inset Feed Technology

The impedance matching between the power supply line (with a characteristic impedance of 50 Ω) and the patch was achieved by the insertion technique. The input impedance of a patch antenna varies along its surface: it is maximum at the edges and zero in the center. By making two symmetrical notches at the junction point, as shown in the diagram below, it is possible to "penetrate" the power line inside the patch.

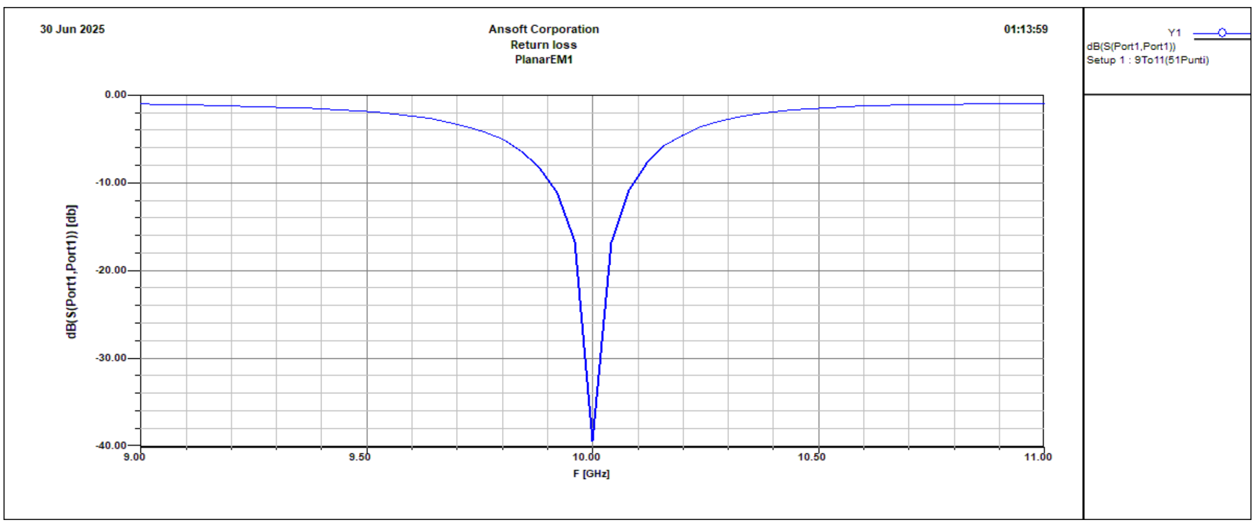
This allows the feed point to be moved to an indoor position where the antenna impedance is precisely 50 Ω. The **depth of the inlet** then becomes the critical design parameter to be modulated to achieve an optimal fit.

1.3. Analysis of simulation results

Simulations were conducted to evaluate performance. To obtain an accurate characterization of the radiating element alone, a **de-embedding** technique was applied that mathematically removes the effect of the 10 mm feed line used to excite the structure.

1.3.1. Impedance Matching (Return Loss)

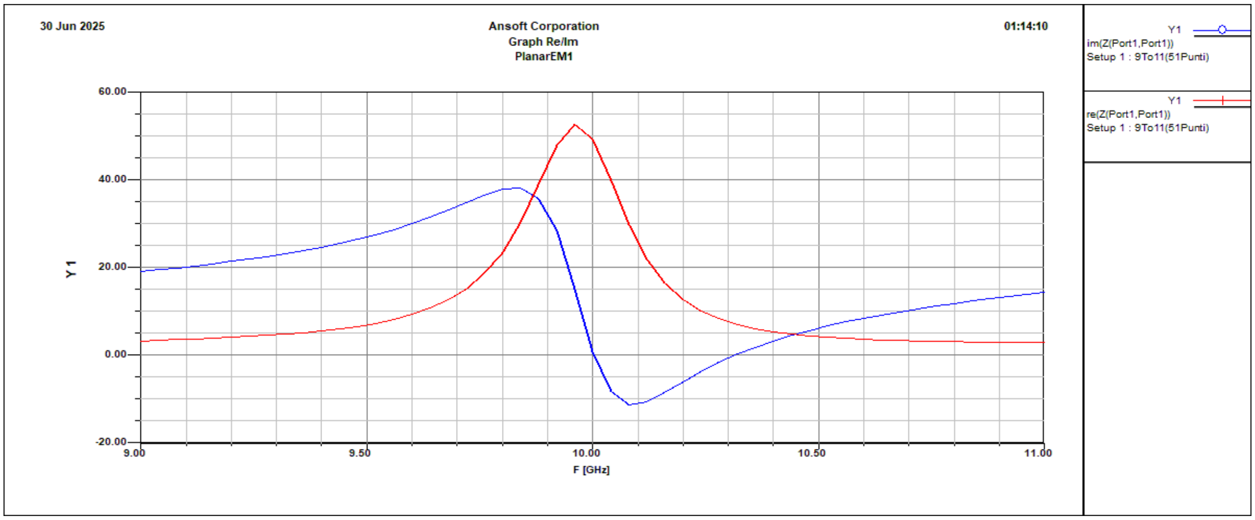
The metric graph shows the efficiency of the power coupling.



- **Considerations:** The chart shows an excellent fit. A well-defined resonance peak is observed at the frequency of 10.05 GHz. At this frequency, the return loss value is approximately -28 dB, indicating that only a minimal fraction of the power (less than 0.2%) is reflected back to the generator. This confirms the success of the fitting technique.

1.3.2. Input impedance

Analysis of the real and imagined part of the input impedance provides further confirmation of resonance and adaptation conditions.



- **Considerations:** The graph shows that at the resonant frequency:
  - The **imaginary part** (blue curve, Im(Z)) crosses the zero axis. This condition defines the resonance of the system.
  - At the same time, the **real part** (red curve, Re(Z)) takes on a value very close to 50 Ω.

The simultaneous occurrence of these two conditions at the same frequency (about 10.05 GHz) is the definitive proof of a very good impedance match.

The simulation results show that the project has successfully achieved its objectives. The use of the insertion power supply technique made it possible to obtain a patch antenna with excellent adaptation at 50 Ω to the operating frequency of 10.05 GHz, without the need for external matching elements.

It was also observed that patch size is a key control parameter for the resonant frequency, following the expected physical relationship:

- **As the patch size increases** , the resonant frequency decreases.
- **As the patch size decreases** , the resonant frequency increases.

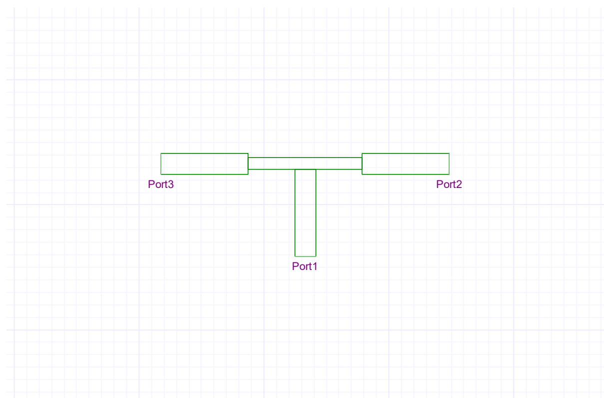
2. Analysis of a T-Junction

2.1. Objective

The goal is the design and analysis of the first section of a power divider, made by means of a T-Junction in microstrip technology. The analysis focuses on the evaluation of two fundamental parameters for the characterization of the component: the power division between the output ports and the Return Loss at the input port, which indicates the degree of adaptation.

2.2. Description of the structure

The structure being analyzed is a three-port passive component, as shown in the layout geometry.



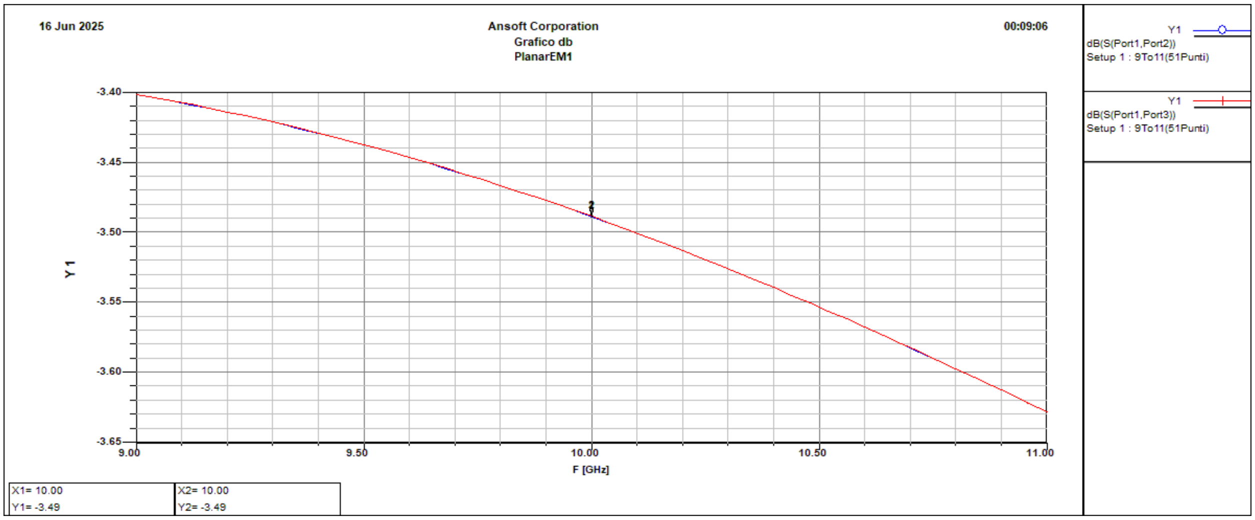
Port 1 serves as the signal input, while ports 2 and 3 represent the outputs. The working principle of a T-Junction is to split the input signal strength into two lower power signals on the output ports. The physical size of the splice branches (their length and width) is critical, as it determines the characteristic impedance and phase of the signal, directly affecting the performance of the device at the desired working frequency.

2.3. Analyzing simulation results

Electromagnetic simulations were performed to characterize the behavior of the device over a frequency range. The main results are presented in the graphs below.

2.3.1. Power Division (S21 & S31 Parameters)

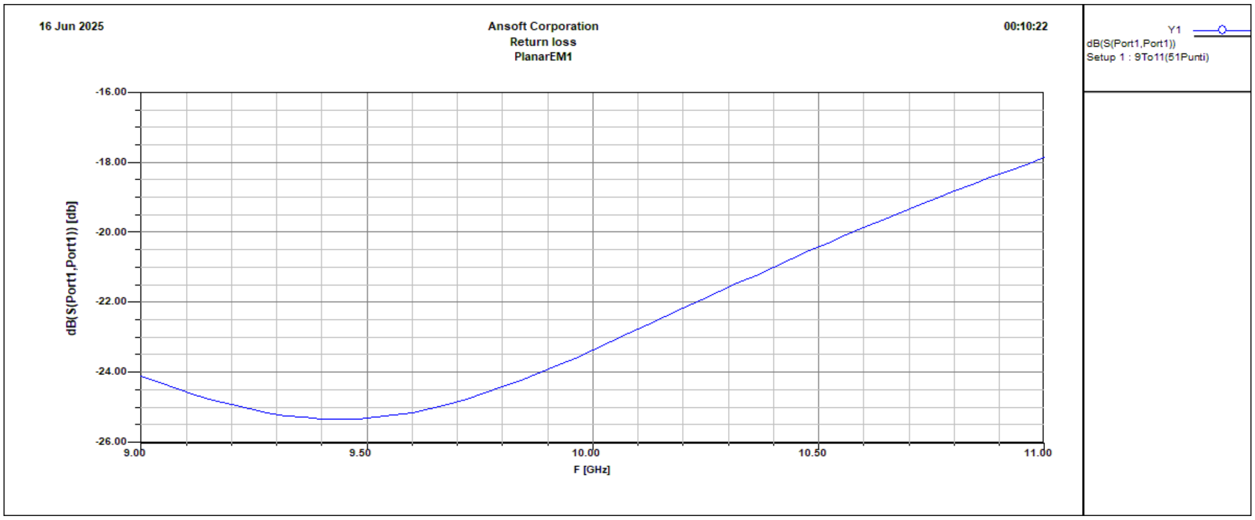
The first graph shows the response of the system in terms of transmission parameters S21 (Port 1 to Port 2) and S31 (Port 1 to Port 3), expressed in dB. These parameters quantify how much power is transferred from the input to the outputs.



- **Result:** At the design frequency of 10 GHz, the measured attenuation value is approximately -3.49 dB.
- **Considerations:** In an ideal, lossless, and perfectly matched power divider, the input power would be divided equally between the two outputs, resulting in a transmit value of exactly -3 dB for each port. The value obtained of -3.49 dB is very close to the theoretical one, indicating a good efficiency in the power division. The 0.49 dB deviation is attributable to material losses, reflections, and other non-ideal effects intrinsic to the physical structure. Achieving an exact value of -3 dB is extremely complex, and for most applications, a result like this is considered more than acceptable.

2.4. Return Loss (Parameter S11)

The second chart analyzes the Return Loss at the entry port (Port 1), represented by the S11 parameter in dB. This parameter is a key indicator of port impedance matching: lower (i.e. more negative) values indicate that less power is reflected back to the generator and, consequently, better coupling.



- **Result:** At the frequency of 10 GHz, the value of S11 is -23 dB.
- **Considerations:** A value of -23 dB is generally considered a good matching result, as it means that less than 1% of the incident power is reflected. However, if you look at the trend of the graph, you can see that the optimal fit point (the minimum of the curve) is not at the design frequency. The minimum of the Return Loss occurs at about 9.50 GHz, where it reaches an even better value of about -25 dB.

The designed T-Junction demonstrates proper operation as a power divider, with a signal split close to ideal. However, the Return Loss analysis shows a misalignment between the target working frequency (10 GHz) and the optimal matching frequency (9.50 GHz).

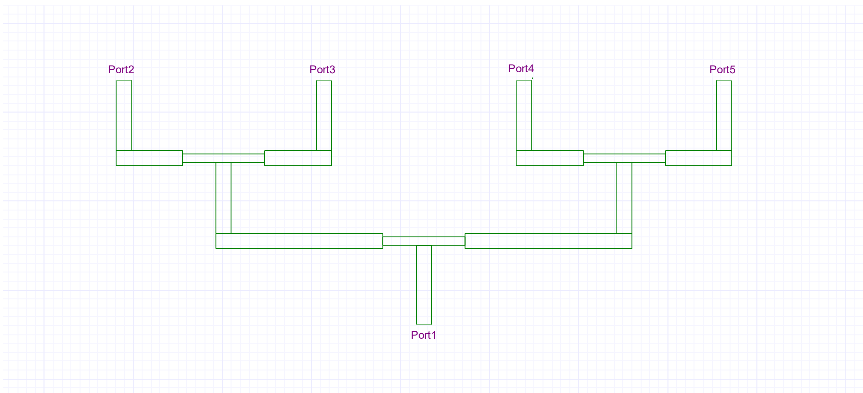
3. Design and analysis of a 4-way power divider in microstrip technology

3.1. Introduction and objective of the project

The purpose of this technical report is to analyze the design and simulation results of a passive power divider. The primary objective of the exercise, as stated in the paper, was the design of a circuit capable of splitting an input power over four output ports. This type of component is critical in numerous radio frequency and microwave systems, such as power networks for antenna arrays, signal distribution systems, and test and measurement equipment. The analysis is based on the provided simulation graphs, which characterize the performance of the device over a frequency range of 9.0 to 11.0 GHz.

3.2. Description of the designed circuit

The designed component is a 4-way power divider that uses a "tree" (or corporate) power supply topology. Made of microstrip technology, the circuit is composed of a single input port (Port 1) which, through a series of T-shaped forks, distributes the signal to four symmetrical output ports (Port 2, Port 3, Port 4, Port 5).



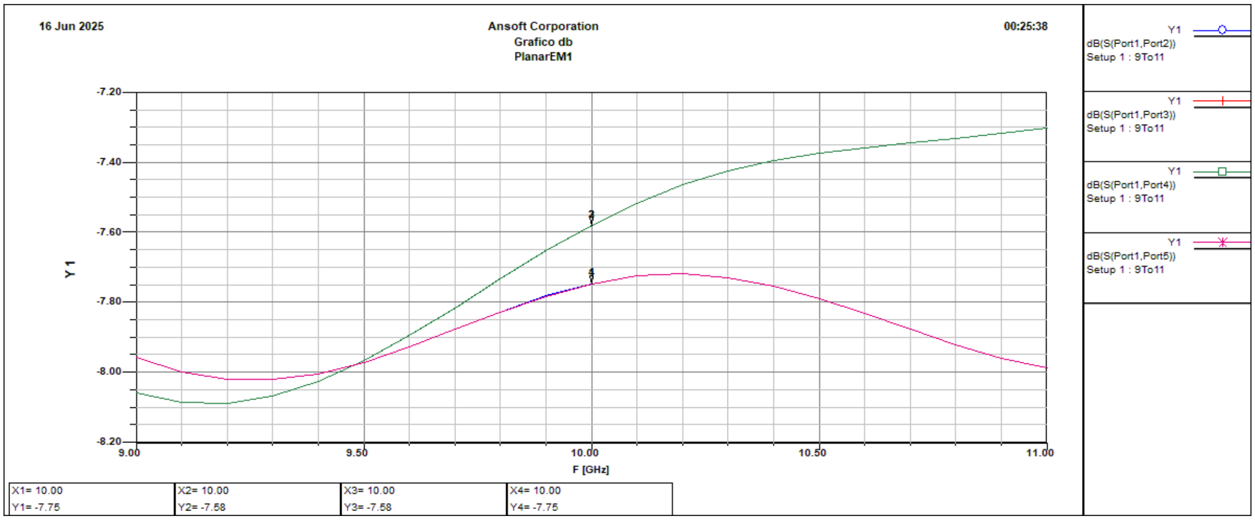
The key feature of the design is its **geometric symmetry**. This choice ensures that the electrical path from the input to each of the outputs is identical, a necessary condition for achieving an equal power division and in-phase signals on all outputs. The different widths of the transmission lines have been calculated to obtain specific characteristic impedances, in order to achieve a correct impedance adaptation throughout the network and minimize power reflections.

3.3. Analysis of simulation results

The results of the electromagnetic simulation characterize the performance of the divider in terms of power division, phase and impedance matching.

3.3.1. Power Division (Transmission Parameters)

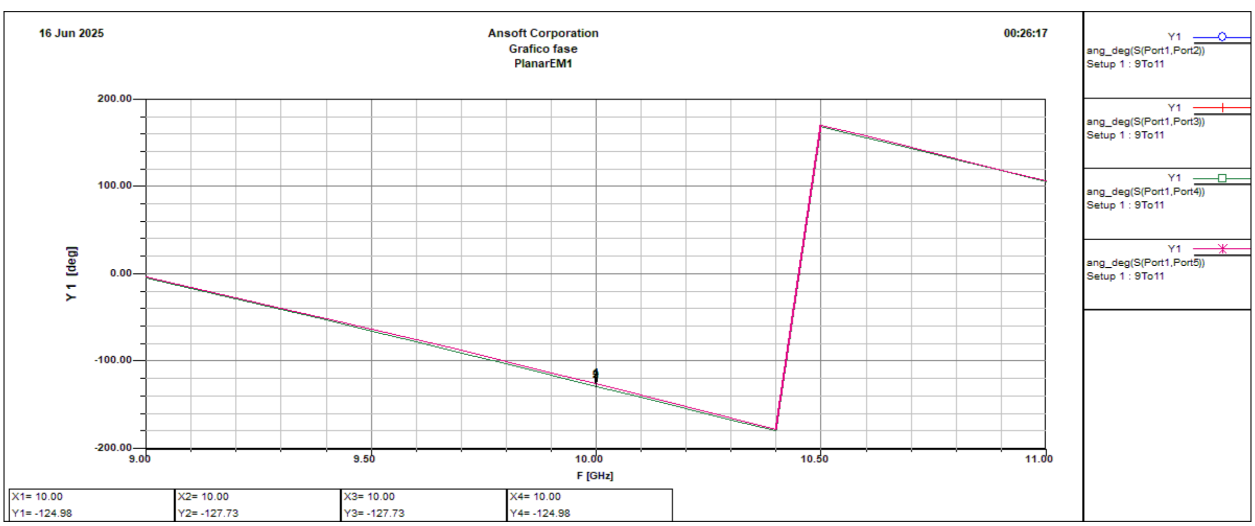
The dB response graph shows the transmission parameters (Sx1) from the input to the outputs.



Ideally, a lossless 4-way divider should feature an attenuation of -6 dB on each output. The simulation shows a value of about **-7.5 dB at the 10 GHz frequency**. The difference of 1.5 dB compared to the ideal case represents the **total insertion losses of** the device, due to both the intrinsic losses of the material (conductors and dielectric) and the losses due to mismatch. As expected by the symmetrical structure, the port responses are equal in pairs, confirming an even distribution of power.

3.3.2. In-phase behavior

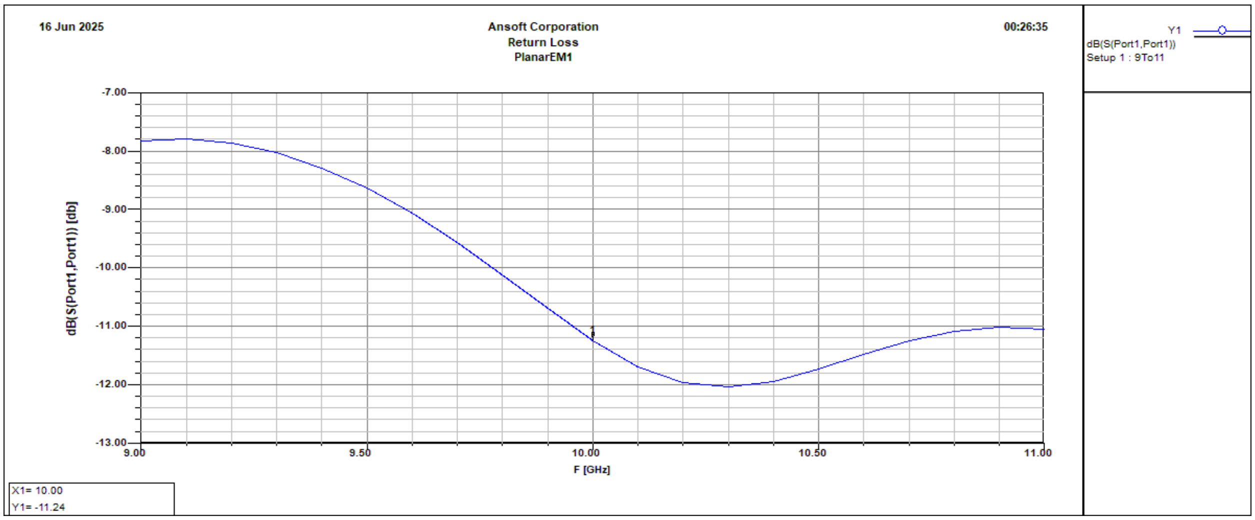
Phase graph analysis is a crucial point in design validation.



The phase curves of the signals at the four output ports are almost perfectly overlapped throughout the analyzed frequency range. This result confirms that the output signals are **in phase** with each other, a desired and expected characteristic for this topology, as correctly pointed out in the report's considerations ("The gates all cover the same phase and do not have phase shifts between them").

3.3.3. Impedance Matching (Return Losses)

Return Loss, represented by the S11 parameter in dB, measures the effectiveness of impedance matching on the input port.



A low (very negative) value is an indication of a good fit. The simulation shows a value of **-11.24 dB at 10 GHz**. Although functional, this result is considered suboptimal for high-performance applications (where values below -15 dB are sought). A value of -11.24 dB indicates that approximately 7.5% of the incident power is reflected back to the generator, a factor that can degrade the overall performance of the system in which the component is inserted.

3.4. Areas for improvement and design considerations

The analysis of the results, and the considerations of the report themselves, clearly identify the main area for improvement. Performance, especially return losses, is limited by the presence of discontinuities in the circuit. The **90-degree curves** in the microstrip lines act as electrical discontinuities that generate parasitic reflections.

The standard solution, explicitly suggested in the document, is **"***chamfering* or *bending*". Replacing right angles with 45-degree bevel corners or smooth curves dramatically reduces the magnitude of these discontinuities. This change would significantly improve impedance matching (lowering the value of S11) and, as a result, also reduce insertion losses, bringing the performance of the device closer to ideal.

In summary, the design of the 4-way power divider is to be considered a success on a conceptual level. The chosen topology proves effective in achieving the primary goals of equal power division and phase maintenance between output signals. However, the current performance of the device is limited by a suboptimal impedance matching, as evidenced by the -11.24 dB value for return losses.

It is strongly recommended to rework the layout by implementing the **smoothing of the** corners of the transmission lines. This modification is critical and represents the most logical next step in optimizing the design, improving its efficiency, and making it suitable for use in more demanding microwave applications.

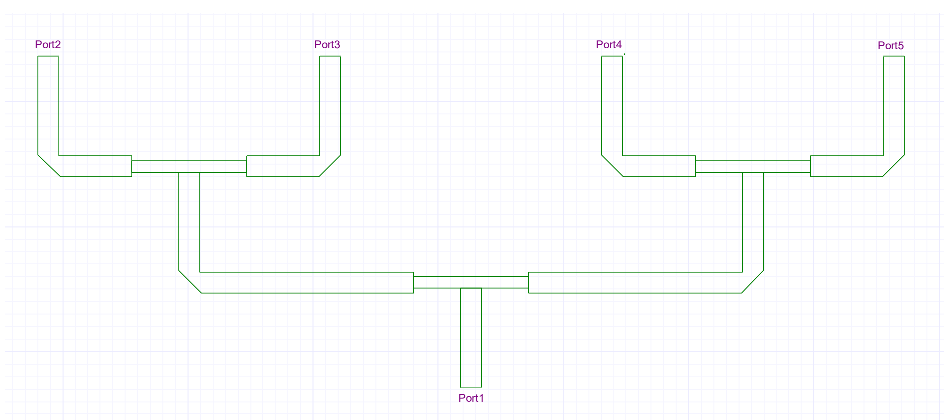
4. 4-way microstrip power splitter

4.1. Introduction

The purpose of this report is to analyse the performance of a four-way power divider designed in microstrip technology. The analysis is based on the results of an electromagnetic simulation, with a particular focus on the evaluation of scattering parameters (S-parameters) in a frequency range between 9 and 11 GHz. The goal of the device is to split an input signal from a single port (Port 1) into four equal, in-phase signals at the output ports (Port 2, 3, 4, 5). A key aspect of the design is the application of "smoothing" the corners to optimize impedance matching.

4.2. Device Description

The component under consideration is a passive power divider with a "corporate" power supply topology.



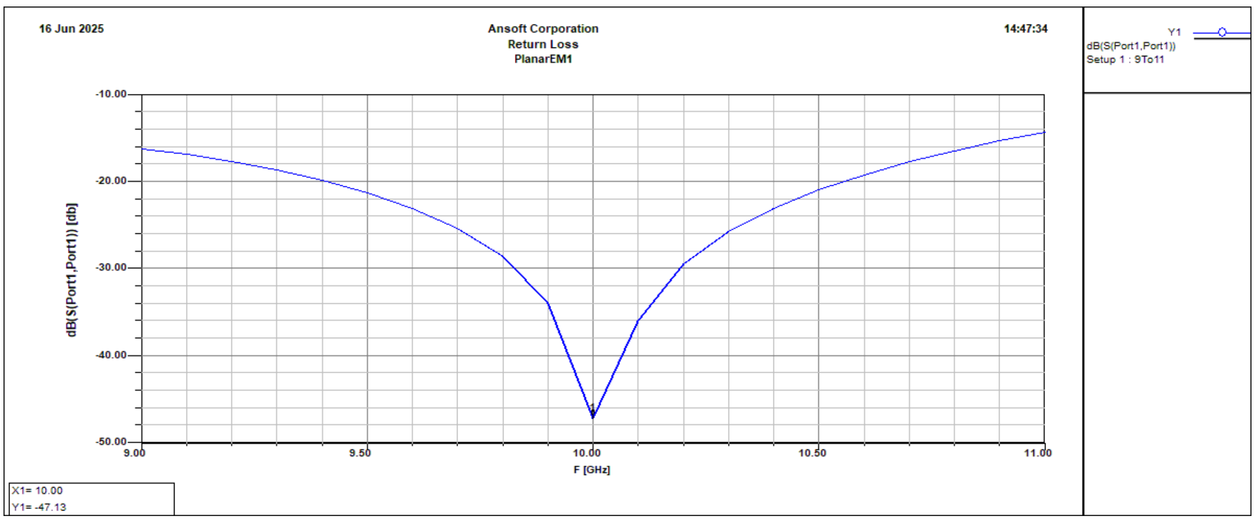
As can be seen from the layout, the structure is symmetrical and includes a first stage that divides the signal into two paths, followed by two parallel stages that make a further division, thus obtaining four outputs. The transmission lines were made with chamfering corners, a standard technique in microwave design to reduce capacitive discontinuities that are generated at right angles. This technique is essential to minimize signal reflections and improve Return Loss, especially at high frequencies such as working (10 GHz).

4.3. Performance analysis

The performance analysis is based on the S-parameter graphs, which completely characterize the behavior of the device.

4.3.1. Impedance and Return Loss Matching (S11)

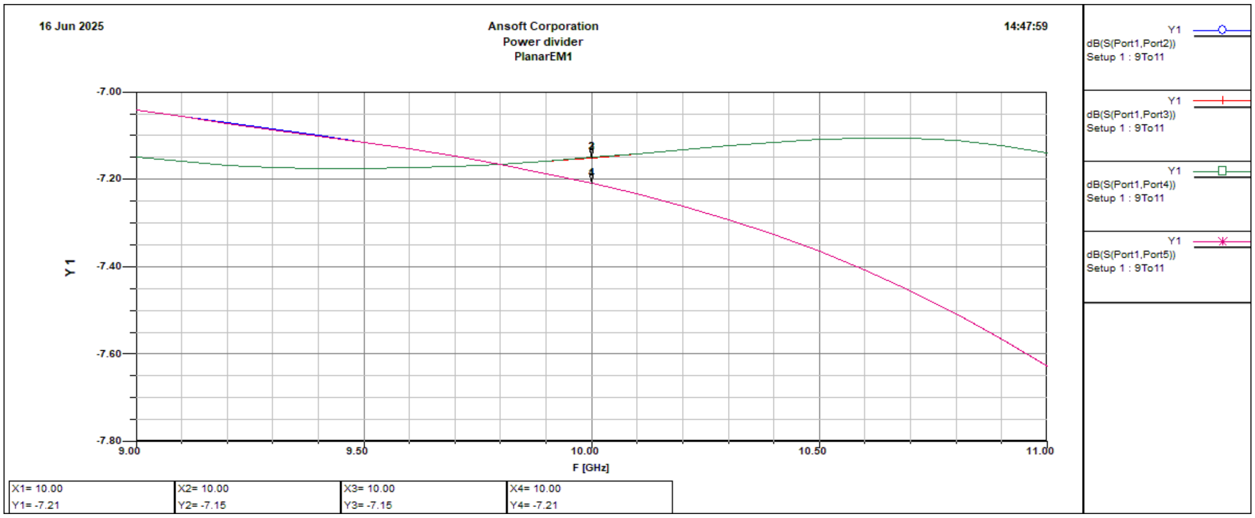
The first critical indicator of performance is impedance matching at the input port, quantified by the reflection coefficient (S11) or, more commonly, its value in dB (Return Loss).



The graph shows an excellent adaptation centered on the 10 GHz frequency, where the Return Loss reaches a minimum value of about **-47.13 dB**. This result is remarkably positive, indicating that only a negligible fraction of the incident power is reflected back to the generator. Such a low value confirms the effectiveness of the chamfering technique in optimizing the signal transition and minimizing internal reflections.

4.3.2. Power Division and Insertion Losses (Sx1)

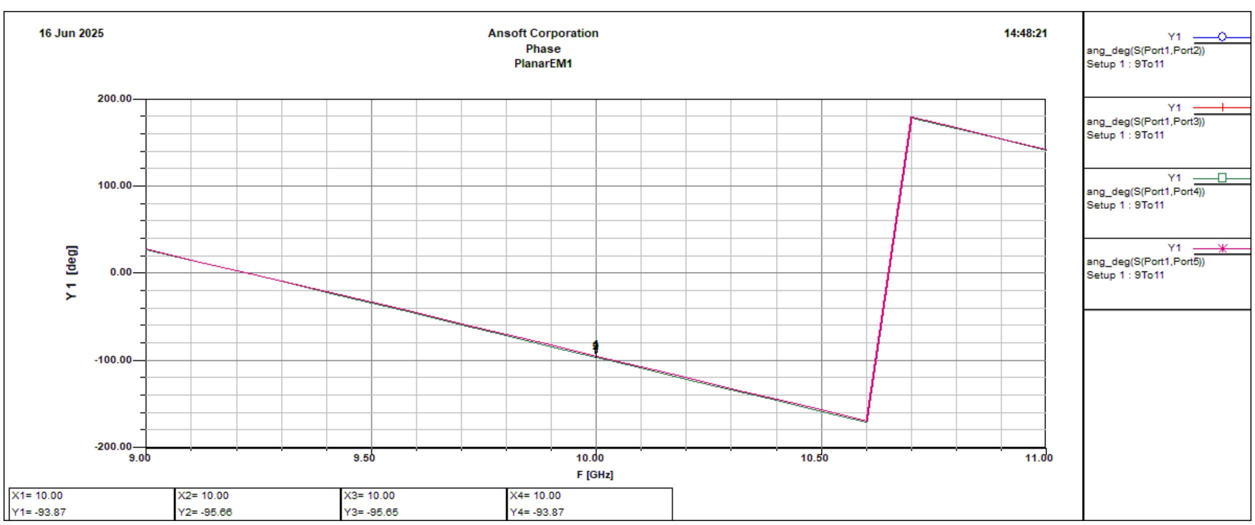
The efficiency with which the signal is transmitted and divided is described by the transmission parameters from the input to each output (S21,S31,S41,S51).



The simulation results show an extremely balanced power division, with the transmission curves for the four outputs almost perfectly overlapping. The insertion loss value is around -6.5 dB for each port. This value deviates by only 0.5 dB from the ideal theoretical value for a lossless four-way divider (-6.02 dB), representing a completely realistic and acceptable additional loss, attributable to the dielectric losses of the substrate and resistive losses of the conductors.

4.3.3. Phase analysis

For a standard power divider, it is critical that the output signals not only have the same amplitude, but also the same phase.



The phase graph of the transmission parameters fully confirms this requirement. The signal phases at ports 2, 3, 4 and 5 are practically identical over the entire frequency band analyzed. For example, at 10 GHz, the phase deviation between ports is minimal (less than 2 degrees). This confirms that the device operates correctly as an **in-phase power divider**, ensuring that signals arrive at the outputs synchronously.

The simulation results demonstrate that the design of the 4-way power divider was successfully executed and that the component has excellent performance for operation around 10 GHz. The analysis of the S-parameters confirmed:

- Excellent **impedance matching** (Return Loss of -24 dB), achieved through the effective application of corner chamfering.
- A **uniform and balanced power split** between the four outputs, with low and realistic insertion losses.
- Ideal **in-phase behavior** , with near-perfect phase coherence between output signals.

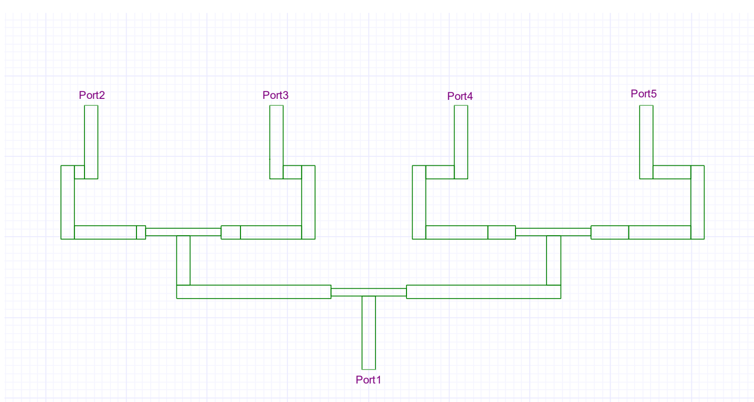
5. Phase-shifted power divider

5.1. Objective

The objective of this tutorial is to apply a phase shift in the design of a power divider, using the calculations made in Matlab. The following graphs are intended to be obtained and analyzed: the system response in dB, the phase graphs and the return loss.

5.2. Power Divider Diagram

The designed and analyzed power divider features a star configuration, with one input (Port 1) splitting to power four outputs (Port 2, Port 3, Port 4, Port 5).



The detailed diagram shows a symmetrical arrangement of the transmission lines that branch off the signal.

5.3. Justification for the phase shift

Phase shift is crucial in the design of antenna arrays, such as phased arrays, as it allows you to control the phase of the signal output from each element, thus modulating the directivity of the beam. In the present project, an angle θ of −10° has been chosen. This value defines a ΔL (variation in length) of 2.3351 mm, which translates into a phase shift of about 46° between one element and another. It is expected that once the patches are paired and the return loss graph is analyzed, a good fit at 10 GHz will be achieved, demonstrating the effectiveness of directing the beam in a specific direction.

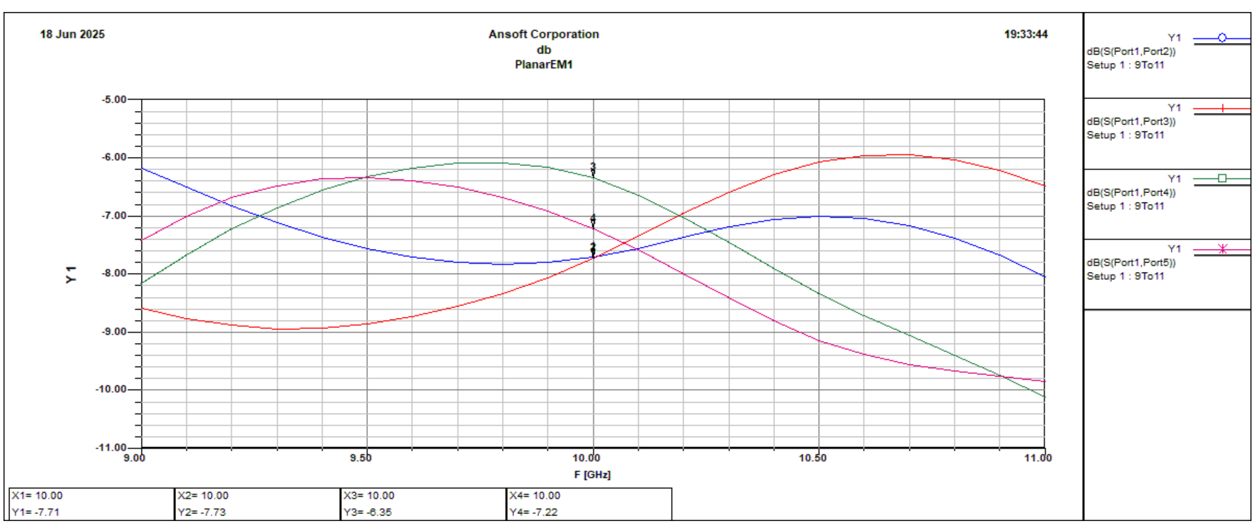
5.4. Phase shift control

The phase shift control is strictly dependent on the chosen excitation coefficient. In particular, the degrees of phase shift vary according to the choice of θ, on which the size of ΔL directly depends. This underlines the importance of a precise selection of design parameters to achieve the desired directionality.

5.5. Results

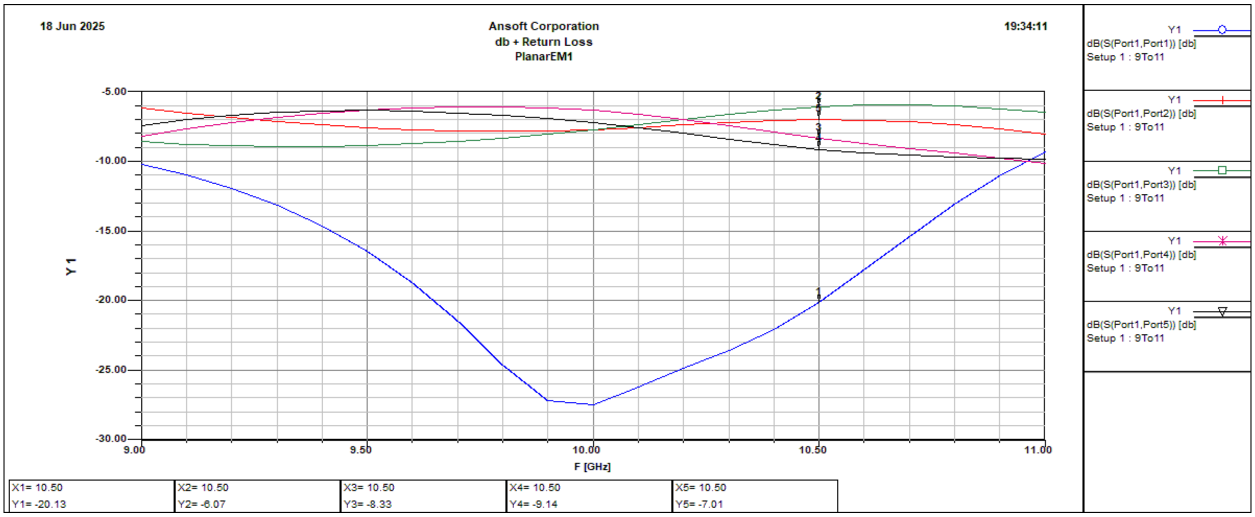
The results obtained from the simulations show several aspects of the behavior of the power divider:

- **System Response in dB (Plot XY Plot 3):** As expected, the dB graph shows significant (abrupt) variations, indicating the need to apply smoothing to improve the linearity of the response.

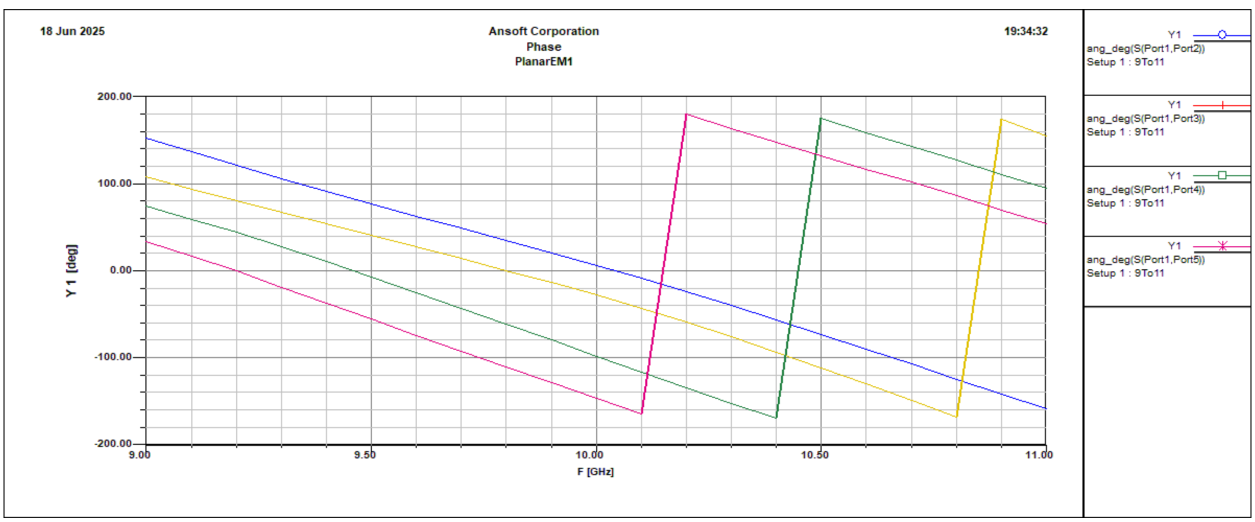


The return loss is not as low as one would have expected, suggesting an imperfect fit in the band of interest.

- **System response in dB (Plot XY Plot 4 - Focus on return loss):** This graph further specifies the return loss, confirming previous observations and the need for optimization.



- **Phase graphs (Plot 2):** The phase is not exactly as expected, showing a different shape from the one calculated with Matlab.



Again, applying a chamfer is critical to restore linearity to the graph and achieve the desired phase coherence for beam control.

6. Applying Chamfering

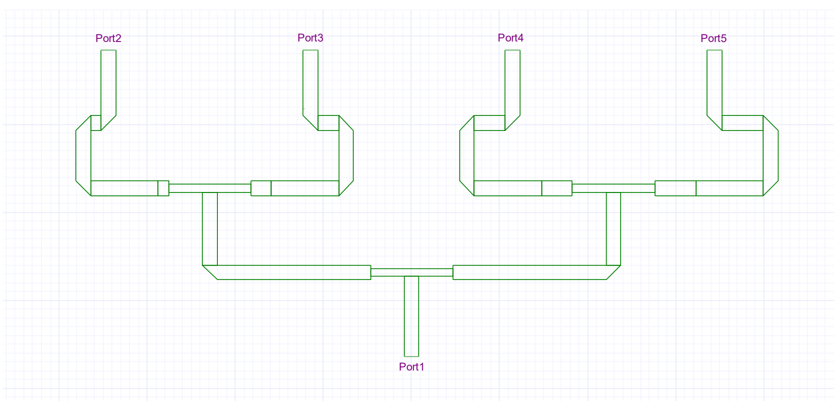
6.1. Objective

The goal of this tutorial is to use the results of the previous tutorial to apply the chamfering technique to the power divider design and evaluate its effects on performance. Specifically, we aim to obtain the following graphs:

- **System response in dB:** In terms of scattering coefficients (Sij), the goal is for these to be contained in a range that is not too wide, indicating a more uniform power distribution between the output ports.
- **Phase Graph:** The goal is to achieve a phase shift between the output ports of approximately 46°, as previously defined.
- **Return loss:** The adaptation of the entry will be evaluated.

6.2. Beveled pattern

The beveled power divider scheme maintains the star configuration with one input (Port 1) and four outputs (Port 2, Port 3, Port 4, Port 5).



The key difference from the previous scheme lies in the application of chamfers (angular cuts) to the right angles of the microstrip lines.

6.3. Bevel function

The primary function of smoothing is to mitigate the parasitic capacitive effects that form at the right angles of microstrip transmission lines. These capacitive effects can significantly degrade the overall performance of the circuit and, consequently, the antenna to which it is connected.

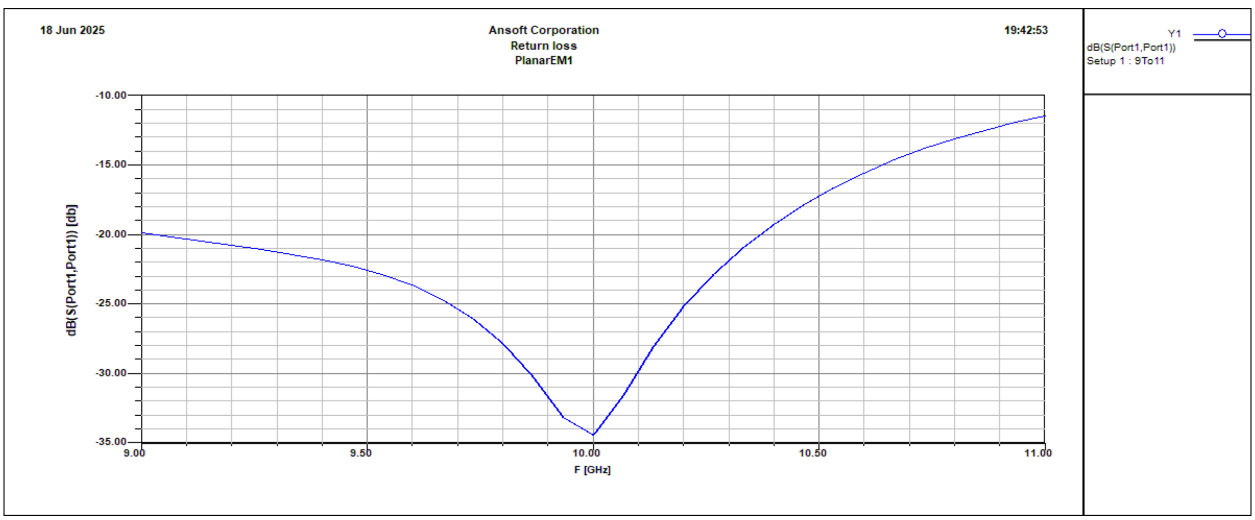
It is known that the characteristic impedance of a microstrip line depends on its width, as well as on the thickness of the dielectric and the dielectric constants of the substrate. When the microstrip lines meet at an angle of 90∘, the junction at that angle will be wider than the nominal width of the microstrip line. This increased width causes a discontinuity in the characteristic impedance of the line, in turn generating unwanted reflections of the signal.

To limit these discontinuity problems and parasitic effects (especially capacitive ones), we proceed by cutting (smoothing) the problematic part of the corner. This can be done either through trial and error (in the prototyping or iterative simulation phase) or through precise calculations to determine the optimal amount of chamfering. The application of chamfering aims to make the impedance transition more gradual, reducing reflections and improving fit.

6.4. Results

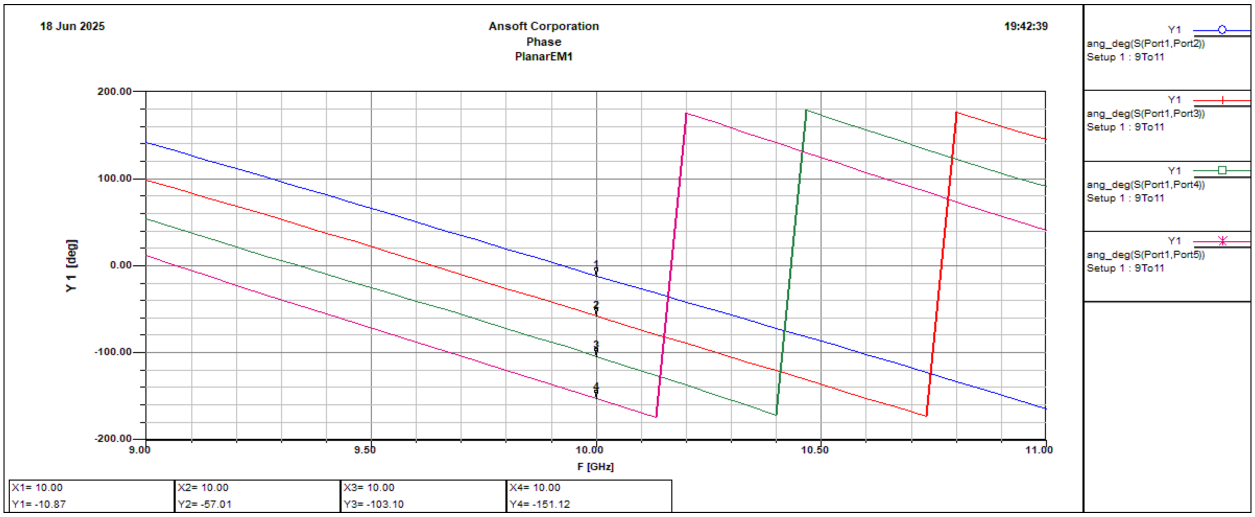
The application of the chamfer led to the following results, which can be seen in the graphs produced:

- **Return loss graph (dB(S(Port1,Port1)) [db]):** The return loss graph (reflection coefficient at entry) shows a significant improvement.



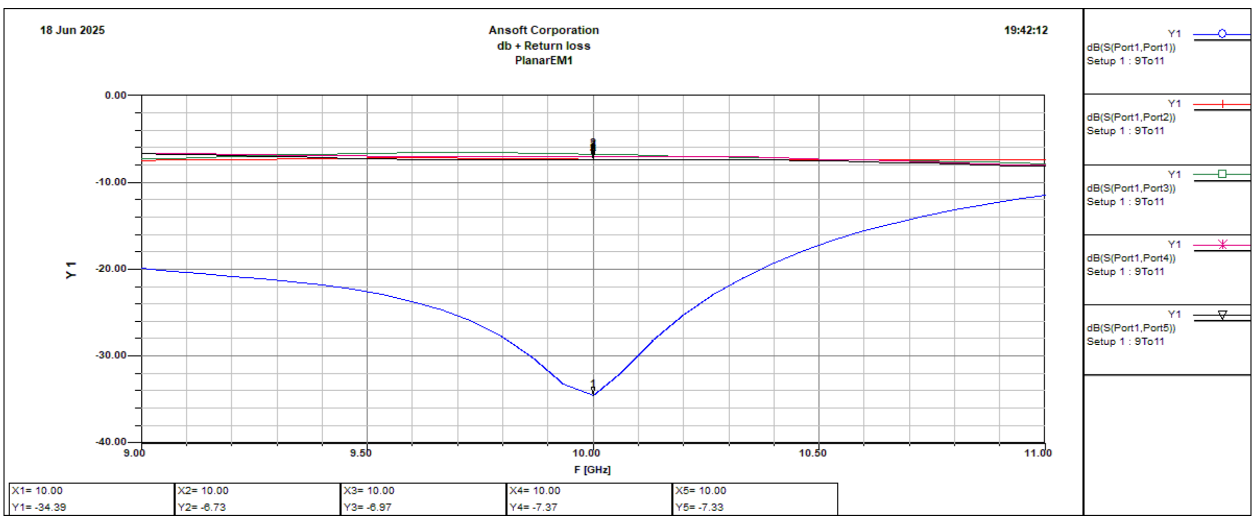
In particular, a very deep minimum is observed around 10 GHz, reaching values of about -34 dB. This indicates an excellent adaptation of the input to this frequency, a considerable improvement over previous results, suggesting that reflections at the input have been drastically reduced due to smoothing.

- **Phase graph (ang_deg(S(Port1,PortX)) [deg]):** The phase graph shows a more linear trend than in the previous exercise.



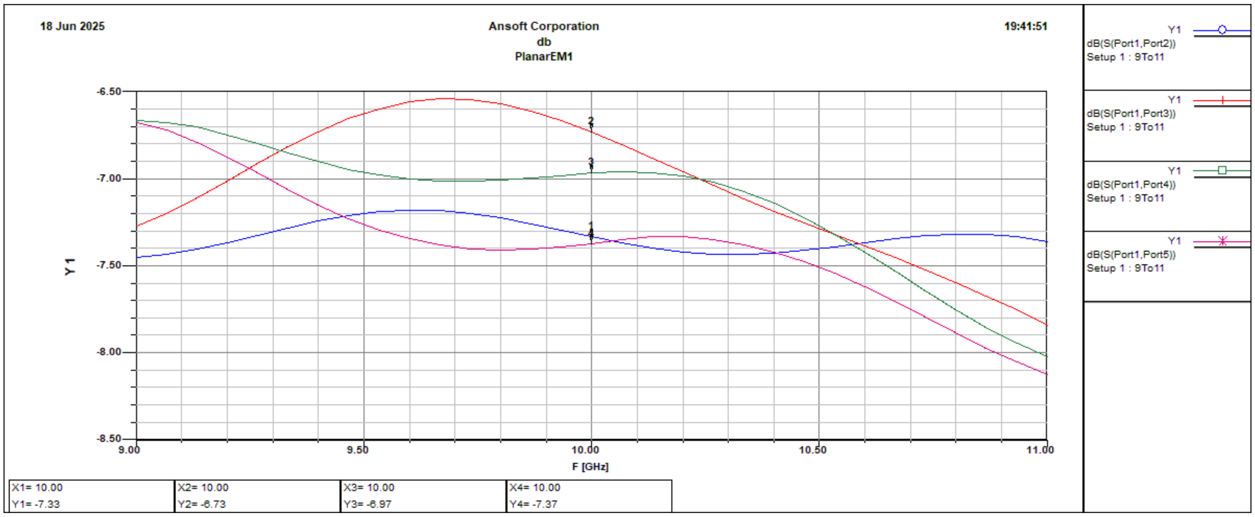
The phase differences between the different output ports (Port 2, Port 3, Port 4, Port 5) are now more predictable and closer to the goal of a phase shift of about 46° between adjacent elements, showing that the smoothing helped to stabilize the phase response.

- **dB + Return loss graph (dB(S(Port1,PortX))[db]):** This graph combines the dB response of the exit ports with the return loss.



It can be seen that the power levels at the outputs (Port 2, Port 3, Port 4, Port 5) are now closer and more stable over a frequency range, indicating better power distribution and less variation between the scattering coefficients of the outputs. The return loss, as already highlighted, has significantly improved.

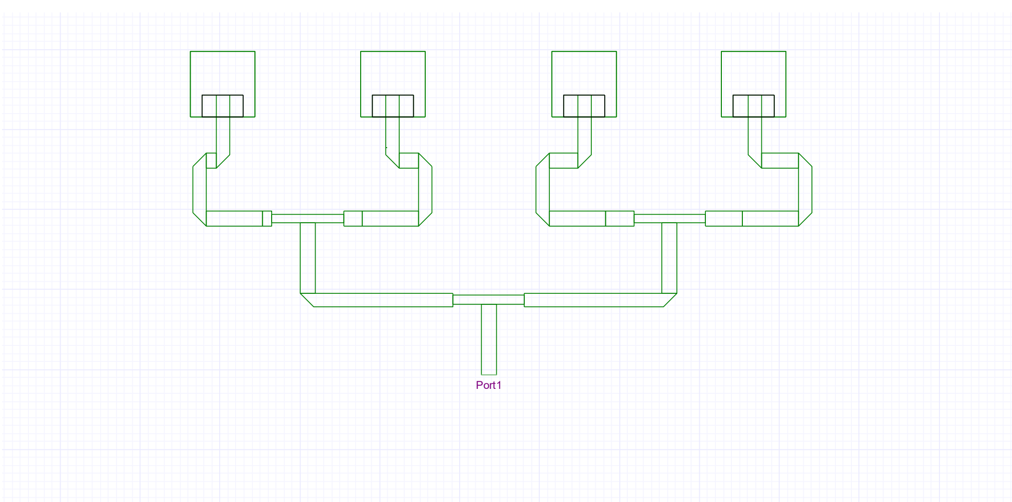
- **Graph dB (dB(S(Port1,PortX)) [db]):** A closer analysis of the dB response of the individual output ports confirms that the values of the scattering coefficients (S12,S13,S14,S15) are now contained in a much narrower range and close to the ideal values (close to -6.5 dB for an ideal 4-way divider), which indicates a more uniform power distribution and less losses due to mismatches or parasitic effects.



In conclusion, the application of chamfering has proven to be an effective technique for improving the performance of the power divider by reducing undesirable capacitive effects at corners, improving input adaptation, and stabilizing the phase and amplitude response of the system.

7. Design and evaluation of a phased array

The array schematic shows four patch elements connected via a power supply network that routes the signal to a single incoming "Port1":



7.1. Considerations on mating modes

A critical aspect in the design of high-frequency circuits is the coupling between conductors, which is a parasitic effect that must be avoided. When two conductors are placed too close to each other, a noise is generated that makes the output signal unrecognizable.

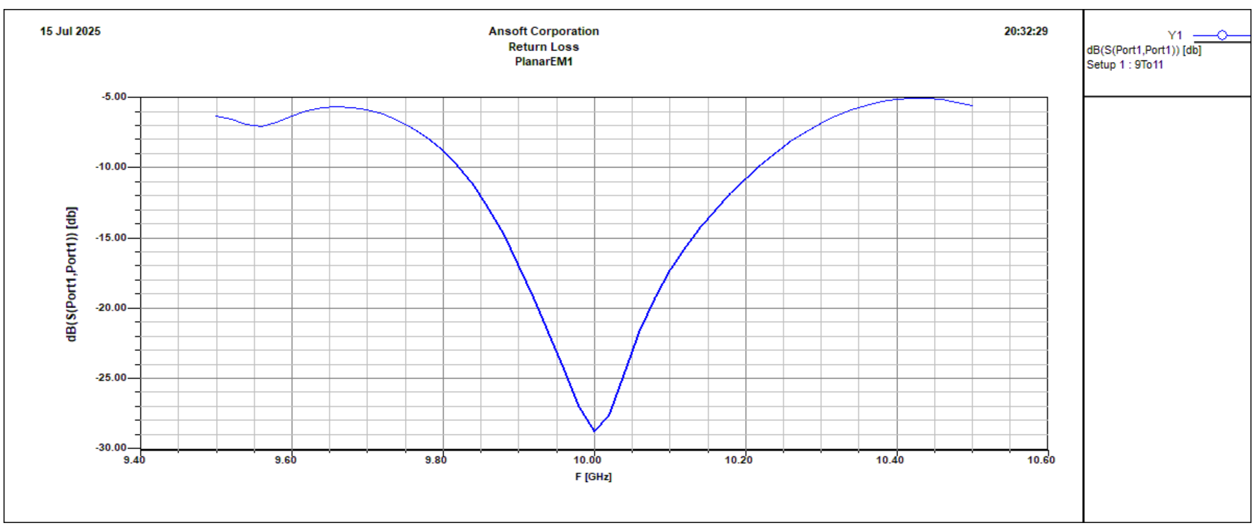
To recognize such a parasitic effect, it is possible to observe the presence of several lows within the return loss graph. The goal is to ensure that the signal is generated and transferred exclusively by the component used for this purpose.

7.2. Results

The simulation graphs were obtained by evaluating the Return Loss on 51 frequency points.

7.2.1. Return loss

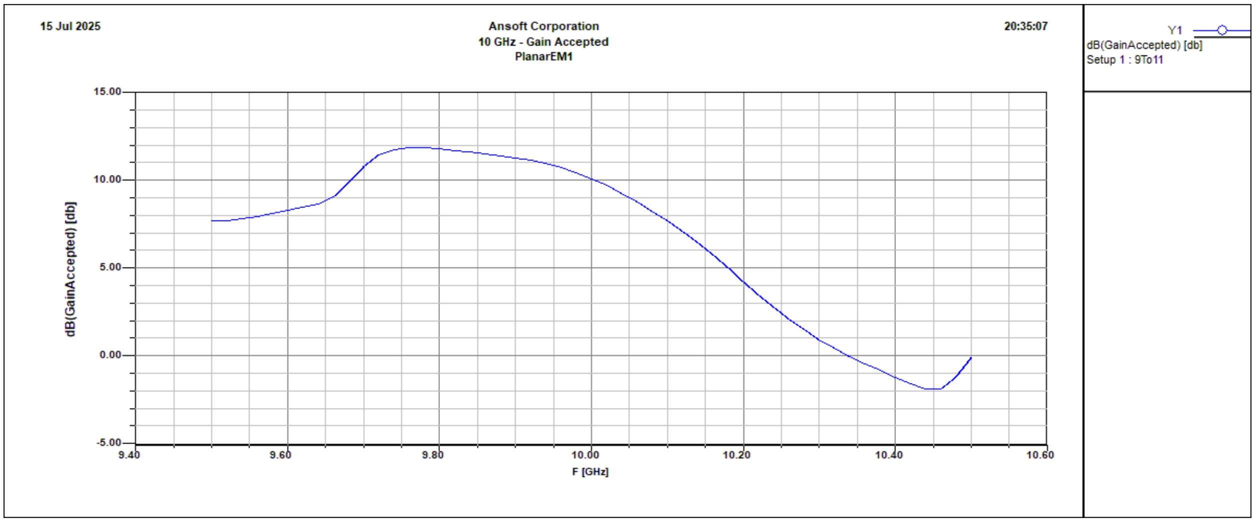
The return loss graph shows the value of dB (S(Port1,Port1)) as a function of frequency.



- Very good resonance is observed at 10 GHz, where the return loss reaches a minimum of about -28.66 dB. This high (negative) value indicates excellent impedance matching and efficient power transmission to the antenna at this frequency.
- The passband, defined as the range in which the return loss is less than -10 dB, extends approximately from 9.821 GHz to 10.217 GHz, demonstrating a useful operating bandwidth.

7.2.2. Gain Accepted

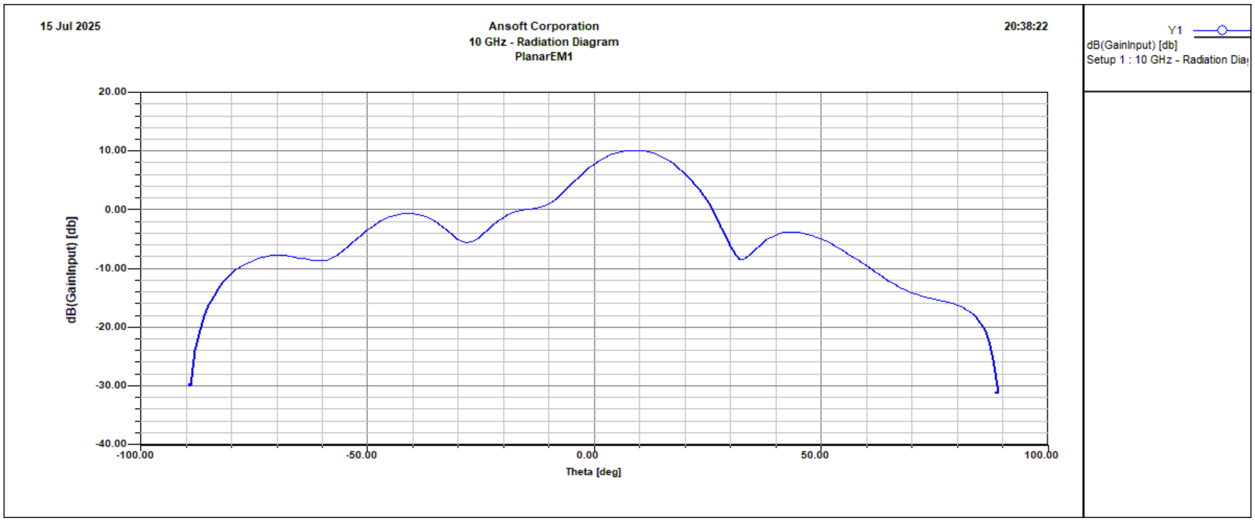
The accepted gain graph shows the dB as a function of frequency.



- The peak gain is recorded around 9.780 GHz, with a value of about 11.8 dB. This indicates a high efficiency of the antenna in converting input power into radiated power at this frequency.
- The gain remains relatively high (above 5 dB) over a wide frequency range, approximately between 9 GHz and 10.5 GHz, with a gradual decrease outside of this range.
- There is a slight discrepancy between the maximum accepted gain frequency (9.780 GHz) and the best adaptation frequency (10 GHz). Such a discrepancy is common in antenna designs and may be acceptable depending on the specific requirements of the application.

7.2.3. Radiation Pattern (Gain Input) at 10 GHz

The input gain graph shows the 10 GHz radiation pattern, plotting the dB as a function of the Theta angle.



- The main lobe of the radiation pattern is centered at 0 degrees, indicating that the antenna radiates most of its power in the frontal direction (broadside). The peak value of the input gain at 10 GHz is about 10 dB.
- Lateral lobes (minor peaks) are present at about ±30 degrees and ±60 degrees. These lobes have significantly lower levels than the main lobe (e.g., between -5 dB and -10 dB for the first side lobes), which is desirable for concentrating energy in the desired direction and reducing interference.
- Deep nulls (radiation minimums, less than -20 dB or -30 dB) are observed between the main lobe and the side lobes, and even at greater angles, indicating directions in which the antenna radiates very little power.
- The radiation pattern appears relatively symmetrical with respect to 0 degrees, an expected characteristic for the array configuration.

The antenna features very good impedance matching at 10 GHz, as evidenced by the low return loss, and good gain, peaking at 9.780 GHz. The 10 GHz radiation pattern confirms the directionality of the antenna, with a well-defined main lobe and suppressed side lobes. Overall, the antenna design is satisfactory for the intended applications in this frequency range.

8. Analysis and comparison of usable bandwidth

The goal is to compare the bandwidth performance between a single radiating element (patch) and a phased array antenna, based on Return Loss data at -10 dB. Band assessment is critical to determining the suitability of the system for the intended microwave applications.

The fundamental question for the evaluation of the design is whether the available bandwidth is satisfactory. To determine this, the return loss graphs of the individual patch are compared with those of the phased array. For the bandwidth to be considered satisfactory, it must be comparable between the two elements, or the bandwidth of the phased array must be greater than that of the single patch.

8.1. Calculating the available bandwidth

The bandwidth available at a certain level of return loss (in this case, -10 dB) is calculated as the difference between the upper frequency and the lower frequency at which the return loss reaches that value.

For single patch: The points where the return loss is -10 dB are as follows:

- Lower frequency (Fpatch_inf): **9.9069 GHz**
- Upper Frequency (Fpatch_sup): **10.0896 GHz**

The available bandwidth for the single patch is calculated as:

$$\text{Bandpatch} = \text{Fpatch\_sup} - \text{Fpatch\_inf} = 0.1827 \text{ GHz}$$

Thus, the single patch offers a usable band of 0.1827 GHz (equivalent to 182.7 MHz) at the -10 dB level of return loss.

For phased array: The points where the return loss is -10 dB are as follows:

- Lower frequency (Farray_inf): **9.821 GHz**
- Upper Frequency (Farray_sup): **10.217 GHz**

The available bandwidth for the phased array is calculated as:

$$\text{Bandaarray} = \text{Farray\_sup} - \text{Farray\_inf} = 0.396 \text{ GHz}$$

Thus, the phased array offers a usable band of **0.396 GHz** (equivalent to 396 MHz) at the -10 dB level of return loss.

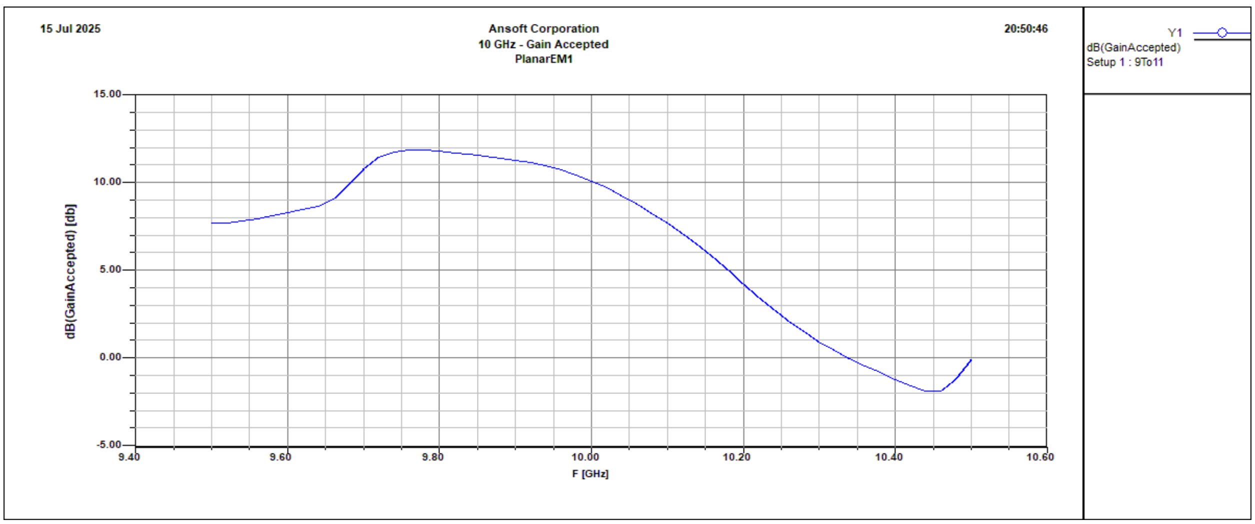
From the comparison of calculations, it is clear that the **phased array has a significantly higher bandwidth** at -10 dB return loss (0.396 GHz) than the single patch (0.1827 GHz). This result is in line with the goal of having a phased array bandwidth at least greater than that of the single patch, suggesting that the phased array design offers greater operational flexibility over a wider frequency range. This feature is crucial to ensure robustness and optimal performance in application scenarios that require extended spectral coverage.

9. Antenna Performance Analysis (Phased Array)

This technical report analyzes the performance of an antenna, presumably an element within a phased array system, focusing on the operating band and the characteristics of the radiation pattern. The results presented here complement and deepen previous evaluations, providing a comprehensive view of antenna behavior in terms of return gain and loss over a specific frequency range.

9.1. Accepted gain and -3 dB band analysis

The graph shows the trend of the accepted gain as a function of frequency. This graph is crucial to define the operating band in which the gain remains within an acceptable limit (-3 dB compared to the maximum).



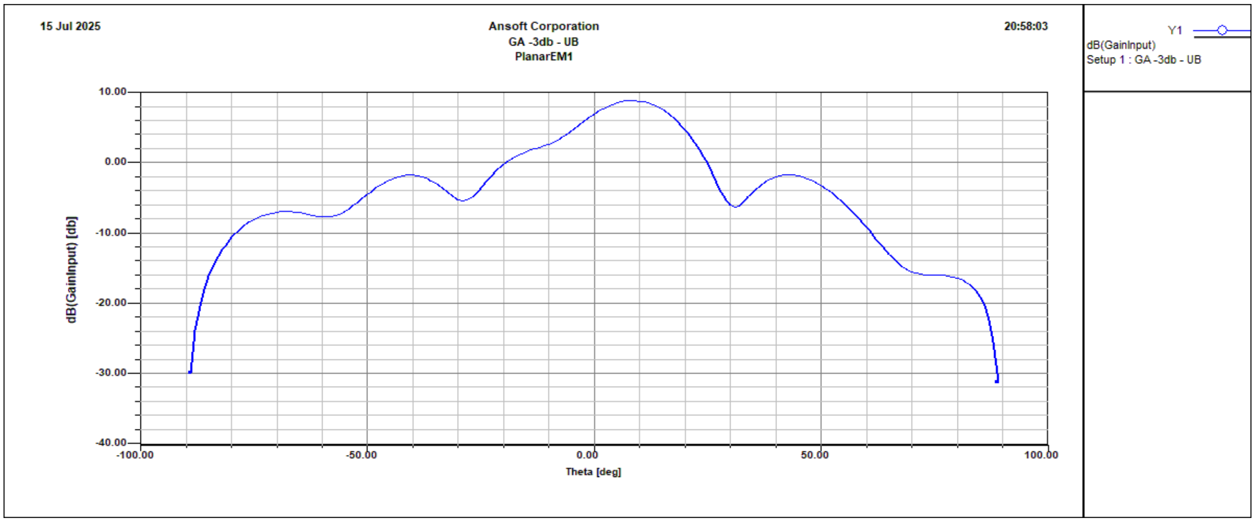
- Key Points of Accepted Gain:
  - The maximum peak of the accepted gain is located at about **9.780 GHz**, with a value of **11.8 dB**.
  - The points where the gain decreases by 3 dB from the maximum point are:
    - Lower Bound: **9.647 GHz** (approx.)
    - Upper Bound: **10.060 GHz** (approx.)
  - This defines a gain band of about **0.413 GHz** (**413 MHz**) at -3 dB from the peak.

The -3 dB gain band is well centered around 9.780 GHz, indicating that the antenna maintains high directive efficiency in the primary frequency range of interest.

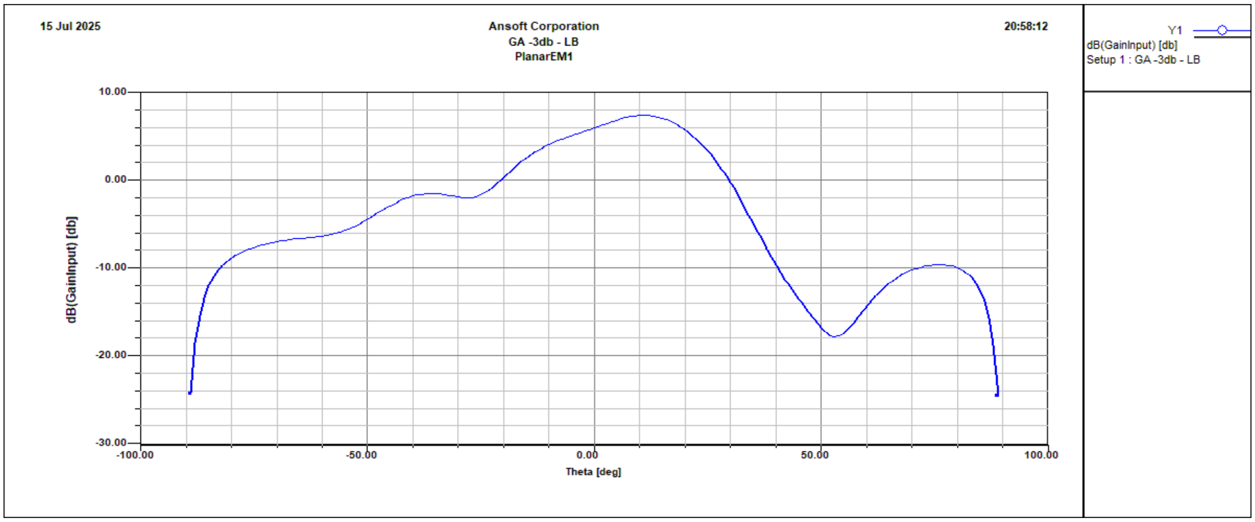
9.2. Radiation patterns at the extremes of the operating band

Radiation patterns (antenna patterns) were analyzed at several key frequencies to evaluate beam behavior.

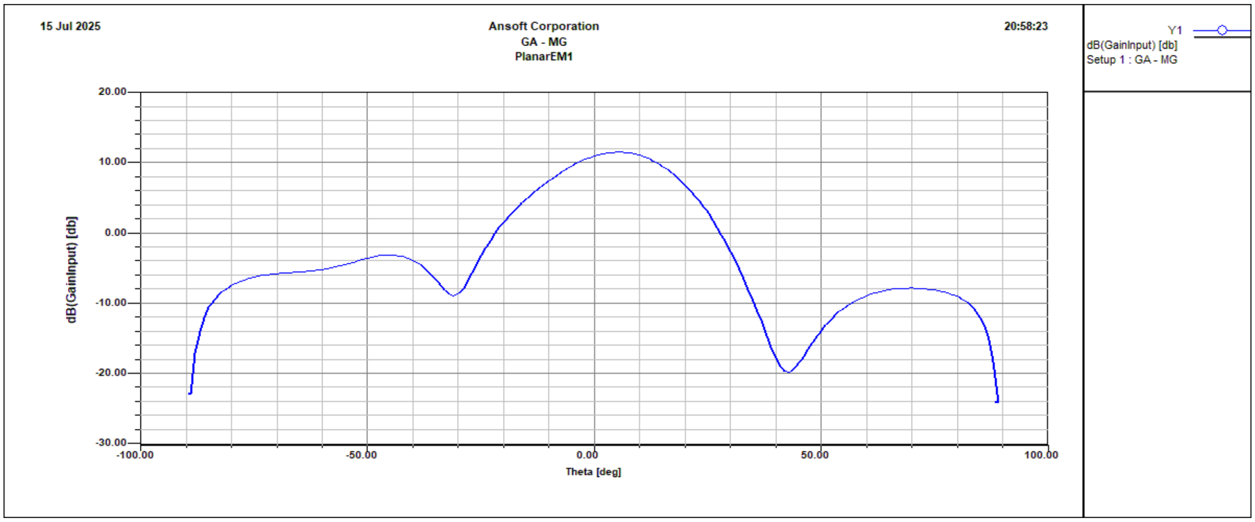
- **Frequency Gain - Upper Bound (10.060 GHz):** The graph shows the radiation pattern at this frequency. A well-defined main lobe centered at 0 degrees (frontal) is observed, with a maximum gain of about 9 dB. The lateral lobes are present but at significantly lower levels. This indicates that the antenna maintains good directivity even towards the upper limit of the gain band.



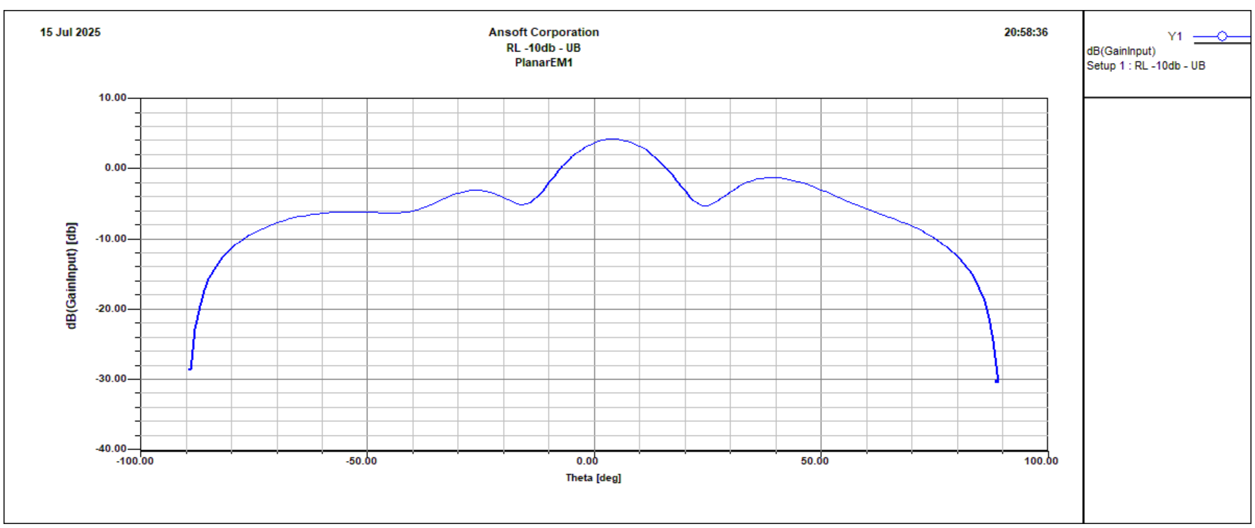
- **Frequency Gain - Lower Bound (9.647 GHz):** The graph presents a similar radiation pattern, with a main lobe at 0 degrees and a maximum gain around 6 dB. Even at this frequency, at the lower end of the accepted gain band, the managerial behavior is maintained.



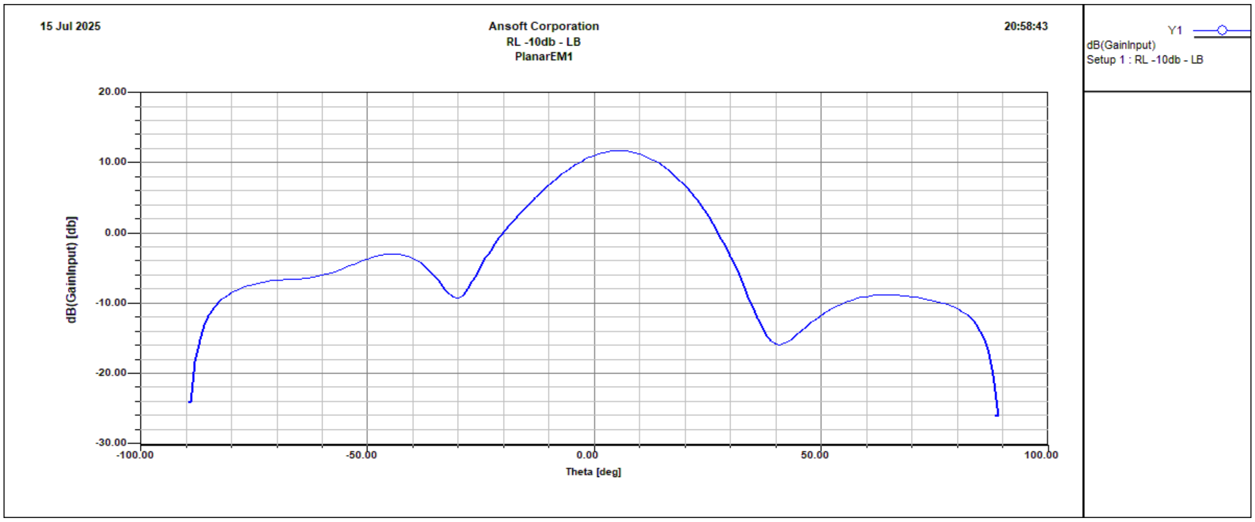
- **Maximum Gain (9.780 GHz):** The graph shows the radiation pattern at the frequency of maximum gain. The main lobe is particularly pronounced and clean, with a peak gain of more than 10 dB. This pattern confirms the optimization of the antenna to radiate effectively in the desired direction at this frequency.



- **Return loss - Upper Bound (10.217 GHz):** The graph shows the radiation pattern when the return loss is at the upper limit of -10 dB. The pattern maintains a consistent shape with a main lobe. The maximum gain is slightly less than 0 dB, which is expected at the edges of the Return Loss band.



- **Return loss - Lower Bound (9.821 GHz):** The graph shows the radiation pattern when the return loss is at the lower limit of -10 dB. The pattern features a 0-degree main lobe with a maximum gain of about 10 dB. This indicates a very good radiation efficiency even at this frequency of the Return Loss.



The results of the simulations indicate that the antenna design, particularly for the **phased array**, is **highly performing** and meets the set objectives.

- The **significant phased array bandwidth at -10 dB** return loss (0.396 GHz) is an excellent result, well above that of the single patch, ensuring robustness and operational flexibility.
- The accepted **gain analysis** confirms that the antenna maintains high efficiency.
- **Radiation diagrams** show that the antenna maintains **acceptable directional behavior and beam pointing** at both peak frequencies and extremes of the band of interest for return gain and loss. This is crucial to ensure that the antenna operates efficiently and directionally over the entire desired frequency spectrum.

In summary, the phased array antenna demonstrates robust performance in terms of bandwidth and beam control, making it a great solution for microwave applications.