POLITECNICO DI BARI

DEPARTMENT OF ELECTRICAL AND INFORMATION ENGINEERING
Master Degree in Telecommunication Engineering

First project for Smart Antennas exam

Design, analysis and optimization of a Planar Inverted-F Antenna (PIFA) for 5G frequencies

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Academic Year 2023 - 2024

Contents

Introduction

Patch antenna

Patch antennas represent an important and widely used category of antennas in modern telecommunications. These antennas are characterized by a planar structure and are known for their simple construction, small size, and reliable performance, which have made them a popular choice in a wide range of wireless applications.

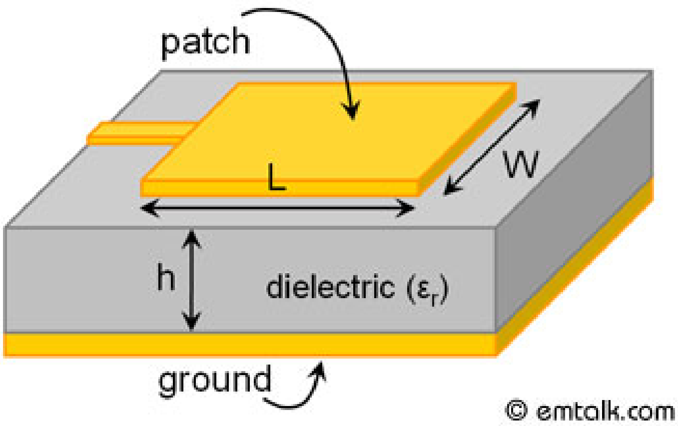


Figure 1: Matlab representation of a simple patch antenna.

Historical notes

The earliest forms of patch antennas date back to the mid-20th century, with the advent of microwave technology and early radar applications. However, it was in the 1970s that patch antennas began to gain significant attention through the work of Professor Robert E. Munson at Georgia Tech Research Institute, who was one of the first to study and develop patch antennas, helping to outline the basic principles guiding their operation and design. Over the past two decades, microstrip antennas have been the subject of study by many researchers around the world given the new possibilities for their use in a wide range of areas. Such antennas were initially used primarily in the military, for example on missiles and high-performance aircraft, where low weight, size, cost, and aerodynamic performance were determining and necessary factors [3].

Operating principle

The basic structure of a patch antenna consists of a thin radiating element, usually made on a dielectric substrate, which is placed above a conductive ground plane. This ground plane may be a conductive substrate or a metal layer on a printed circuit board. The radiating element and ground plane are often separated by a dielectric layer that determines the operating frequency and other characteristics of the antenna. In addition, these antennas are distinguished by their planar configuration, which allows easy integration on printed circuit boards and other flat surfaces. This makes patch antennas ideal for integration into compact electronic devices, such as smartphones, laptops, Wi-Fi routers, IoT devices and more.

Conclusion

Patch antennas provide a versatile and efficient solution for wireless communication needs, offering simplicity of construction, compact size, and reliable performance, continuing to play a key role in the modern telecommunications landscape.

Planar Inverted-F antenna (PIFA)

The object of study and analysis in this report are Planar Inverted-F antennas (also known as PIFAs), which have captured the attention of the student authors because of their wide application in the fields of mobile telephony, wireless networks and IoT devices. This type of microstrip antenna represents the planar implementation of the inverted-F antennas, which in turn represent an evolution of the simple quarter-wave monopole antenna. This antenna is distinguished by its small size, ease of integration into devices, and good performance in terms of radiation and frequency bandwidth. In fact, thanks to its design, PIFA antennas can be easily integrated into portable devices without taking up much space and yet manage to maintain high efficiency, making them ideal for applications where space is limited. In addition, these antennas can be designed to operate in different frequency bands but still manage to keep the specific absorption rate (SAR) low. [1]

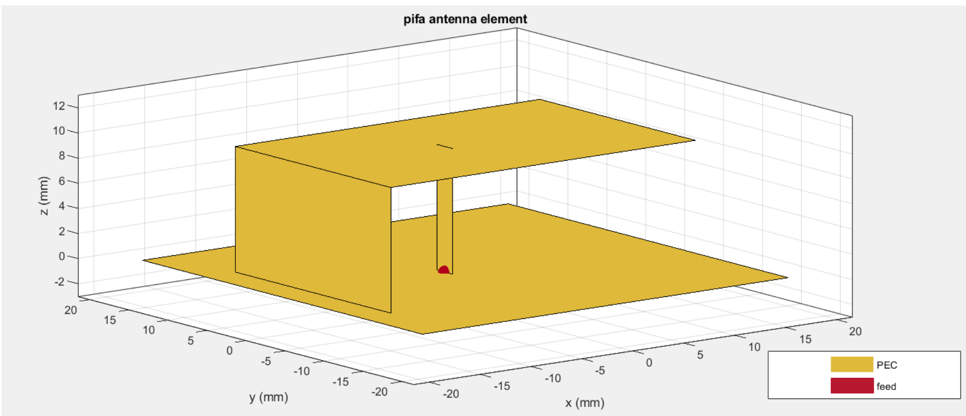


Figure 2: Rappresentazione di una antenna PIFA.

Characteristics

The input impedance of the PIFA is controlled by the distance from the shorting sheet (pin) to the feed point. The magnitude of the input impedance decreases as this distance decreases, and vice versa. To match the antenna to a 50-ohm transmission line, the feed should be closer to the shorting sheet (pin) than to the open end of the PIFA. The radiation pattern is a hybrid between a patch antenna and an Inverted-F Antenna (IFA). Several modifications, such as U-slots, can be incorporated to the PIFA to obtain multiple resonances required in mobile communications.

PIFA terminology

The term PIFA by many authors (e.g., Sánchez-Hernández [2]) is reserved for the short-circuited patch antenna where the antenna element is as wide as the ground plane underneath. The inverted F-shaped thin-line type of antenna with the ground plane on one side is simply called an IFA even though it is in planar format. Some authors may also refer to an IFA of this type as a printed inverted F antenna but still reserve the term PIFA for the type corresponding to the shorted patch antenna.

Workflow

The design in Matlab of each antenna can be summarized in 3 steps:

1. Initial design and evaluation: antenna parameters were defined through the use of the Antenna Toolbox and the Statistics and Machine Learning Toolbox, and then its performance was evaluated.

2. Optimization: by means of cycles `for` the variation and identification of optimal parameters to improve the performance of the antenna was carried out.

3. Final evaluation: the difference in performance between the initially designed antenna and the optimized antenna was finally evaluated.

Evaluation parameters

The following describes the parameters that will be used for choosing the optimal values as well as for comparing the optimized antenna with the initial antenna designed with the Antenna Toolbox and the Statistics and Machine Learning Toolbox.

Mesh

This is used in methods of moments to discretize the geometry of the electromagnetic problem. The geometry is then divided into discrete elements, such as triangles, where each mesh element represents a portion of the geometry and can be associated with a set of basis functions (e.g., polynomial basis functions) that approximate the behavior of the electromagnetic field within the element. Each mesh element is considered in pairs with another element, one positive and the other negative, so that the entire structure is considered as a composition of individual elementary dipoles interacting with each other. In addition, areas with higher current density will be discretized more.

Impedance

During the optimization phase, the graph showing how the impedance of the antenna varies with frequency will be evaluated. On the x-axis is the frequency, and on the y-axis is the impedance, which indicates the resistance (in blue) and reactance (in red) that the antenna presents at its input at a given frequency, so we will be able to observe how the impedance varies as the frequency varies. This may indicate the antenna's ability to adapt to different frequencies of operation: for example, it is desirable for the impedance to be close to the impedance of the incoming transmission line (usually 50 ohms) for maximum power transfer.

S11 parameter and Bandwidth

The S11 parameter is a measure of power reflection by the antenna. Lower values of S11 indicate a more efficient antenna in accommodating incident energy. On the x-axis is the frequency, and on the y-axis is the amplitude of S11 in decibels. Ideally, you want the S11 parameter to be as low as possible, especially in the frequencies of interest, which would mean that the antenna is transferring as much energy as possible to the load instead of reflecting it. Conversely, high S11 values indicate greater reflection of input energy, which may result from a poor impedance match between the antenna and the power system. In addition, the operating band will be considered by evaluating the S11 parameter at -10 dB.

VSWR (Voltage Standing Wave Ratio)

This parameter measures the transmission efficiency of the antenna and indicates how well it is adapted to the transmission system. VSWR is defined as the ratio between the maximum (V_i+V_r) and minimum (V_i-V_r) standing wave voltage along a transmission line. On the x-axis is the frequency, and on the y-axis is the VSWR value in decibels. A VSWR of 1 indicates a perfect impedance match, which means that all energy is transmitted to the antenna without reflections. In contrast, higher VSWR values indicate some of the energy being reflected, making the antenna less efficient.

Pattern 2D and 3D

These graphs represent the radiation pattern in the surrounding space. The 2D pattern shows the directivity of the antenna with respect to the azimuth plane and the elevation plane, while the 3D pattern shows the directivity in space and the spatial distribution of the energy emitted by the antenna. This graph shows us the intensity of the radiated signal in various directions, thus providing information about the directivity of the antenna, that is, how concentrated the energy is in the desired direction.

Current distribution

This parameter refers to the spatial distribution of electric currents on the antenna. This parameter directly affects the efficiency with which the antenna transmits or receives signals; in fact, a uniform current distribution along the antenna's radiating elements can help maximize radiation efficiency.

EH fields

Electric and magnetic fields (EH) are the main components of the electromagnetic fields emitted by an antenna and are essential for the transmission and reception of electromagnetic waves. On the x-axis we have the frequency of the electromagnetic signal, and on the y-axis we have the electric and magnetic field components. This graph shows how the electric and magnetic fields generated by the antenna vary with frequency, thus providing information about the spatial distribution of the fields around the antenna and how this distribution changes with frequency.

Axial ratio

This parameter provides information regarding the polarization of the antenna: it can be understood as the ratio between the two axes of the polarization ellipse of the field radiated by the antenna. To have a circular polarization this value should therefore be as close as possible to 1 (on a linear scale, to 0 dB on a logarithmic scale), high values on the other hand indicate a linear polarization.

The next chapters will present the design and analysis work of two PIFA antennas, the first for 5G low-band frequencies (690 MHz - 790 MHz) and the second for 5G mid-band frequencies (3.3 GHz-3.8 GHz). The above-mentioned frequencies were chosen for affinity to the study topics of the Telecommunications Engineering degree program, such as IoT and Radio Mobile Network. The designed antennas were evaluated according to the following parameters: impedance, S11 reflection coefficient, -10dB band, 2D/3D pattern, current distribution, electric field, magnetic field and polarization.

Chapter 1

PIFA antenna operating at 750 MHz

In the first design phase, we used the Antenna Toolbox and the Statistics and Machine Learning Toolbox to obtain the first version of the antenna to be optimized later. The obtained parameters are as follows:

- `Length: 0.0933 m`
- `Width: 0.0622 m`
- `ShortPinWidth: 0.0622 m`
- `Height: 0.0311 m`
- `FeedOffset: [-0.0062 m 0]`
- `Feed Width: 0.0062 m`
- `GroundPlaneLength: 0.1120 m`
- `GroundPlaneWidth: 0.1120 m`
- `SubstrateEpsilonR: 1`
- `Conductor: PEC`

Then with the antenna optimization phase, for loops were implemented to find the best values of the Feed Offset, Lenght and Width, based on the various action of the parameters given below. Finally, a comparison will be performed between the antenna generated by the Antenna Toolbox and the optimized one.

1.1 Performance based on changes in Feed Offset

It was decided to vary the value of the parameter `Feed Offset` in the range of 0.004 m from 0.004 m to 0.008 m, with a step size of 0.001 m so as to evaluate 5 different values. Below are graphs of the various parameters and an evaluation of them after variation for each value.

1.1.1 Impedance

It can be seen from the following graphs how the variation of the Feed Offset concretely affects the impedance of the antenna. For values farther from the initial value, the resulting impedance of which is shown in Figures 1.1 and Figures 1.5, the reactance takes a larger absolute value, in the negative for 0.004 m and in the positive for 0.008 m, while the resistance varies slightly in the negative as the Feed Offset value increases.

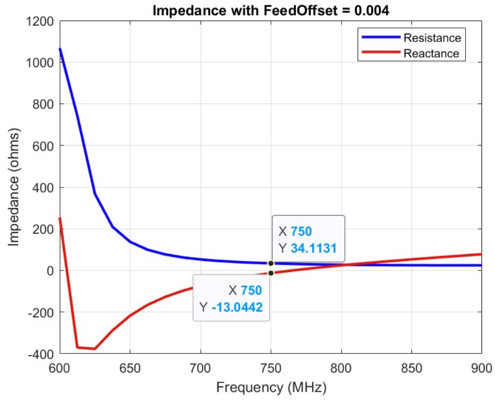


Figure 1.1

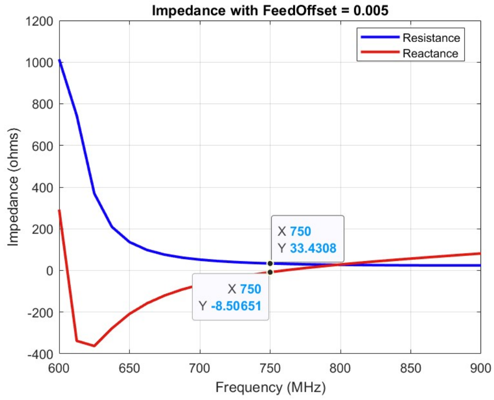


Figure 1.2

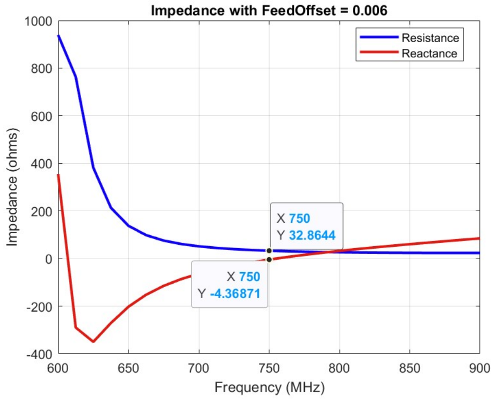


Figure 1.3

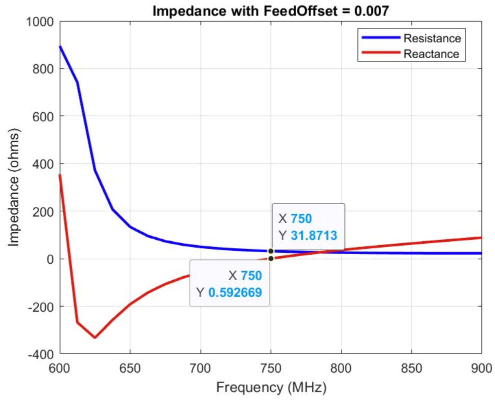


Figure 1.4

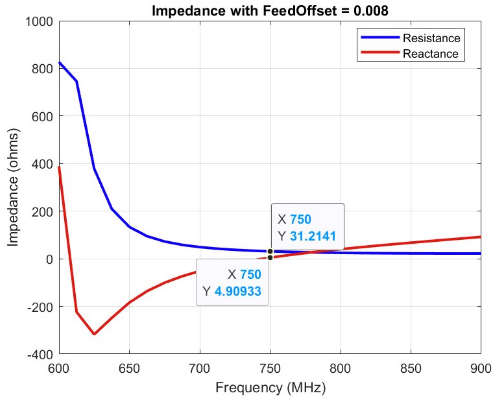


Figure 1.5

1.1.2 S11 parameter

It can also be seen from these graphs how important the variation of the Feed Offset is for the design of a PIFA antenna, not so much for the magnitude variation as for the frequency shift made explicit in Figure 1.6, Figure 1.9 and Figure 1.10. Also it can be seen that among all the values, the S11 of 0.006 m is the best at 750 MHz.

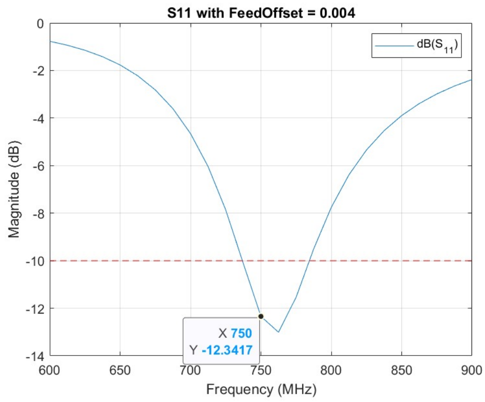
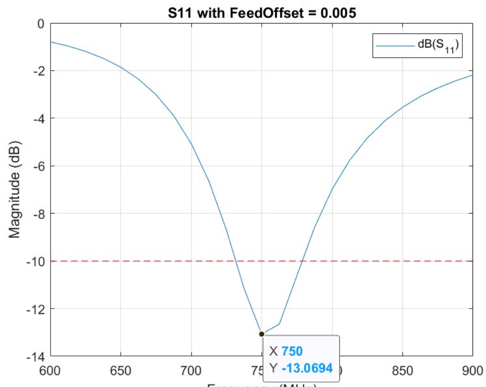


Figure 1.6



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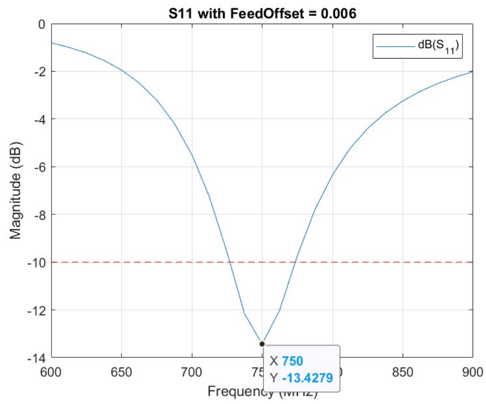


Figure 1.8

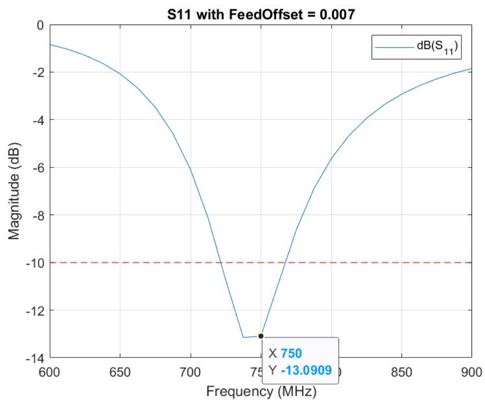


Figure 1.9

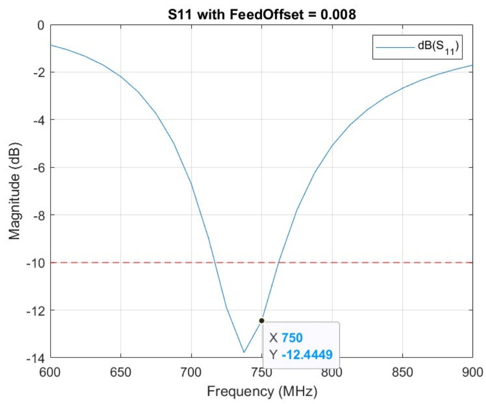


Figure 1.10

1.1.3 3D Pattern

For 3D Pattern evaluation, changing the Feed Offset produces no particular change in maximum and minimum values of directivity.

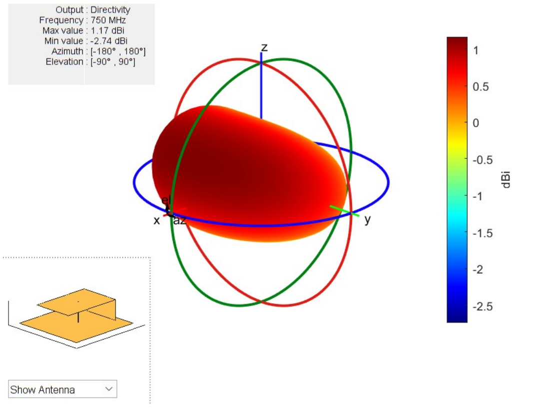


Figure 1.11: 3D pattern with 0.004 m value

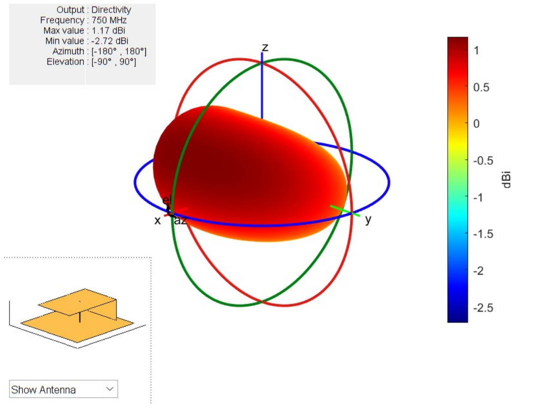


Figure 1.12: 3D pattern with 0.005 m value

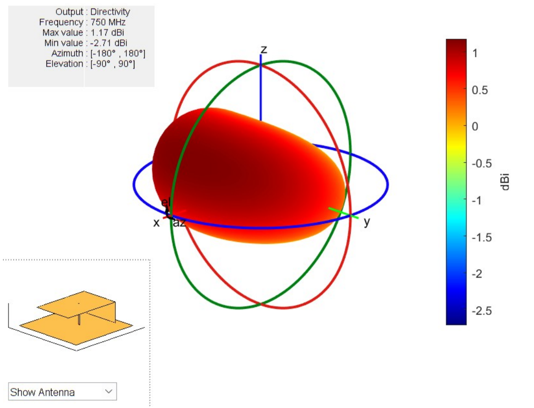


Figure 1.13: 3D pattern with 0.006 m value

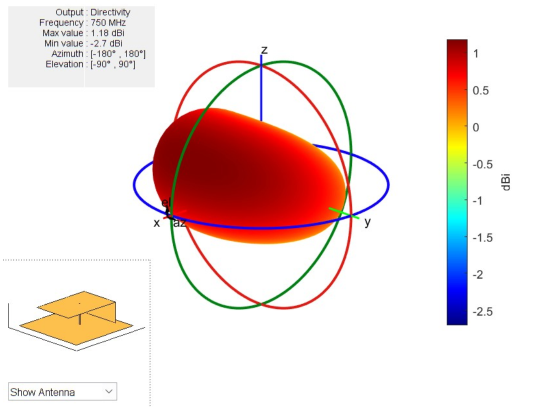


Figure 1.14: 3D pattern with 0.007 m value

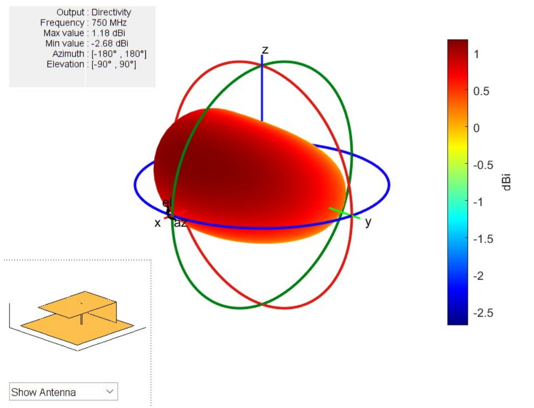


Figure 1.15: 3D pattern with 0.008 m value

1.1.4 Current distribution

Even for the evaluation of current distribution, changing the Feed Offset produces no particular change. The current distribution is uniform for all these values, in fact it can be seen that the current is lower in the open circuit zone and higher in the short-circuited zone.

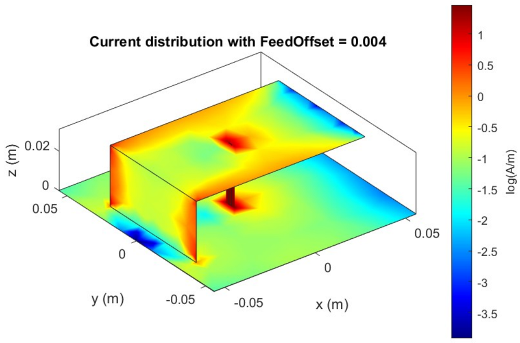


Figure 1.16

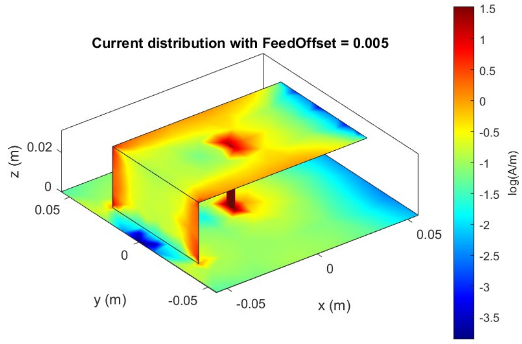


Figure 1.17

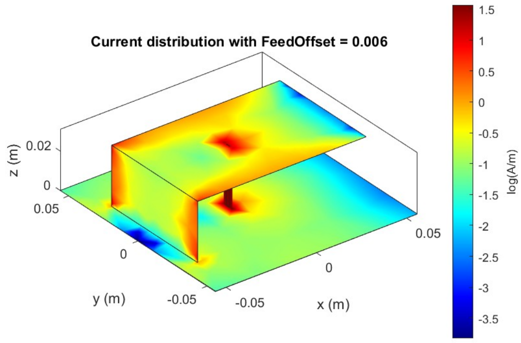


Figure 1.18

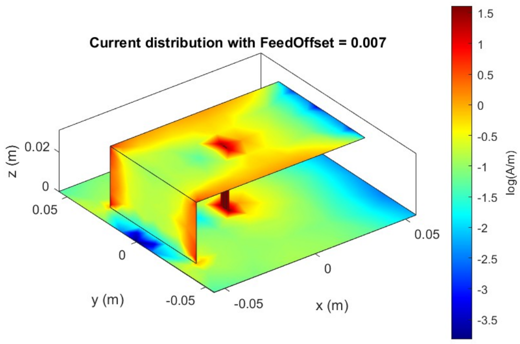


Figure 1.19

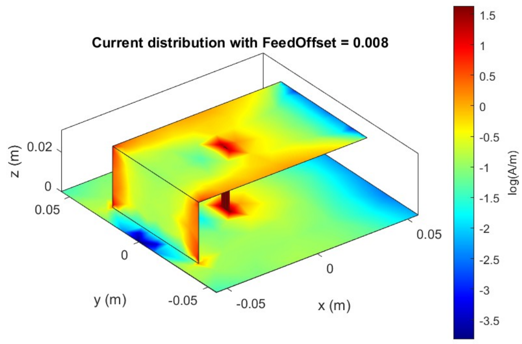


Figure 1.20

Conclusion of Feed Offset sweep

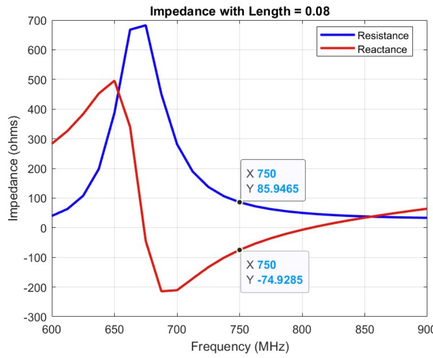
After evaluating the effects of changes in the Feed Offset parameter, 0.006 m was chosen as the best value: this does not result in frequency shifts and at the same time results in good impedance values. For all future evaluations, the value of the Feed Offset parameter will be set to 0.006 m.

1.2 Performance based on changes in Length

It was decided to vary the value of the parameter `Length` in a range of 0.02 m from 0.08 m to 0.1 m, with a step of 0.005 m so as to evaluate 5 different values. The graphs of the various parameters after variation for each value are shown below.

1.2.1 Impedance

It is clear how length is a key parameter in the design of a PIFA antenna; in fact, it can be seen that variation results in large changes in impedance with respect to frequency.



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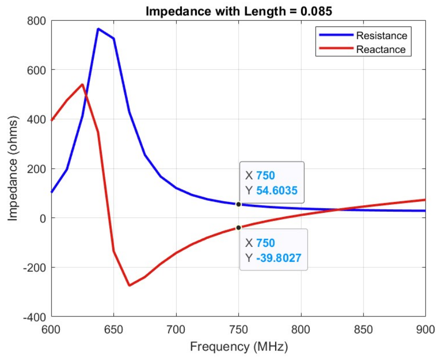

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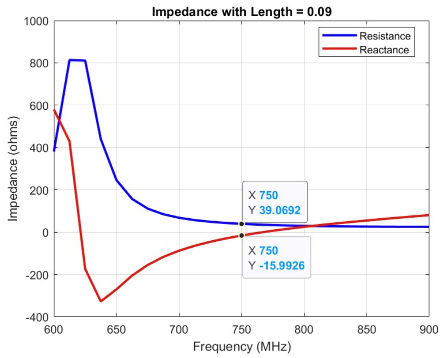

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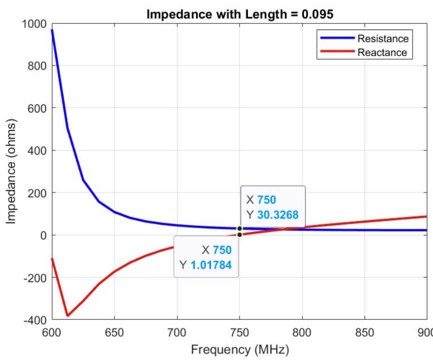

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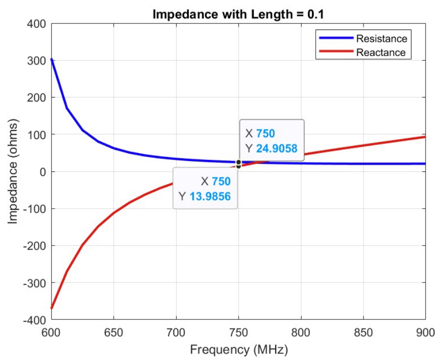
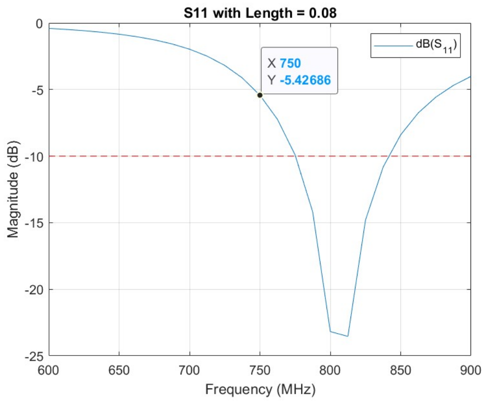


Figure 1.25

1.2.2 S11 parameter

As already noted in the evaluation with respect to impedance, the change in length results in a consistent shift in frequency. For values below the initial one, such as 0.08, there is an increase in resonant frequency that is between 800 and 810 MHz. Conversely for values above the initial one, for which the resonant frequency decreases, respecting the direct proportionality between wavelength and size indicated by the antenna theory.



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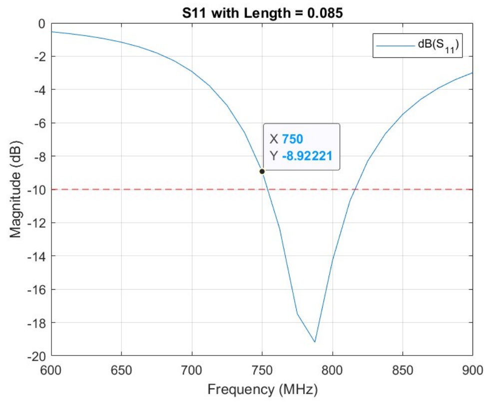

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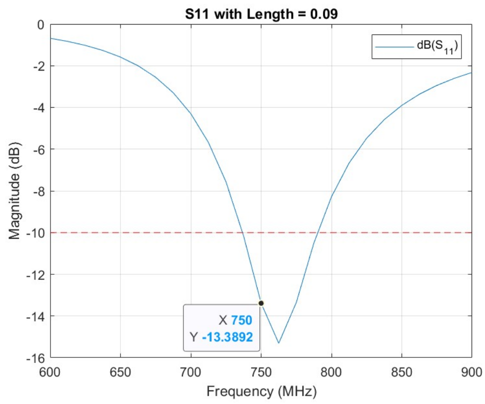

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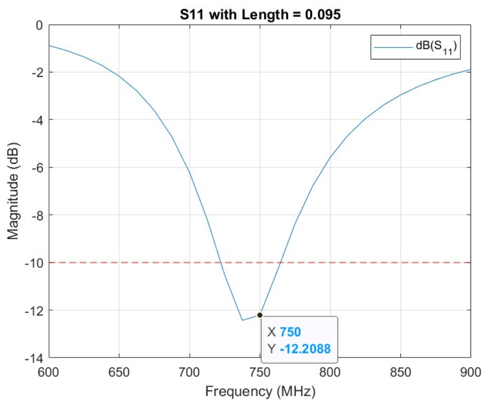

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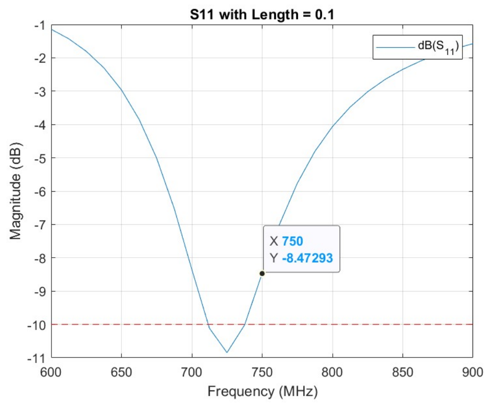


Figure 1.30

1.2.3 3D Pattern

It can be seen that increasing the length affects the direction of maximum antenna irradiation, in fact for the value 0.08m we will have an antenna radiating upward, as represented in Figures 1.31. Conversely, increasing the value of the length will result in more directional irradiation along the azimuth plane, as depicted in Figures 1.35.

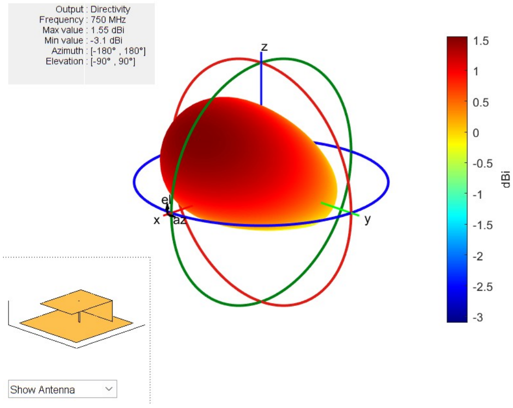


Figure 1.31: Pattern 3D with Lenght=0.08 m

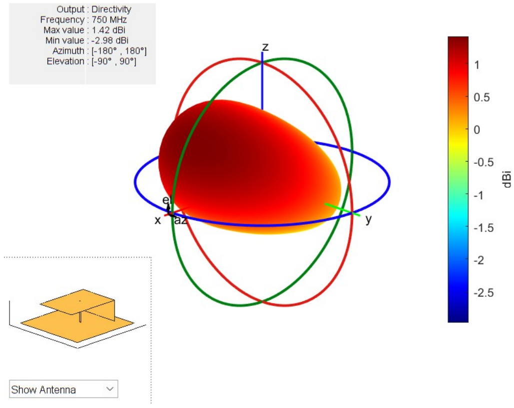


Figure 1.32: Pattern 3D with Lenght=0.085 m

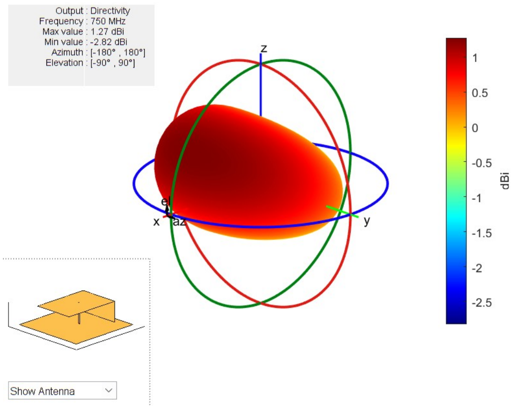


Figure 1.33: Pattern 3D with Lenght=0.09 m

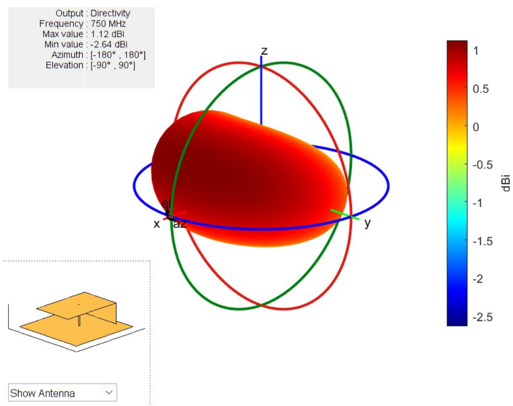


Figure 1.34: Pattern 3D with Lenght=0.095 m

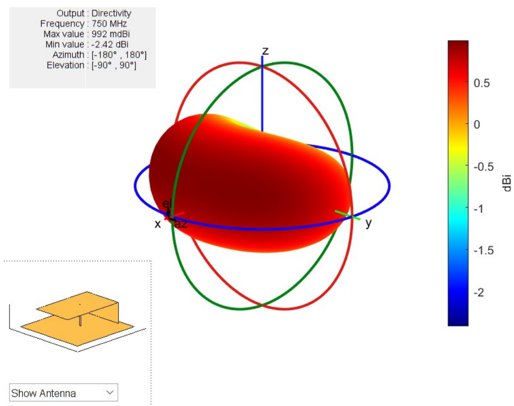


Figure 1.35: Pattern 3D per Lenght=0.1 m

1.2.4 Current distribution

From the following graphs can be seen that the current distribution is more concentrated on the edges of the antenna when the Length parameter is set to lower values such as 0.08 m, vice versa for higher values such as 0.1 m, for which the current distribution is more uniform.

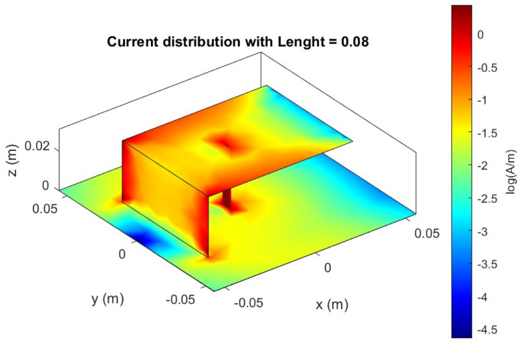
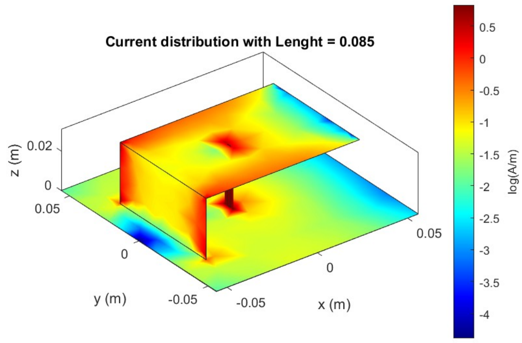


Figure 1.36



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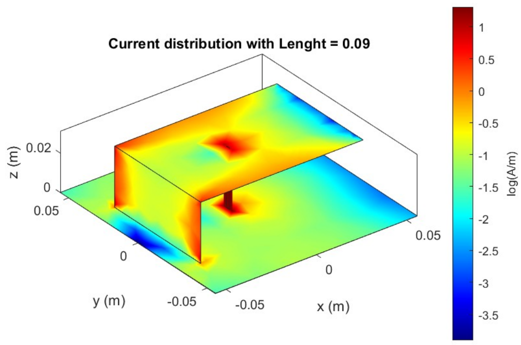
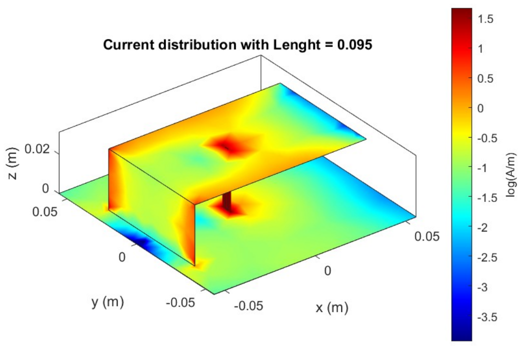


Figure 1.38



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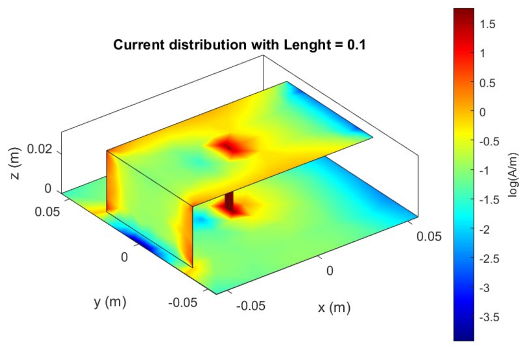

Figure 1.40

Conclusion of Legth sweep

Variation in the Length parameter proved to be crucial in the design of the PIFA antenna; in fact, even a small variation in this parameter results in large changes in its optimization.

After evaluating the effects of the variations, was chosen 0.09 m as the best value: this implies a slight shift in frequency that can be compensated later with the width variation but at the same time makes good impedance values as well as good directionality and current distribution. For all future evaluations the value of the Length parameter will be set to 0.09 m. The graphs of S11 before and after the variation of the Lenght parameter are shown below.

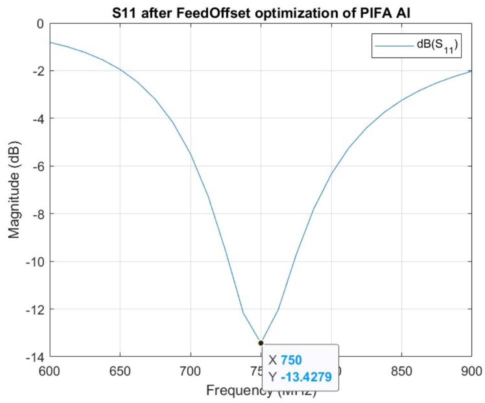

Figure 1.41

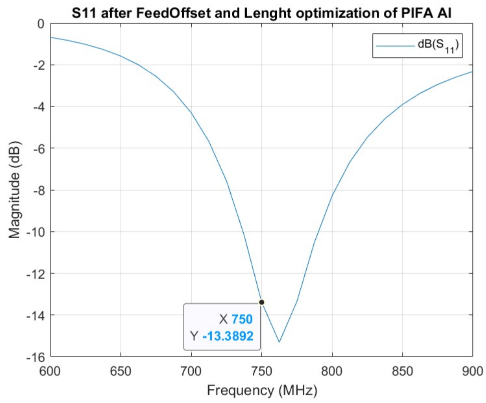

Figure 1.42

1.3 Performance based on changes in Width

It was decided to vary the value of the parameter `Width` in a range of 0.04 m from 0.05m to 0.09 m, with a step of 0.01 m so as to evaluate 5 different values. The graphs of the various parameters after variation for each value are shown below.

1.3.1 Impedance

Just as with the past parameters, we can see how the variation of the parameter greatly affects the impedance of the antenna. In particular we can see that for lower values of Width the reactance and resistance are lower, vice versa for higher values.

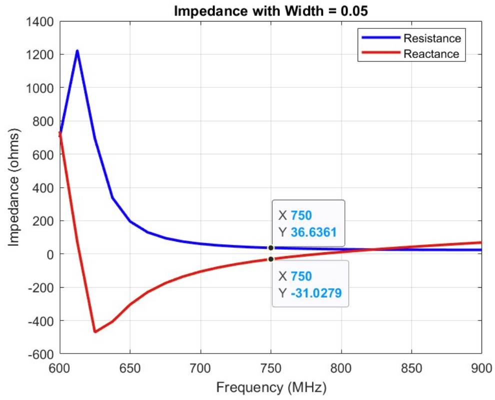

Figure 1.43

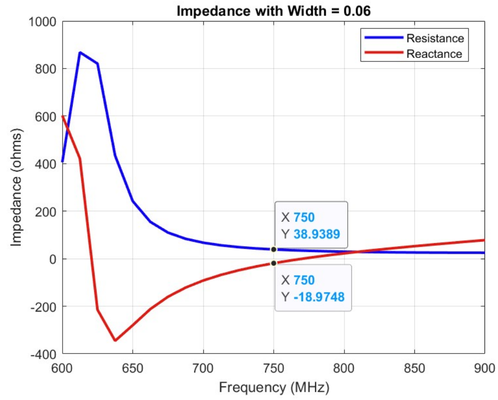

Figure 1.44

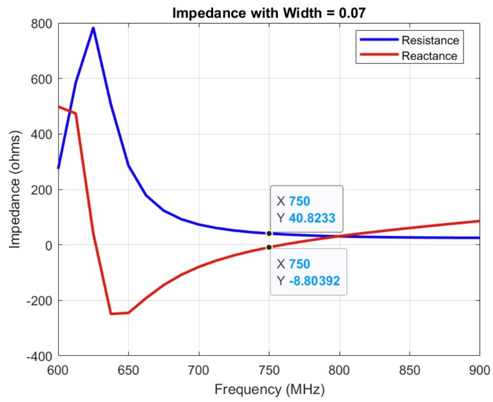

Figure 1.45

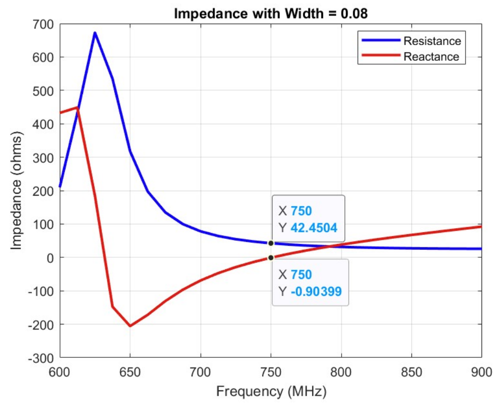

Figure 1.46

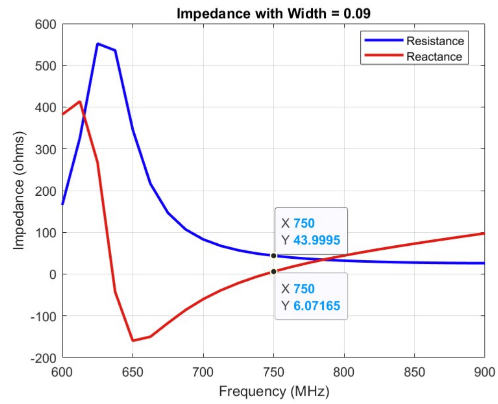

Figure 1.47

1.3.2 S11 parameter

Just as with the variation of the Length parameter, the variation of the Width parameter also involves a shift in frequency, as can easily be seen for the values 0.05 m (in Figure 1.48) and 0.09m (in Figure 1.52). Since we will need to compensate for the shift caused by the previous change in the Length parameter, it can already be seen that the 0.08 m value results in an S11 with a minimum peak of -21dB at our frequency of interest (750 MHz).

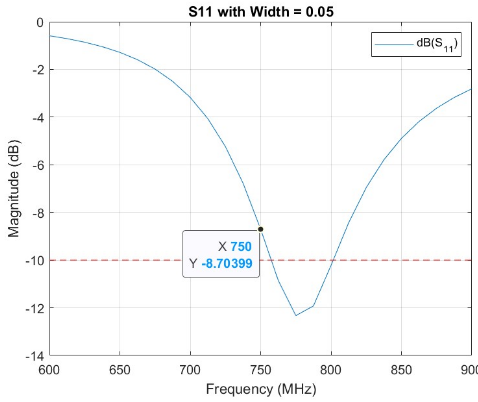

Figure 1.48

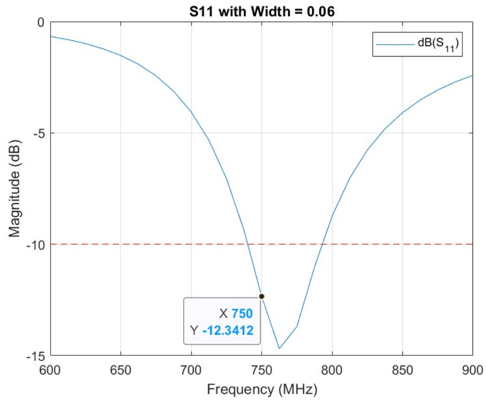

Figure 1.49

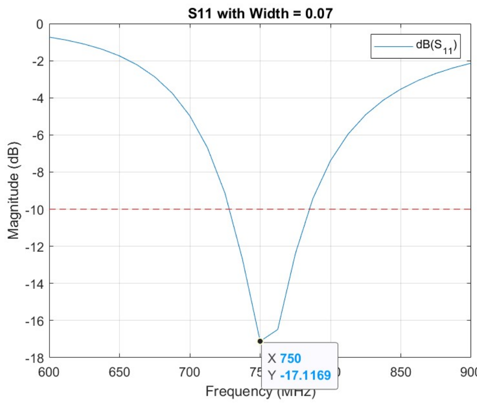

Figure 1.50

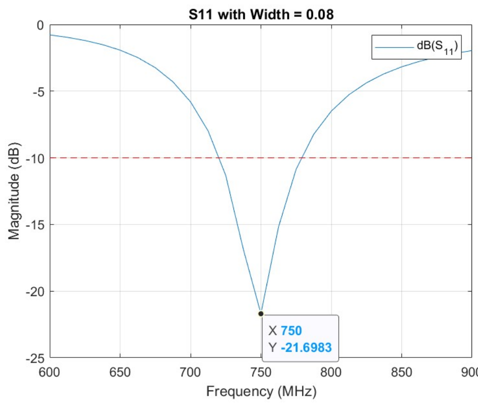

Figure 1.51

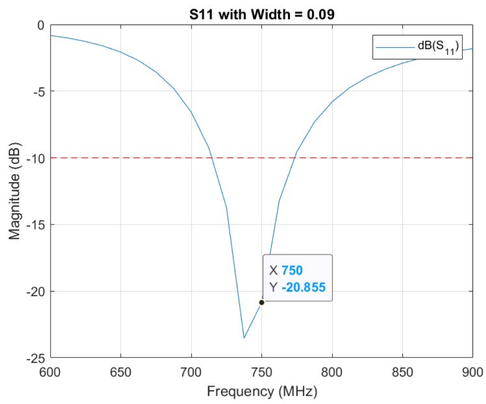

Figure 1.52

1.3.3 3D Pattern

From the 3D Pattern evaluation, it can be seen that increasing the width affects the directivity of the antenna. In fact, from Figure 1.53 it can be seen that for the value 0.05 m the antenna appears to have a wider beamwidth, while for higher values of the Width parameter the antenna radiates more directionally (as depicted in Figure 1.57).

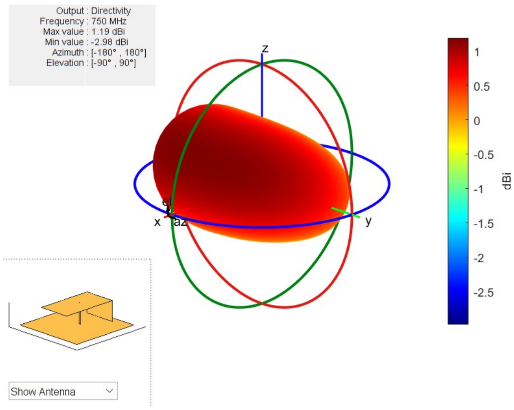

Figure 1.53: Pattern 3D per Width=0.05m

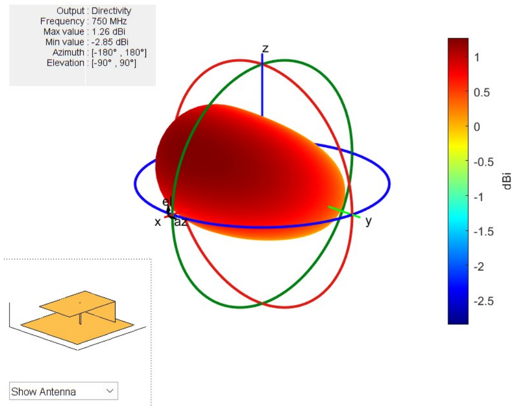

Figure 1.54: Pattern 3D per Width=0.06m

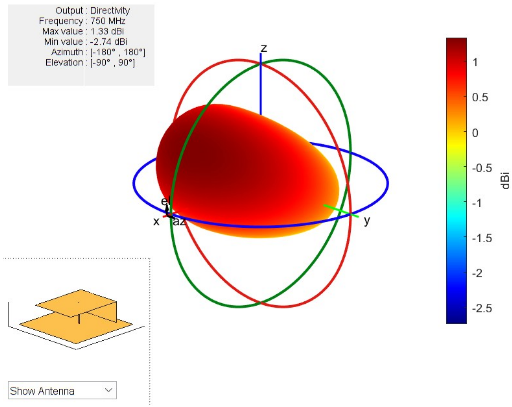

Figure 1.55: Pattern 3D per Width=0.07m

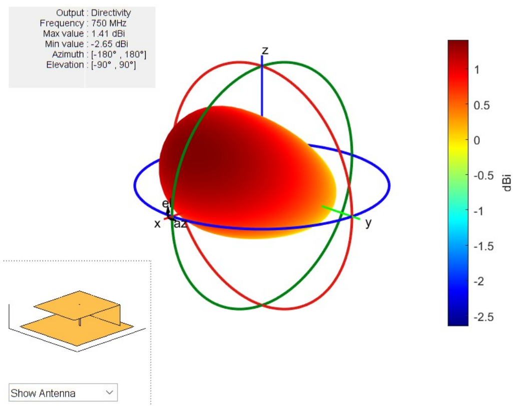

Figure 1.56: Pattern 3D per Width=0.08m

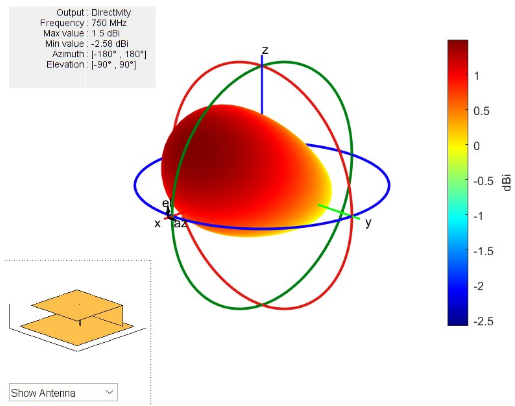

Figure 1.57: Pattern 3D per Width=0.09m

1.3.4 Current distribution

From the following graphs we can see that the current distribution is more concentrated on the edges of the antenna when the Width parameter is set at the most extreme values such as 0.05 m and 0.09 m, vice versa for intermediate values such as 0.7 m and 0.08 m, for which the current distribution is more uniform.

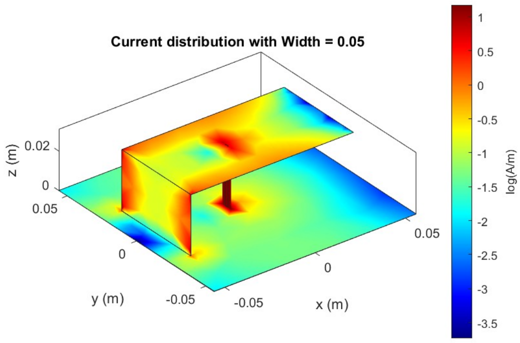

Figure 1.58

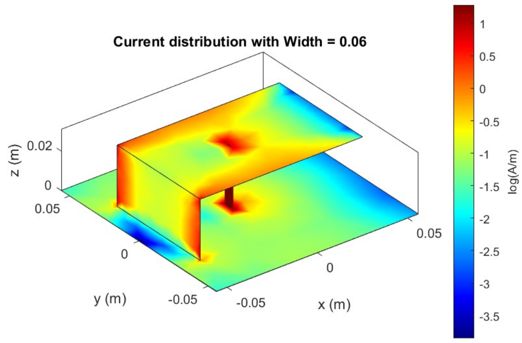

Figure 1.59

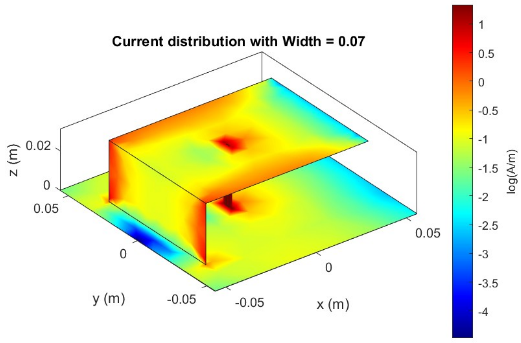

Figure 1.60

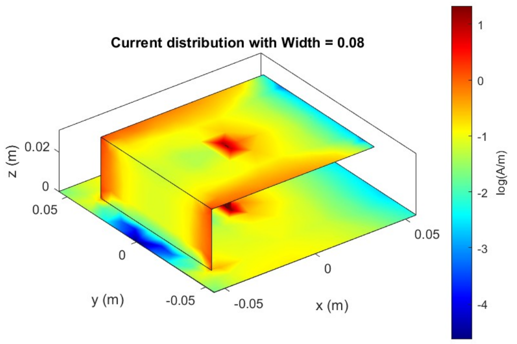

Figure 1.61

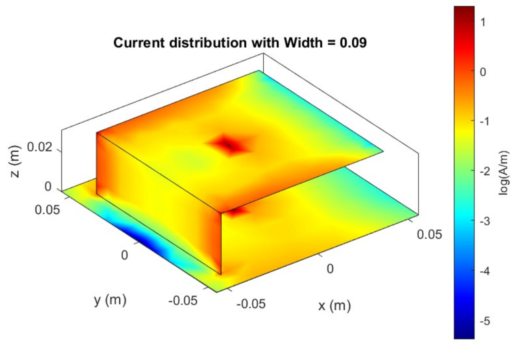

Figure 1.62

Conclusion of Width sweep

Variation in the Width parameter proved to be crucial in the design of the PIFA antenna; in fact, even a small variation in this parameter results in large changes in its optimization.

After evaluating the effects of the variations, the following was chosen 0.08m as the best value: with this value, the resonant frequency can be brought back to 750 MHz and at the same time excellent impedance values can be obtained as well as a more directive antenna. The graphs of S11 before and after the Width parameter variation are shown below.

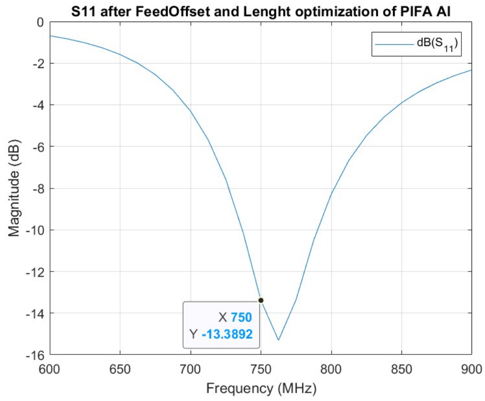

Figure 1.63

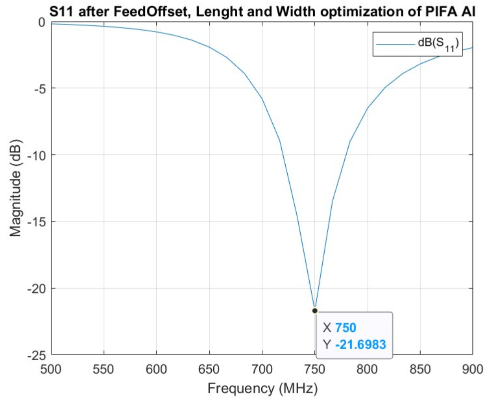

Figure 1.64

1.4 Comparison of initial and optimized antenna

In this section, a comparison will be made between the initial antenna (generated with the Antenna Toolbox and the Statistics and Machine Learning Toolbox) and the antenna resulting from the antenna optimization phase, according to the parameters mentioned in section .

- **Geometry**: the optimization process was carried out downstream of the parametric sweep of the Feed Offset, Length and Width, in fact it can be seen that the optimized antenna geometry is very different from the initial one.

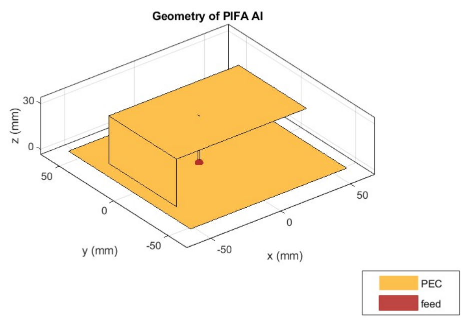

Figure 1.65

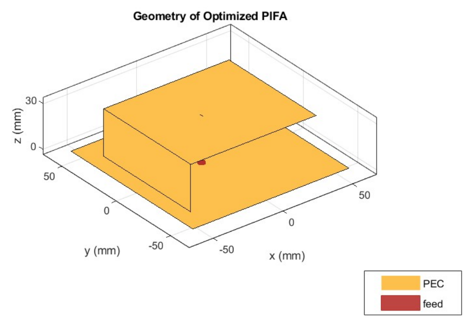

Figure 1.66

- **Mesh**: discretization of the two antennas appears to be similar, although differences can be seen due to the different current distribution. In fact the discretization is more intense on the edge of antenna.

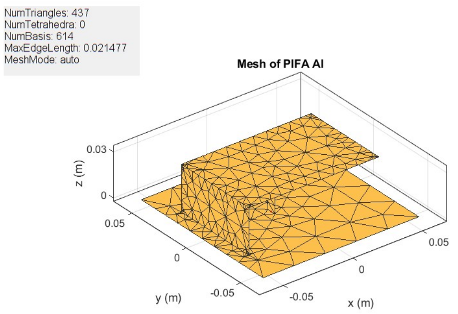

Figure 1.67

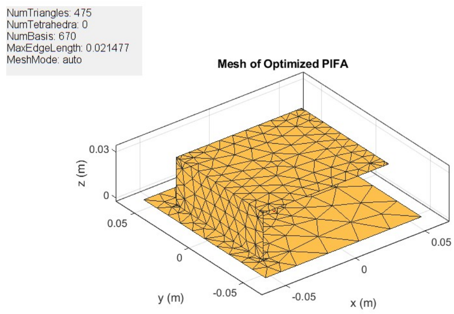

Figure 1.68

- **Impedance**: as can be seen from the graphs below, the impedance of the optimized antenna is improved over that of the initial antenna with a lower reactance and resistance value closer to the default value of 50 Ohms.

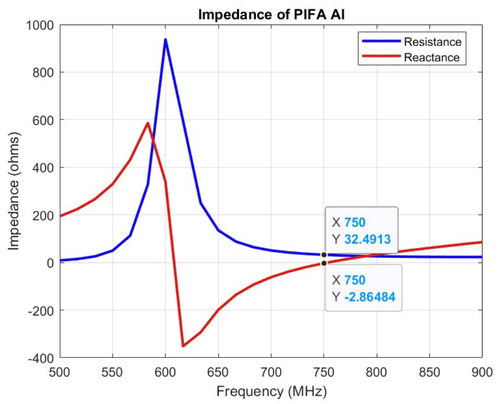

Figure 1.69

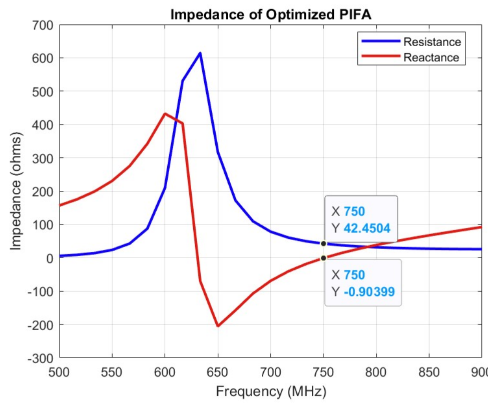

Figure 1.70

- **S11 parameter and Bandwidth at -10dB**: with the process of parameter variation and optimization, the minimum peak of S11 has dropped from about -13dB to about -21db and the -10dB operating bandwidth is also increased.

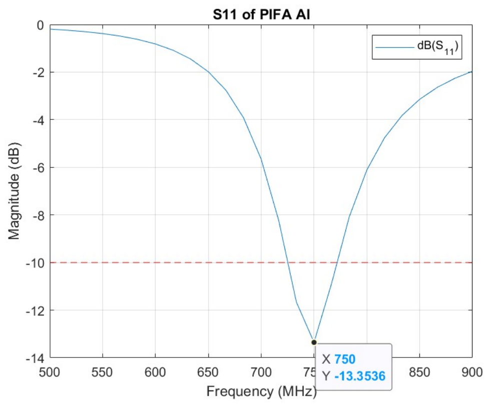

Figure 1.71

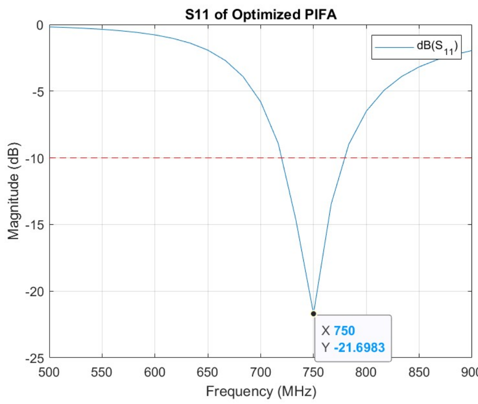

Figure 1.72

- **VSWR**: as well as the previous parameters, VSWR is also improved after the optimization phase, in fact in the Figure 1.74 can be seen that the value of VSWR is closer to 1.

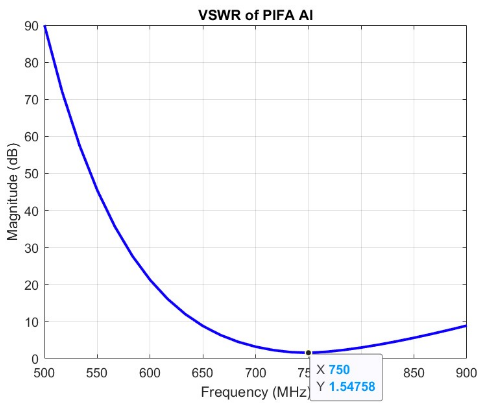

Figure 1.73

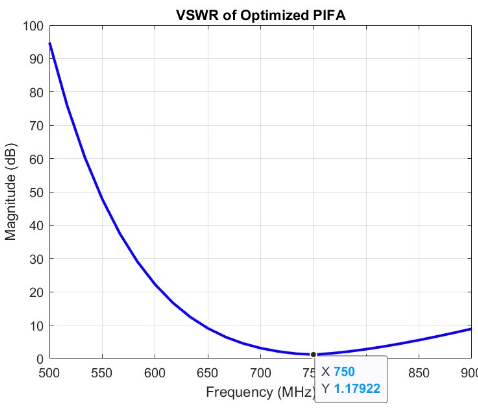

Figure 1.74

- **Pattern 2D and BeamWidth**: from Figures 1.75 and 1.76, it can be seen that the direction of maximum radiation is shifted 30 degrees above the azimuth plane and about 30 degrees from the elevation plane for the PIFA made by AI. The beamwidth (-3dB) for the PIFA AI in these two planes are plotted in Figure 1.77 and 1.78. On the other hand, from Figures 1.79 and 1.80 it can be seen that it radiates more in the open circuit direction (at 0 degrees) and not in the short circuit direction at 180 degrees. The latter property is crucial for the application of PIFA antennas in cellular devices, in order to obtain a good level of SAR. Moreover, the beamwidth (-3dB) for the optimized PIFA in the two planes are plotted in Figure 1.81 and 1.82.

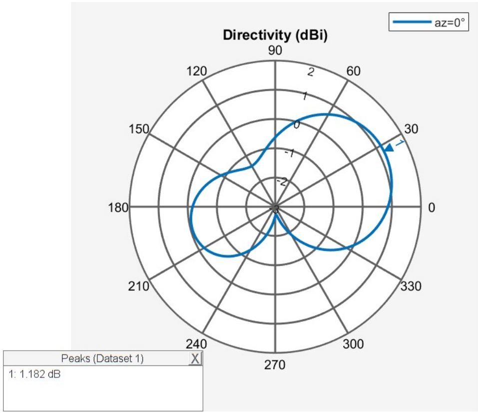

Figure 1.75: Pattern in the Elevation Plane of PIFA AI

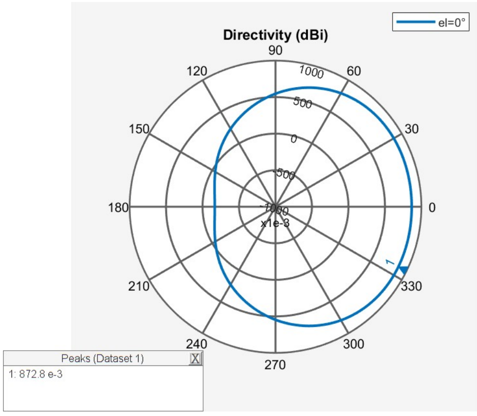

Figure 1.76: Pattern in the Azimuth Plane of PIFA AI

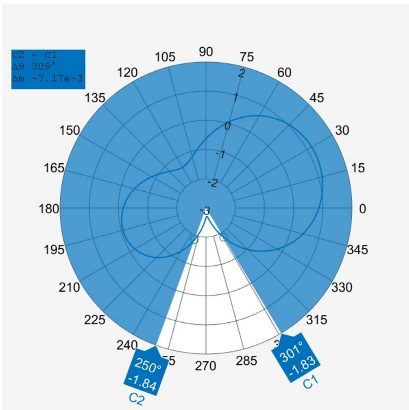

Figure 1.77: Beamwidth in the Elevation Plane of PIFA AI

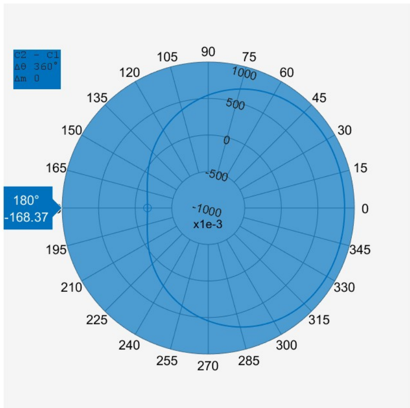

Figure 1.78: Beamwidth in the Azimuth Plane of PIFA AI

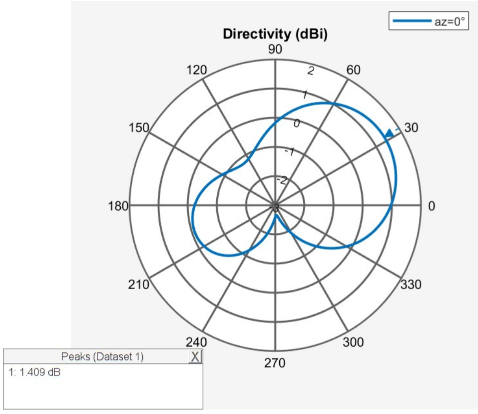

Figure 1.79: Pattern in the Elevation Plane of Optimized PIFA

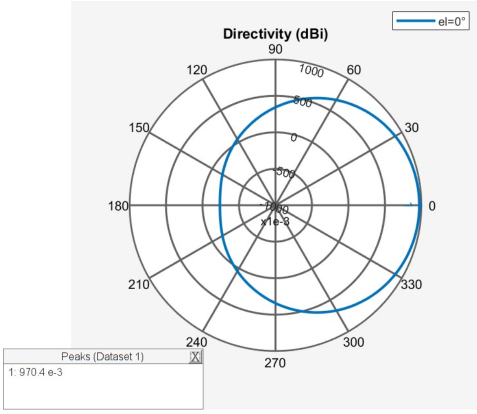

Figure 1.80: Pattern in the Azimuth Plane of Optimized PIFA

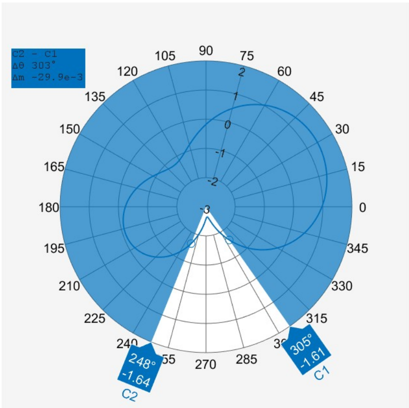

Figure 1.81: Beamwidth in the Elevation Plane of Optimized PIFA

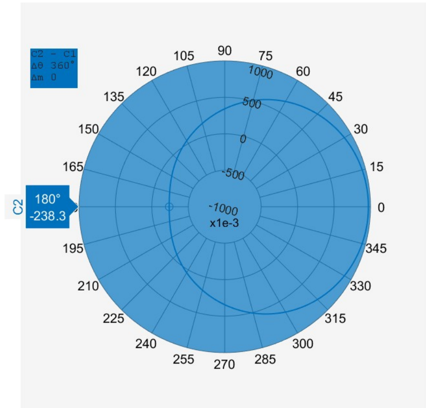

Figure 1.82: Beamwidth in the Azimuth Plane of Optimized PIFA

- **Pattern 3D**: as already noted in the 2D pattern analysis, after the optimization process the directivity of the antenna improved, in fact the maximum value of directivity changes from 1.18 dBi to 1.41 dBi.

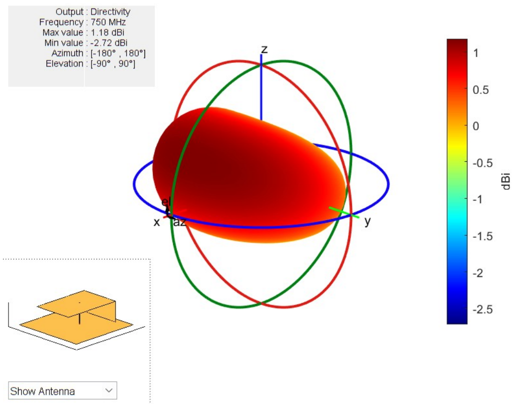

Figure 1.83: Pattern 3D of PIFA AI

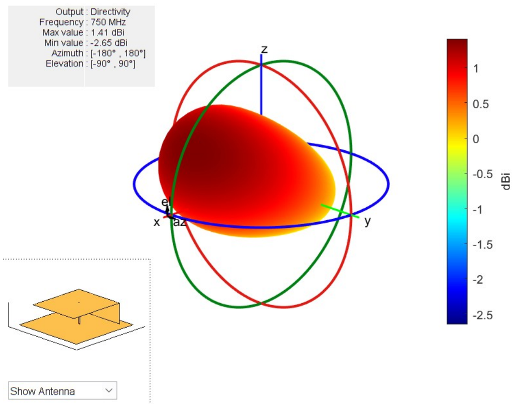

Figure 1.84: Pattern 3D of Optimized PIFA

- **Current distribution**: it can be seen that the current distribution is different since, for example, more current circulates on the open circuit of the optimized antenna than the initial one.

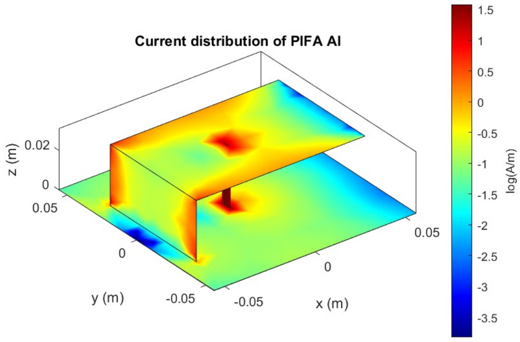

Figure 1.85

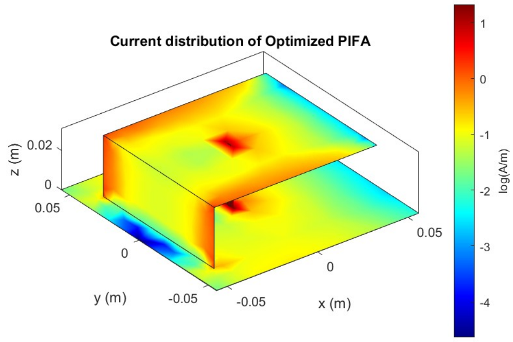

Figure 1.86

- **EH fields e Axial ratio**: From the figures below, can be seen the distribution of electric and magnetic fields in the various directions. In particular, it can be seen from Figure 1.89 and Figure 1.90 that the polarization of the PIFA AI antenna turns out to be elliptical and constant in the band under consideration, unlike the optimized antenna, which while remaining constant in the band of interest turns out to have more linear polarization.

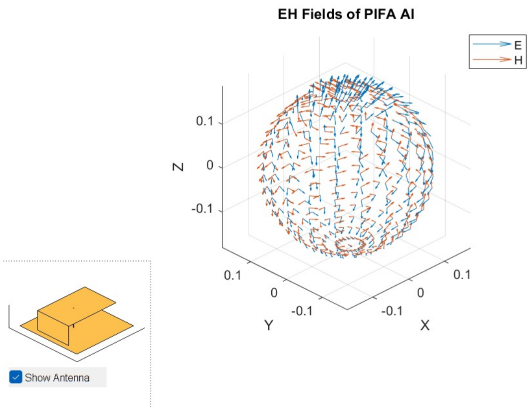

Figure 1.87

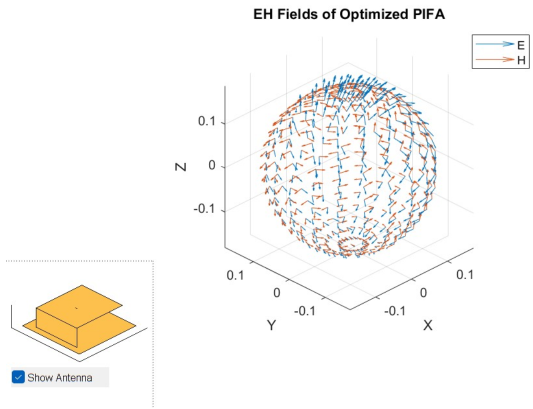

Figure 1.88

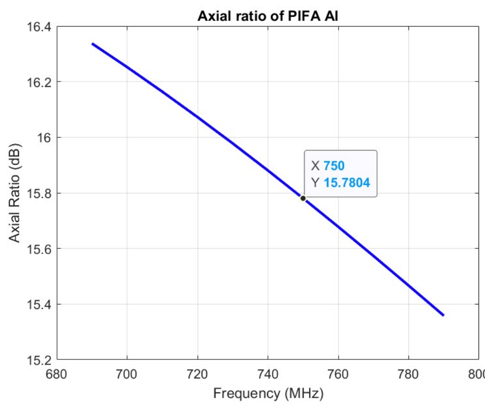

Figure 1.89

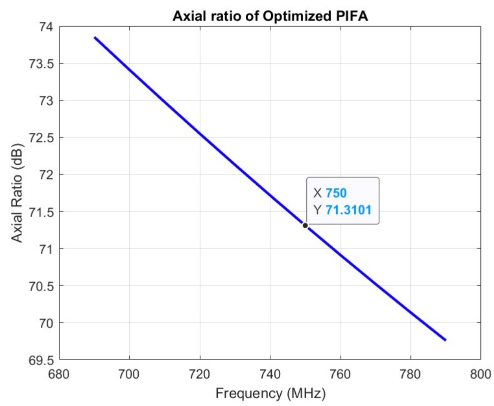

Figure 1.90

Chapter 2

PIFA Antenna operating at 3.5 GHz

In the first design phase, we used the Antenna Toolbox and the Statistics and Machine Learning Toolbox to obtain the first version of the antenna operating at this frequency, in order to be optimised later. The obtained parameters are as follows:

- `Length: 0.0200 m`
- `Width: 0.0133 m`
- `ShortPinWidth: 0.0133 m`
- `Height: 0.0067 m`
- `FeedOffset: [-0.0013 0] m`
- `Feed Width: 0.0013 m`
- `GroundPlaneLength: 0.0240 m`
- `GroundPlaneWidth: 0.0240 m`
- `SubstrateEpsilonR: 1`
- `Conductor: PEC`

Then, the project continued with the optimisation of the antenna by implementing for-loops, in order to find the best values for the Feed Offset, GroundPlaneLength, GroundPlaneWidth and Length, based on the variation of the parameters described below. Finally, a comparison was made between the antenna generated by the Antenna Toolbox and the optimised antenna.

2.1 Performance based on changes in Feed Offset

It was decided to vary the value of the parameter `Feed Offset` in the range of 4 mm, from 1 mm to 5 mm, with a step of 1 mm, in order to evaluate 5 different values. Below are the graphs of the various parameters and an evaluation of them after variation for each individual value.

2.1.1 Impedance

The following graphs show how the variation of the Feed Offset concretely affects the impedance of the antenna. In fact, for values of Feed Offset, closer to the short circuit, farther from the initial value given by AI, the reactance moves away from the original value of -3.5 ohm and also the resistance with the initial value of 32 ohm. These images reveals that moving the feed point closer to the short circuit on a PIFA antenna can increase the reactance. This fact is visible especially in Figure 2.5.

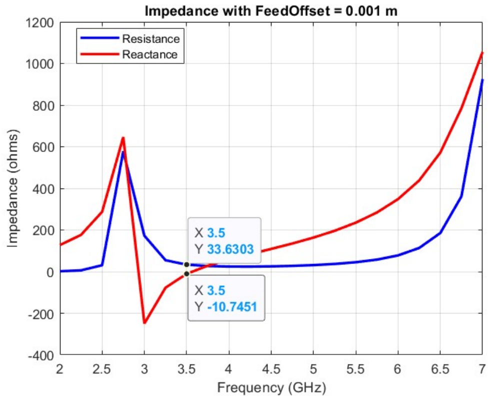

Figure 2.1

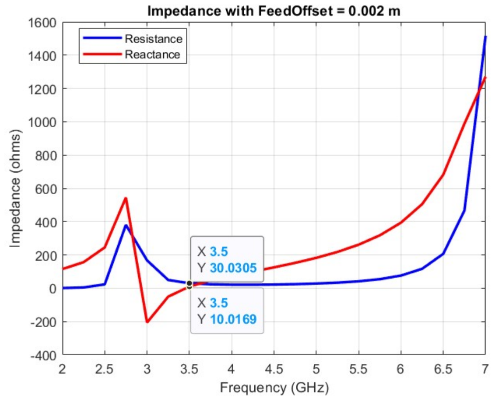

Figure 2.2

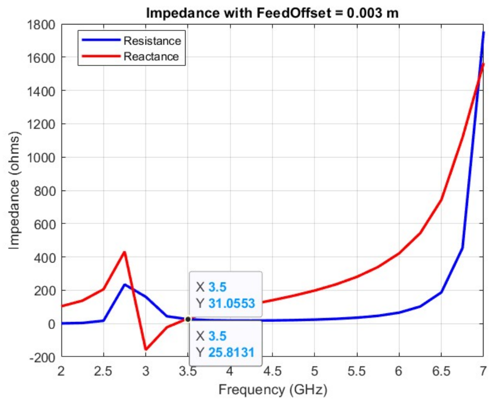

Figure 2.3

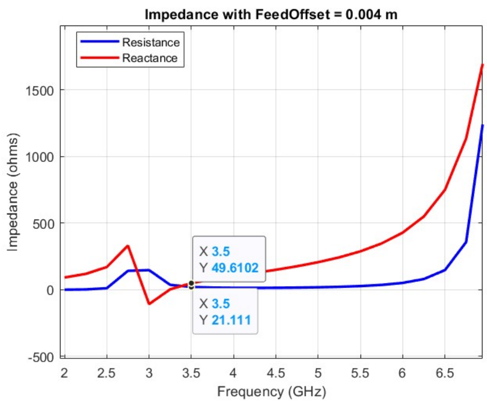

Figure 2.4

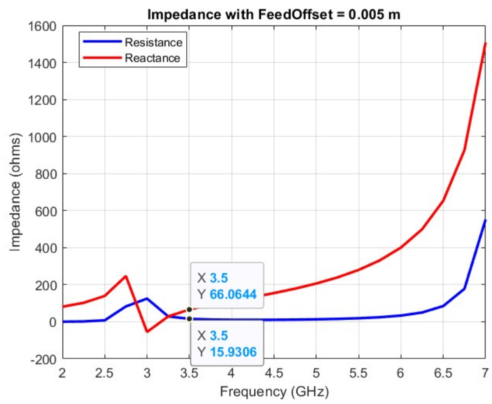

Figure 2.5

2.1.2 S11 parameter

It can also be seen from these graphs how important the variation of the Feed Offset is for the design of a PIFA antenna, not so much for the magnitude variation, which is also modified, as for the frequency shift. In fact, this is shown in Figure 2.8, Figure 2.9 and Figure 2.10. Although there is a shift, the value of S11, considering a reference impedance of 50 ohm, is better in Figure 2.8 and Figure 2.9.

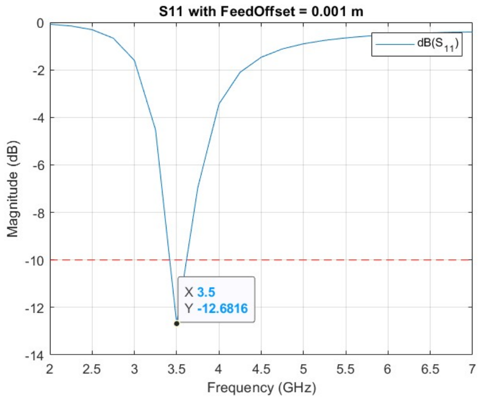

Figure 2.6

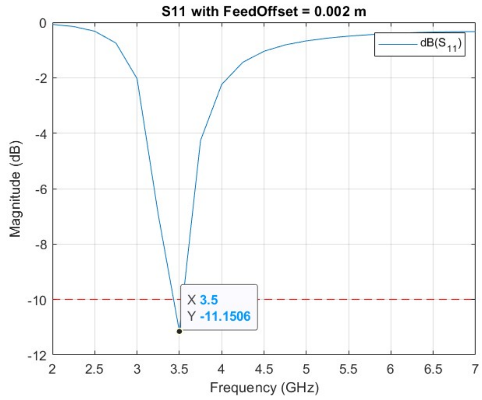

Figure 2.7

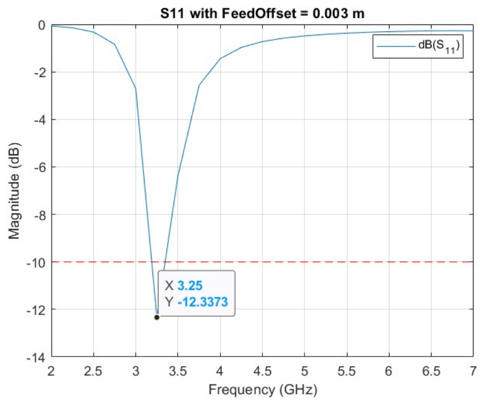

Figure 2.8

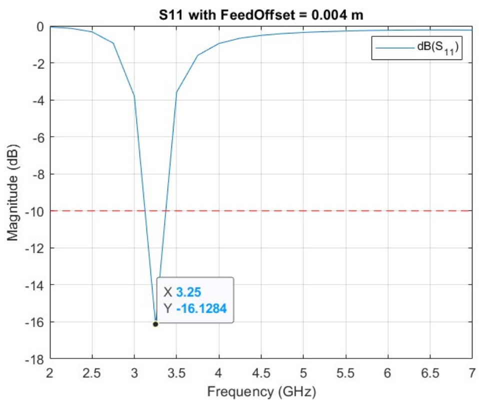

Figure 2.9

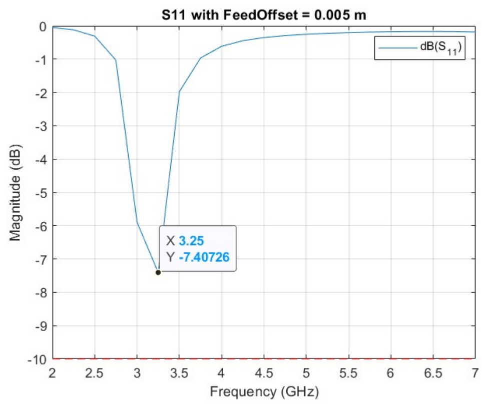

Figure 2.10

2.1.3 3D Pattern

For 3D Pattern evaluation, made at 3.5 GHz, changing the Feed Offset produces small change in maximum and minimum of directivity, reducing also the the beam-width, as it can be seen below. The reason is the fact that the feed point is closer to the short circuit, as mentioned before.

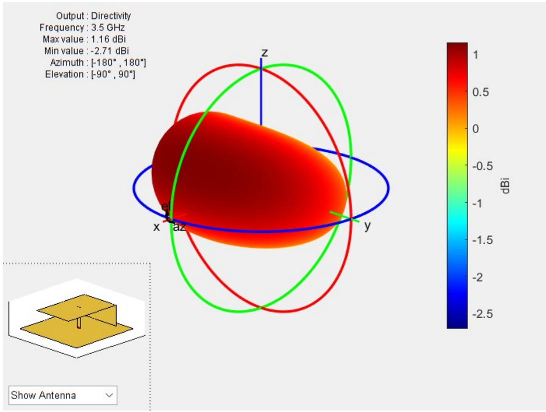

Figure 2.11: 3D pattern with FeedOffset=[-1, 0] mm

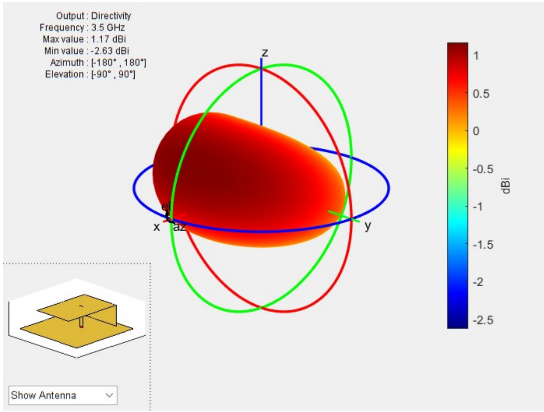

Figure 2.12: 3D pattern with FeedOffset=[-2, 0] mm

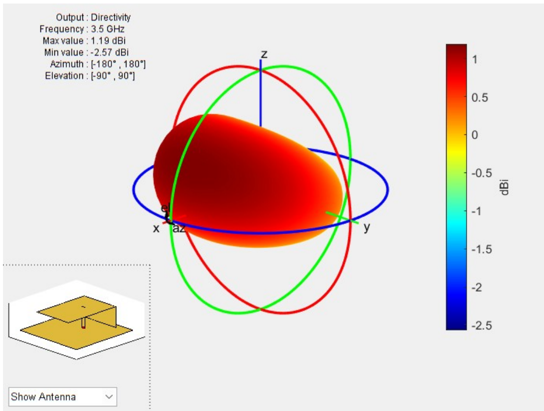

Figure 2.13: 3D pattern with FeedOffset=[-3, 0] mm

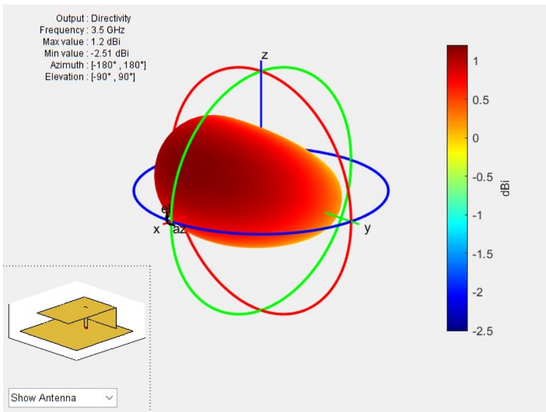

Figure 2.14: 3D pattern with FeedOffset=[-4, 0] mm

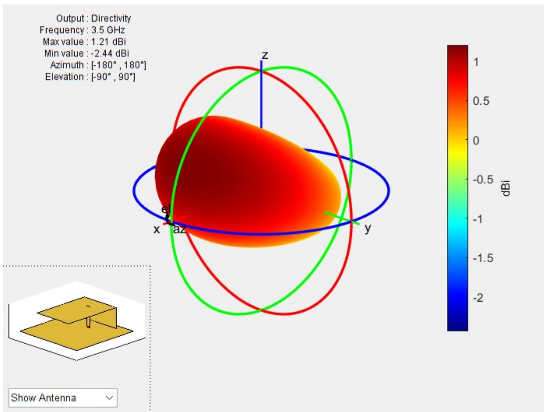

Figure 2.15: 3D pattern with FeedOffset=[-5, 0] mm

2.1.4 Current distribution

Even for the evaluation of current distribution, made at 3.5 GHz, changing the Feed Offset produces a change in the current distribution. In fact, it can be seen from Figure 2.16 and Figure 2.20.

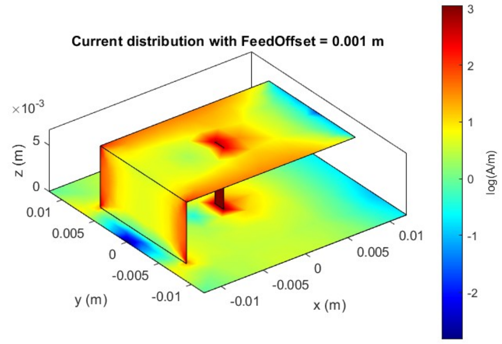

Figure 2.16

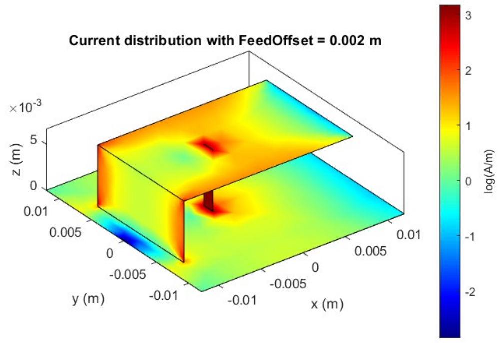

Figure 2.17

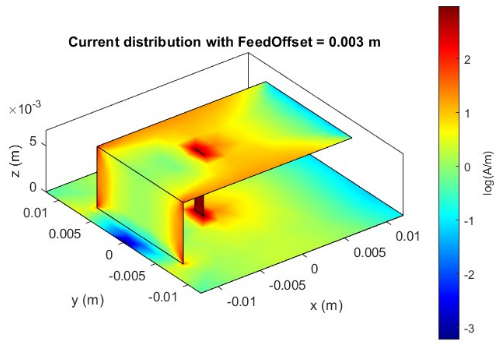

Figure 2.18

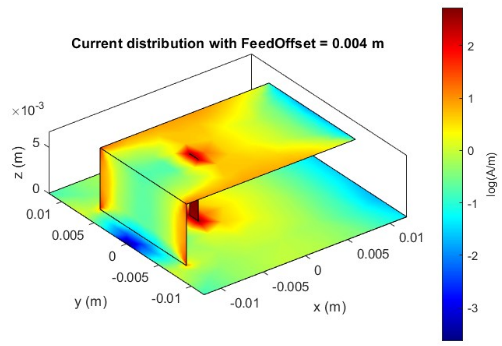

Figure 2.19

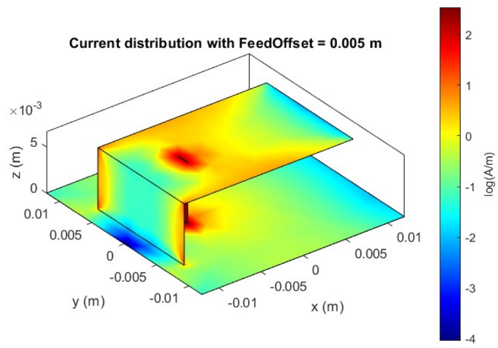

Figure 2.20

Conclusion of Feed Offset sweep

After evaluating the effects of changes in the Feed Offset parameter, [-0.004, 0] m was chosen as the best value: this results in frequency shift to 3.25 GHz but, at the same time, it improves the value of S11 with 50 ohm of reference impedance and indeed reactance was about 3 ohm and resistance about 40 ohm. For the following sweep, the value of the Feed Offset parameter was set to [-0.004,0] m and it was tried to shift again the frequency to the main frequency of 3.5 GHz.

2.2 Performance based on changes in Dimensions of Ground Plane

It was decided to vary the value of the parameters `GroundPlaneLength` and `GroundPlaneWidth` in the same proportional difference between `Length` and `Width` of the top patch. The `GroundPlaneLength` was varied in a range of 4 mm, from 20 mm to 24 mm, with a step of 1 mm. Proportionally, the `GroundPlaneWidth` was varied in a range of 4 mm, from 14 mm to 18 mm, with a step of 1 mm. The graphs of the various parameters after variation for each value are shown from the next page.

2.2.1 Impedance

It is clear that also the dimensions of ground plane are two key parameter in the design of a PIFA antenna; in fact, it can be seen that variation, with only 1 mm of step, results in large changes in impedance with respect to frequency. This is caused by the fact that, thanks to the capability of Ground Plane to reduce interferences and reflections, it is able to modify frequency of resonance and adapt the antenna.

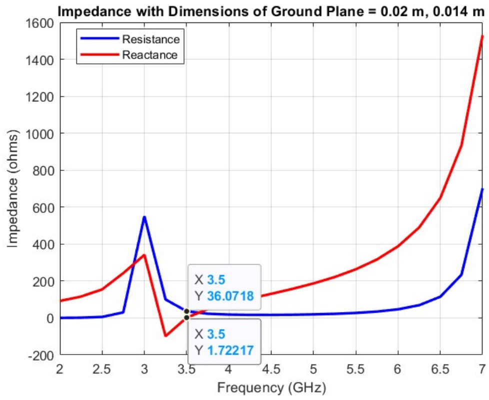

Figure 2.21

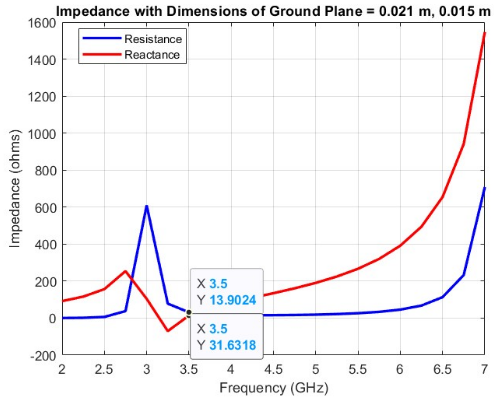

Figure 2.22

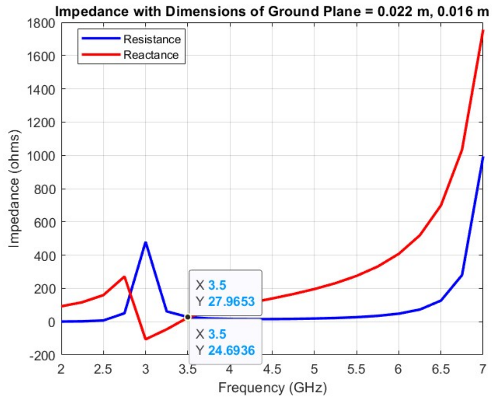

Figure 2.23

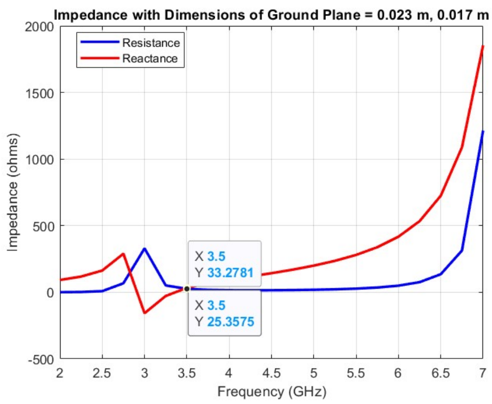

Figure 2.24

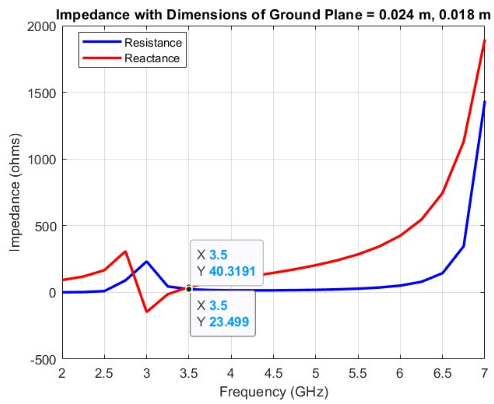

Figure 2.25

2.2.2 S11 parameter

As already noted in the evaluation with respect to impedance, the change in dimensions of the Ground Plane could shift the resonant frequency. In fact, in Figure 2.26 and in Figure 2.27 the resonant frequency returns to 3.5 GHz, after the decision to choose a FeedOffset which brought it to 3.25 GHz. Moreover, also the bandwidth varies with this sweep.

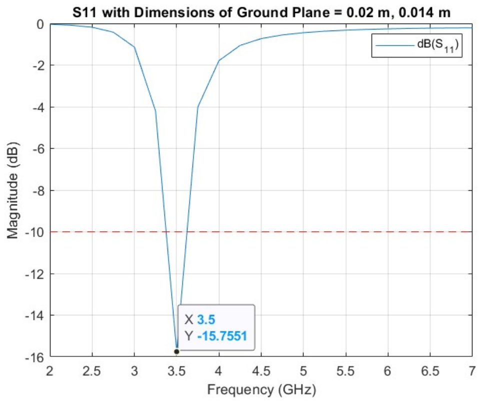

Figure 2.26

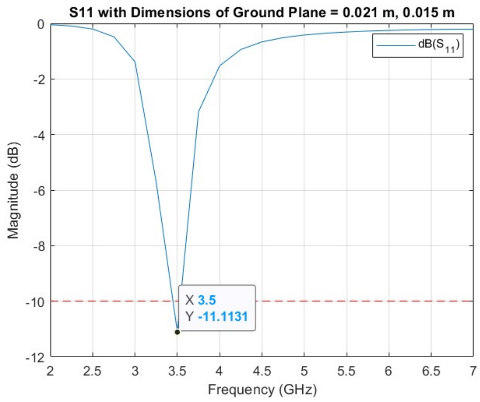

Figure 2.27

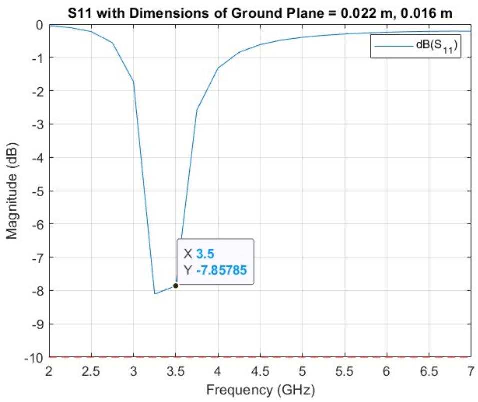

Figure 2.28

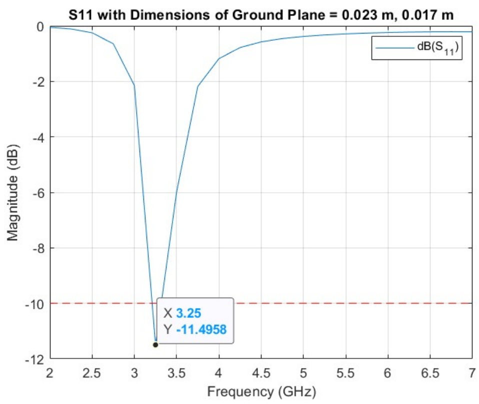

Figure 2.29

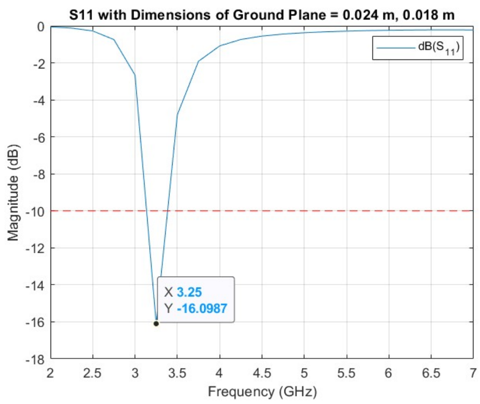

Figure 2.30

2.2.3 3D Pattern

It can be seen that increasing the dimensions of GroundPlane affects the direction of maximum antenna irradiation. In fact, for the values in Figure 2.35, it is found an antenna radiating upward. Conversely, reducing the dimensions of GroundPlane will result in more directional irradiation along the azimuth plane, as depicted in Figure 2.31. This fact happens because a larger ground plane can lead to increased reflection of electromagnetic waves upwards, especially if the antenna is mounted above the ground plane, like in this case for PIFA antenna.

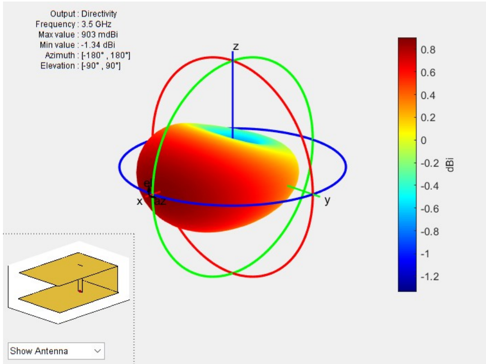

Figure 2.31: Pattern 3D with GroundPlaneLenght=20 mm and GroundPlaneWidth=14 mm

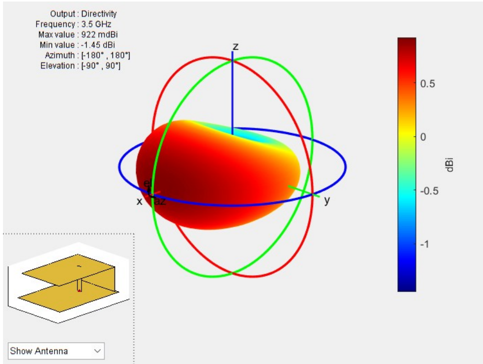

Figure 2.32: Pattern 3D with GroundPlaneLenght=21 mm and GroundPlaneWidth=15 mm

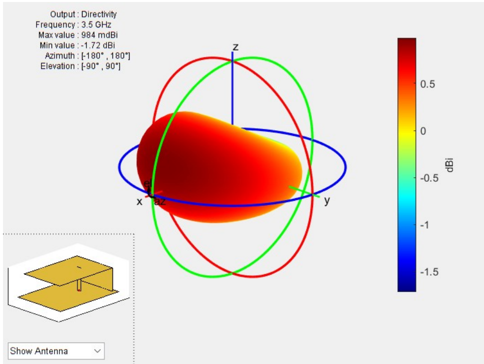

Figure 2.33: Pattern 3D with GroundPlaneLenght=22 mm and GroundPlaneWidth=16 mm

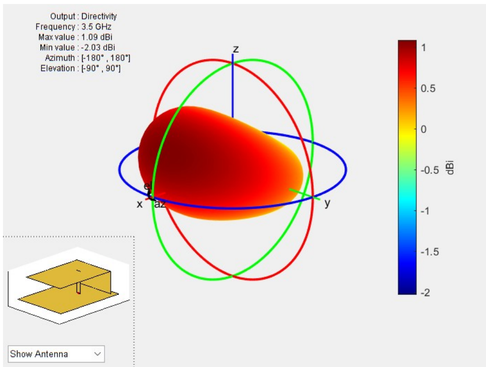

Figure 2.34: Pattern 3D with GroundPlaneLenght=23 mm and GroundPlaneWidth=17 mm

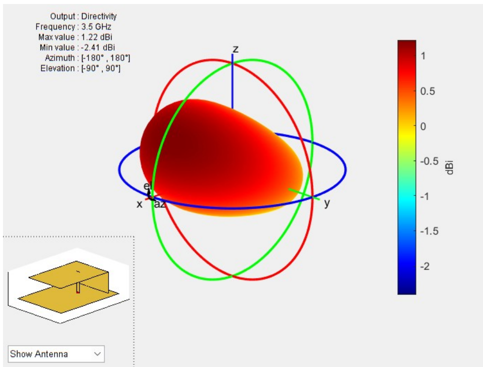

Figure 2.35: Pattern 3D with GroundPlaneLenght=24 mm and GroundPlaneWidth=18 mm

2.2.4 Current distribution

From the following graphs can be seen that the current distribution is affected by different dimensions of GroundPlane for the same reasons mentioned before. It affects the distribution of current, maintaining always greater current near the short circuit and less current close to the open circuit. The uniformity of the current and also the current on the ground regulate the efficiency of this antenna.

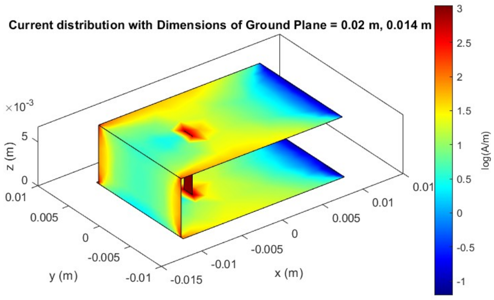

Figure 2.36

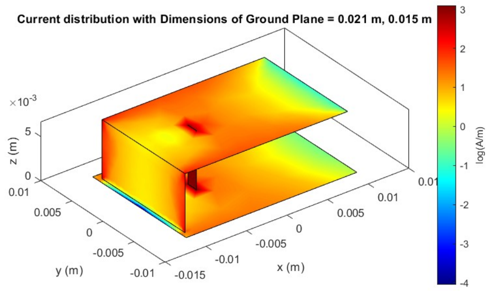

Figure 2.37

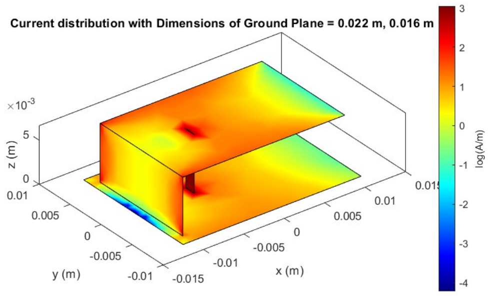

Figure 2.38

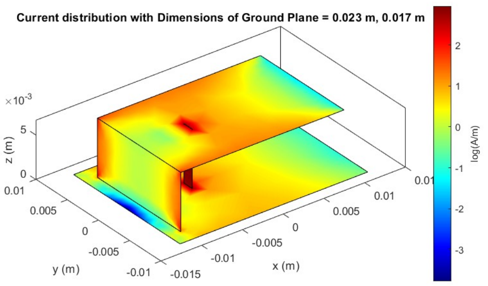

Figure 2.39

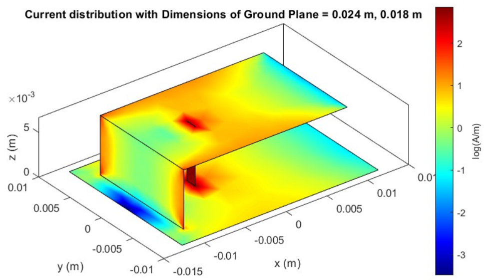

Figure 2.40

Conclusion of GroundPlane dimensions sweep

Variation in the dimensions of ground plane are also crucial in the design of the PIFA antenna. After evaluating the effects of the variations, was chosen 21 mm and 15 mm, respectively for the length and the width of the ground. This implies a slight shift in frequency that can compensate the variation made before by the FeedOffset for the frequency of resonance at 3.5 GHz. For all future evaluations the dimensions of GroundPlane are set to 21 mm and 15 mm. The graphs of S11 before and after the variation of the GroundPlane dimensions are shown below.

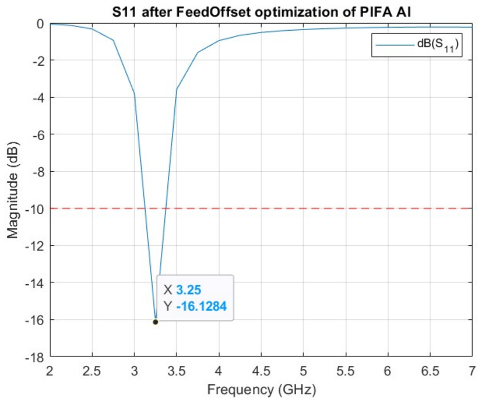

Figure 2.41

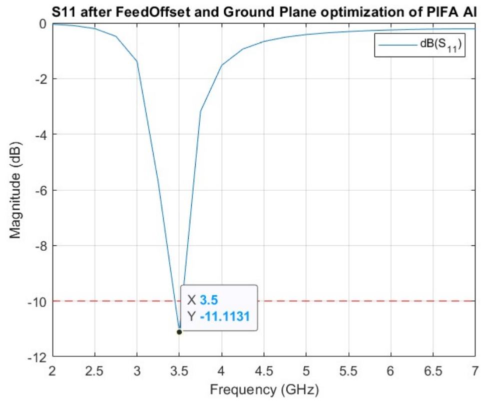

Figure 2.42

2.3 Performance based on changes in Length

Moreover, for the third step, it was decided to vary the value of the parameter `Length` in a range of 4 mm, from 17 mm to 21 mm, with a step of 1 mm. The graphs of the various parameters after variation for each value are shown below.

2.3.1 Impedance

Just as with the past parameters, we can see how the variation of the Length parameter greatly affects the impedance of the antenna. In particular, it is visible that, in relation to other dimensions choosed before, the best length in this case could be 19 mm, as it can seen in Figure 2.45. There, the reactance is very lower and the resistance is near the classic 50 ohm.

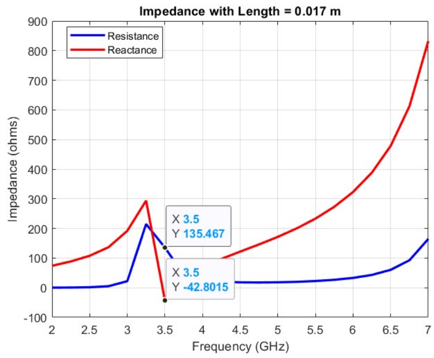

Figure 2.43

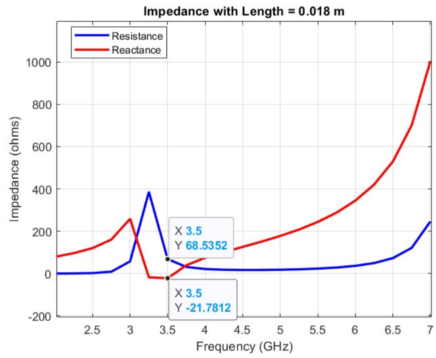

Figure 2.44

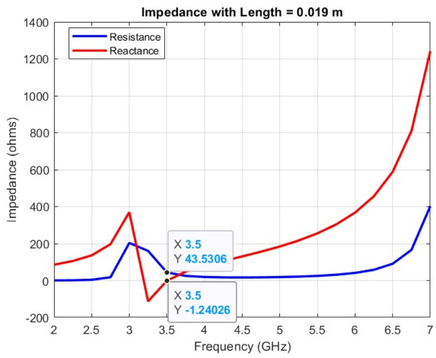

Figure 2.45

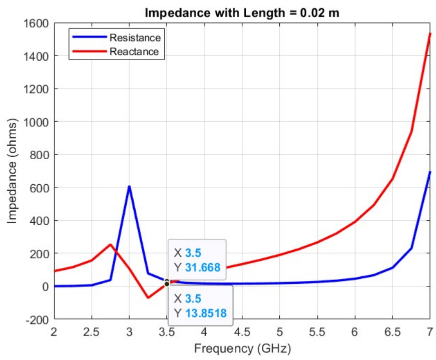

Figure 2.46

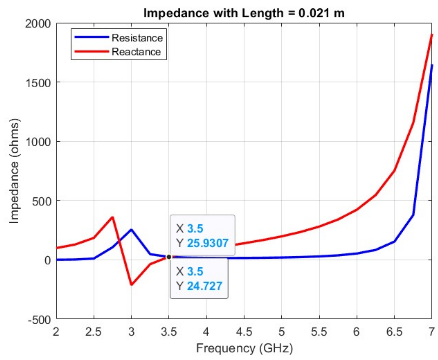

Figure 2.47

2.3.2 S11 parameter

According to what we have seen on impedance, the variation of the Length could improve S11 parameter, as can easily be seen for the value 19 mm (in Figure 2.50). There were a S11 with a minimum peak of -21dB at our frequency of interest (3.5 GHz).

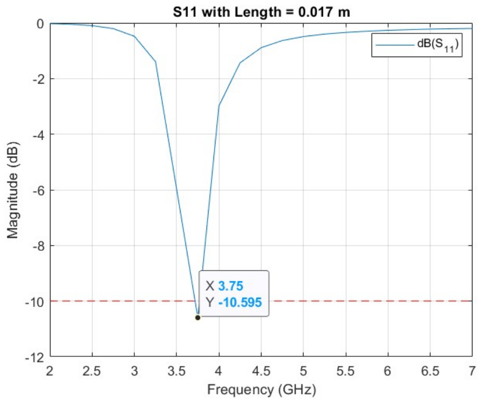

Figure 2.48

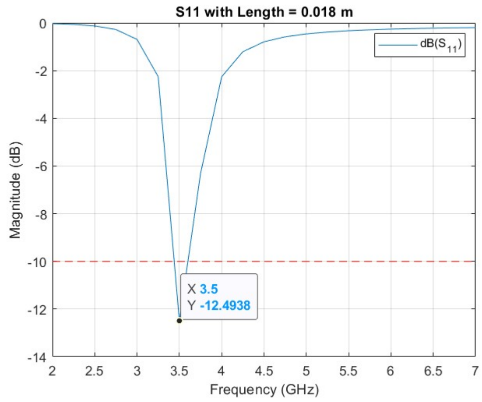

Figure 2.49

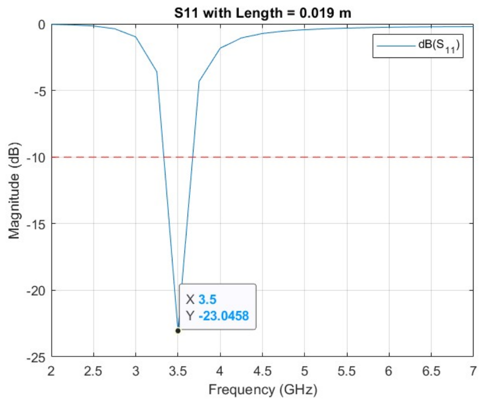

Figure 2.50

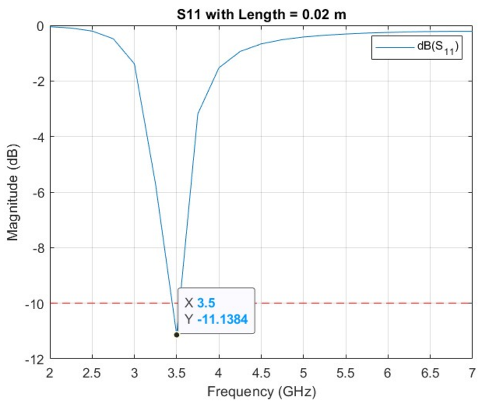

Figure 2.51

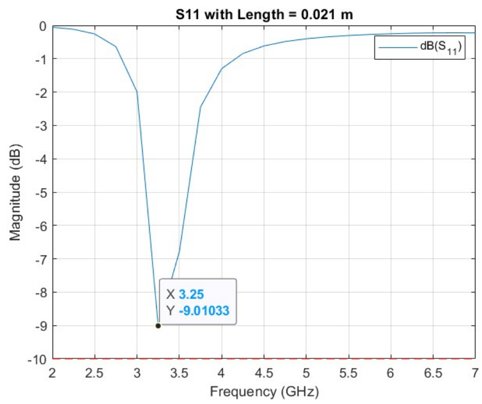

Figure 2.52

2.3.3 3D Pattern

From the 3D Pattern evaluation, it can be seen that increasing the length affects the directivity of the antenna. In fact, from the figures below it can be seen that the antenna radiates with higher intensity upward (in Figure 2.53) with 17 mm of length and with lower intensity and with small angle of elevation with 21 mm of length (in Figure 2.57). Obviously, this values of length depend on the other dimensions of the antenna designed.

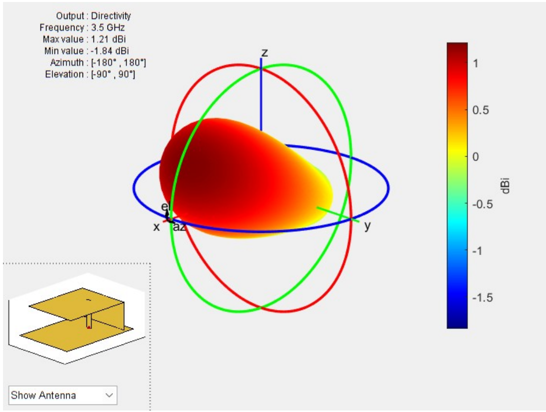

Figure 2.53: Pattern 3D with Length=17 mm

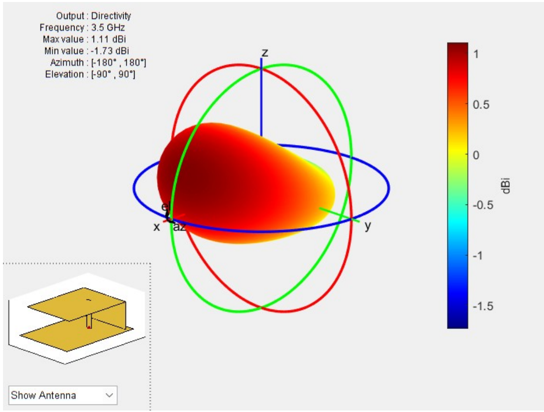

Figure 2.54: Pattern 3D with Length=18 mm

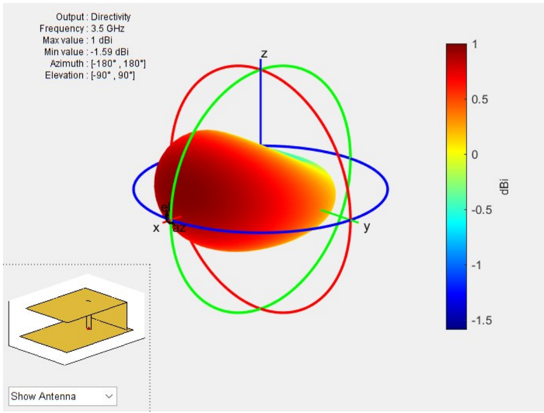

Figure 2.55: Pattern 3D with Length=19 mm

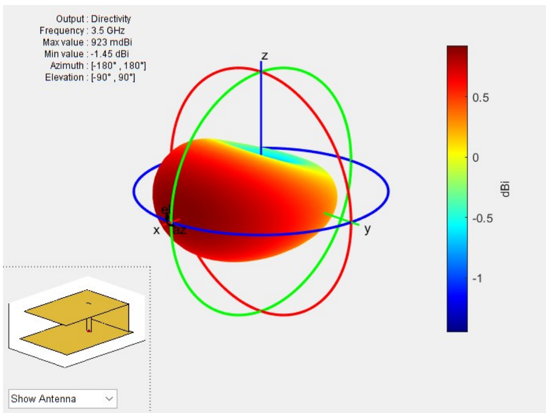

Figure 2.56: Pattern 3D with Length=20 mm

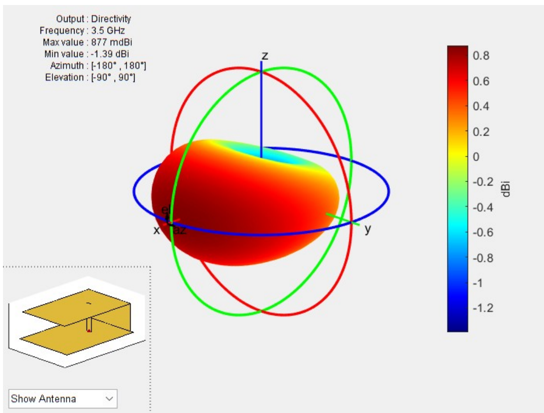

Figure 2.57: Pattern 3D with Length=21 mm

2.3.4 Current distribution

From the following graphs it can visible that the current distribution is more concentrated on the edges of the antenna and in all the cases analyzed is almost uniformed, with the exception of the length=21 mm, where all the parameters analyzed previously (Impedence, S11 and pattern) are also very bad. In this case (Figure 2.62) the length becomes equal to the GroundPlane length and it could be the reason why efficiency is lower.

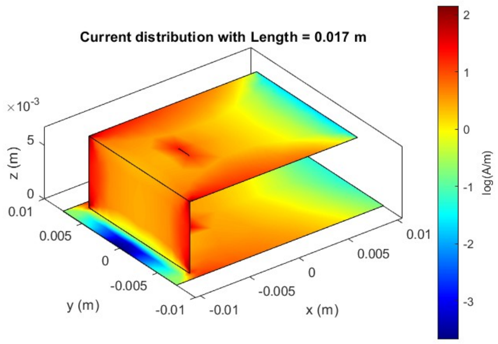

Figure 2.58

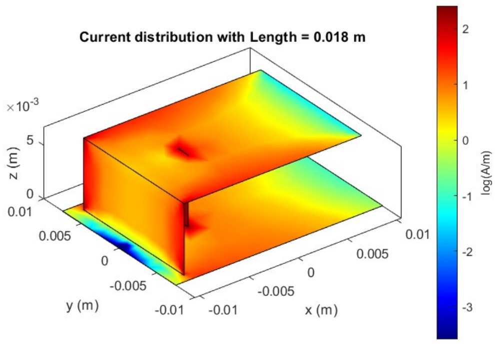

Figure 2.59

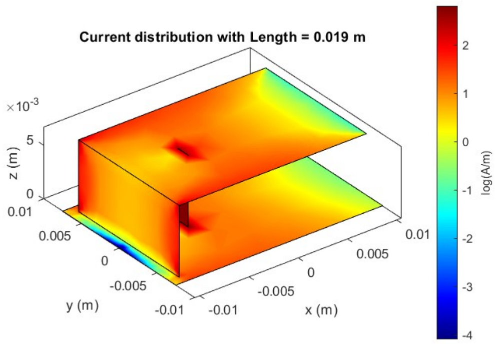

Figure 2.60

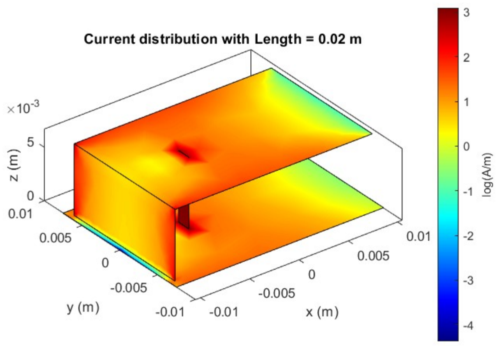

Figure 2.61

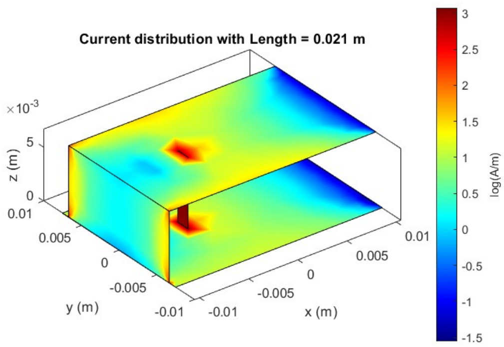

Figure 2.62

Conclusion of Length sweep

Variation in the Length parameter proved to be crucial in the design of the PIFA antenna; in fact, even a small variation in this parameter results in large changes in its optimization, in particular for S11. After evaluating the effects of the variations, the Length was set to 19 mm: with this value, the resonant frequency is confirmed at 3.5 GHz with a good impedance value and a larger bandwidth. The graphs of S11 before and after the Length variation are shown below.

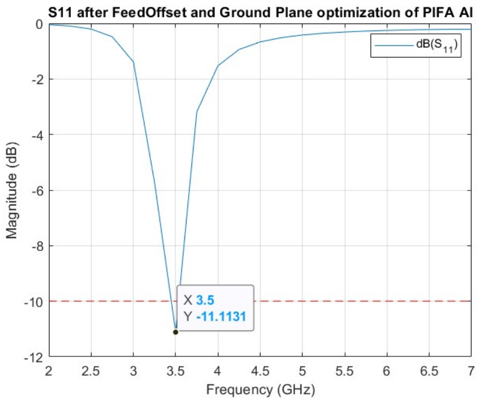

Figure 2.63

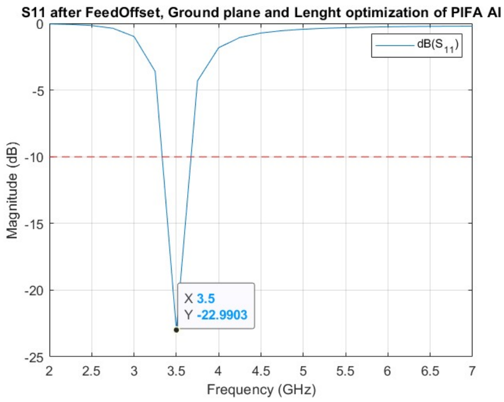

Figure 2.64

2.4 Comparison of initial and optimized antenna

In this section, a comparison will be made between the initial antenna (generated with the Antenna Toolbox and the Statistics and Machine Learning Toolbox) and the antenna resulting from the antenna optimization phase, according to the parameters mentioned in section .

- **Geometry**: the optimization process was carried out downstream of the parametric sweep of the Feed Offset, GroundPlane dimensions and Length of the top patch. In fact, it can be seen that the optimized antenna geometry is different from the initial one.

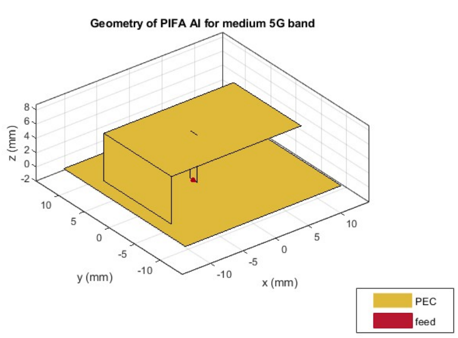

Figure 2.65

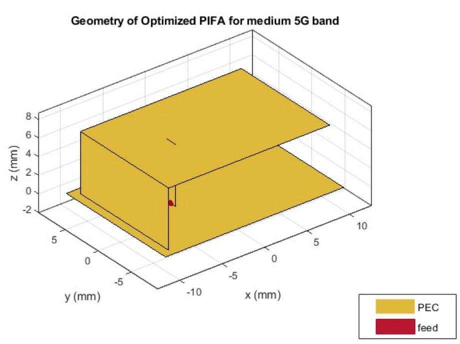

Figure 2.66

- **Mesh**: discretization of the two antennas appears to be similar, although differences can be seen due to the different current distribution, which is more on the edge. The automatic mesh of the antenna made by toolbox needs more triangles (792) than the other optimized (689).

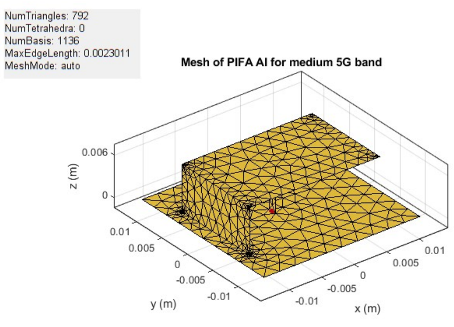

Figure 2.67

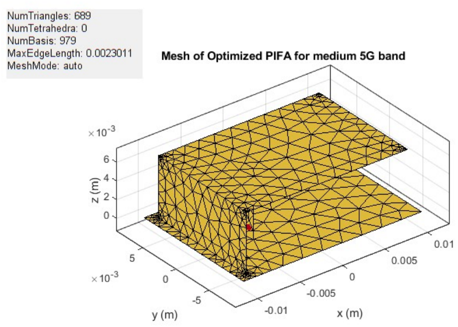

Figure 2.68

- **Impedance**: as can be seen from the graphs below, the impedance of the optimized antenna is improved over that of the initial antenna, for both reactance and resistance, considering a line of classical 50 ohm.

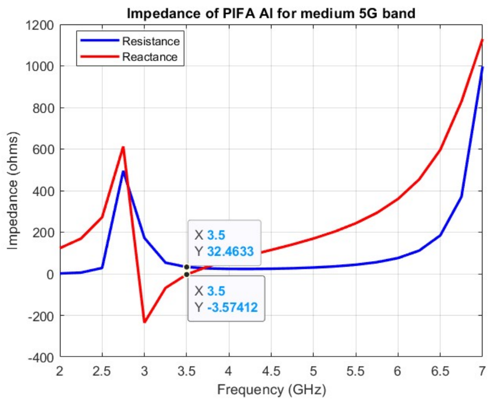

Figure 2.69

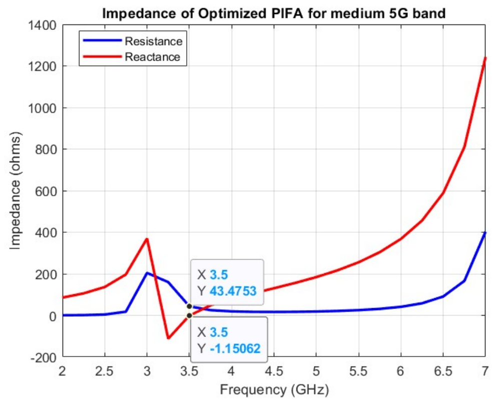

Figure 2.70

- **S11 parameter and Bandwidth at -10dB**: with the process of parameter variation and optimization, the minimum peak of S11 has dropped from about -13dB to about -22db and the -10dB operating bandwidth is also increased.

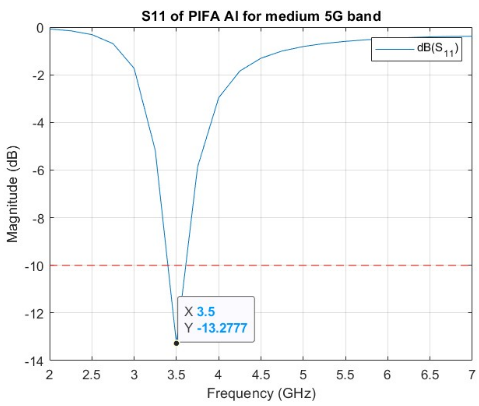

Figure 2.71

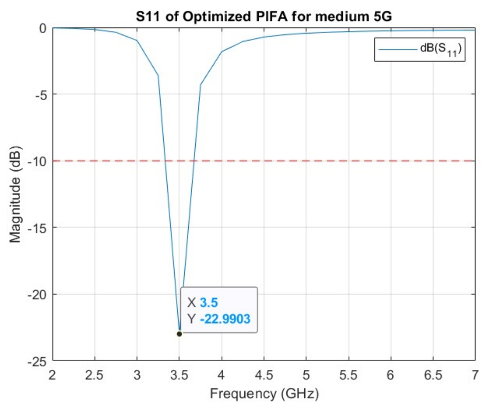

Figure 2.72

- **VSWR**: as well as the previous parameters, VSWR is also improved after the optimization phase. Infact it is closer to 1, which means there is less reflection, and consequently, the ROS decreases, indicating better matching between the antenna and the transmission line.

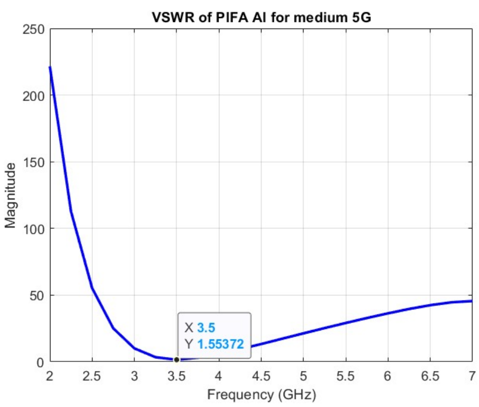

Figure 2.73

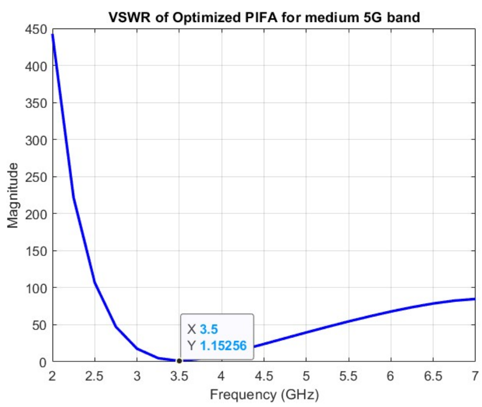

Figure 2.74

- **Pattern 2D and BeamWidth**: from Figures 2.75 and 2.76, it can be seen that the direction of maximum radiation is shifted 30 degrees above the azimuth plane and 30 degrees from the elevation plane for the PIFA made by AI. The beamwidth (-3dB) for the PIFA AI in these two planes are plotted in Figure 2.77 and 2.78. On the other hand, from Figures 2.79 and 2.80 it can be seen that the optimized antenna is more directive in the azimuth plane and especially how it radiates more in the open circuit direction (at 0 degrees) and not in the short circuit direction at 180 degrees. The latter property is crucial for the application of PIFA antennas in cellular devices, in order to obtain a good level of SAR. Moreover, the beamwidth (-3dB) for the optimized PIFA in the two planes are plotted in Figure 2.81 and 2.82 and highlight the fact that there isn't the level in which is found half of power (-3dB).

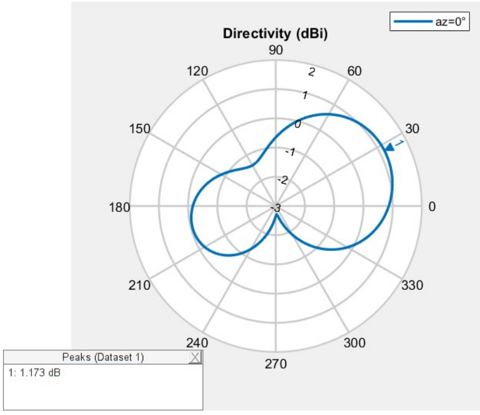

Figure 2.75: Pattern in the Elevation Plane of PIFA AI

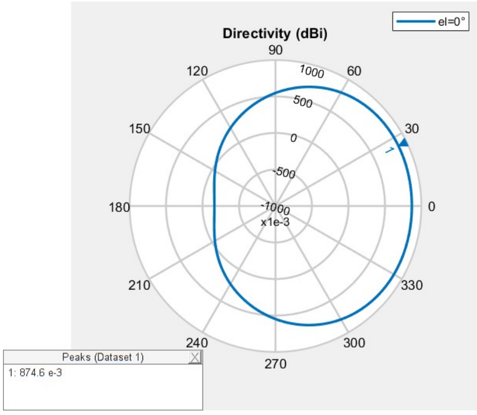

Figure 2.76: Pattern in the Azimuth Plane of PIFA AI

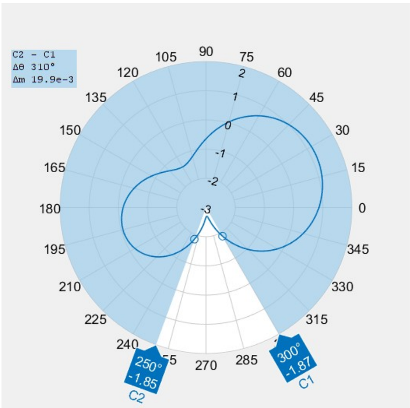

Figure 2.77: Beamwidth in the Elevation Plane of PIFA AI

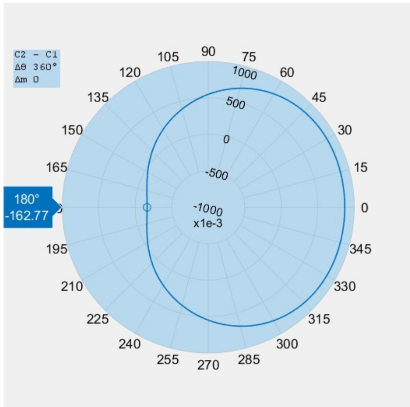

Figure 2.78: Beamwidth in the Azimuth Plane of PIFA AI

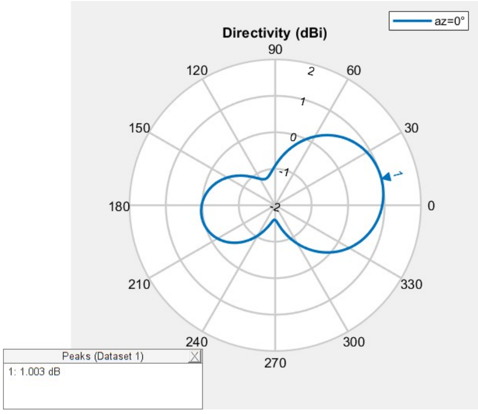

Figure 2.79: Pattern in the Elevation Plane of Optimized PIFA

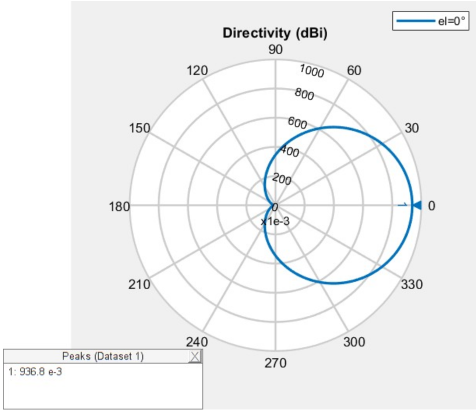

Figure 2.80: Pattern in the Azimuth Plane of Optimized PIFA

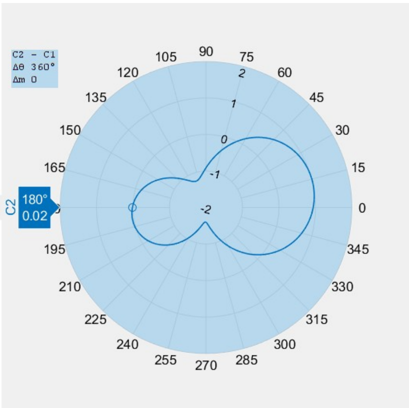

Figure 2.81: Beamwidth in the Elevation Plane of Optimized PIFA

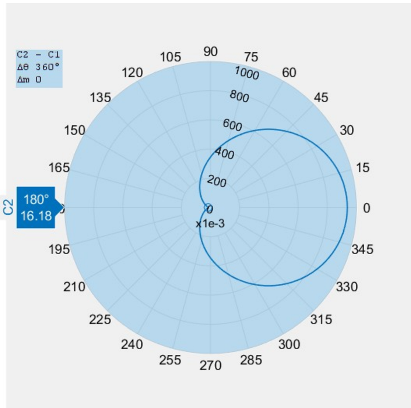

Figure 2.82: Beamwidth in the Azimuth Plane of Optimized PIFA

- **Pattern 3D**: as already noted in the 2D pattern analysis, after the optimization process the directivity of the antenna loses something.

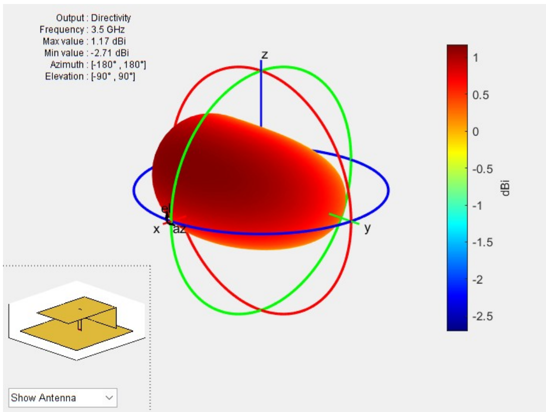

Figure 2.83: Pattern 3D of PIFA AI

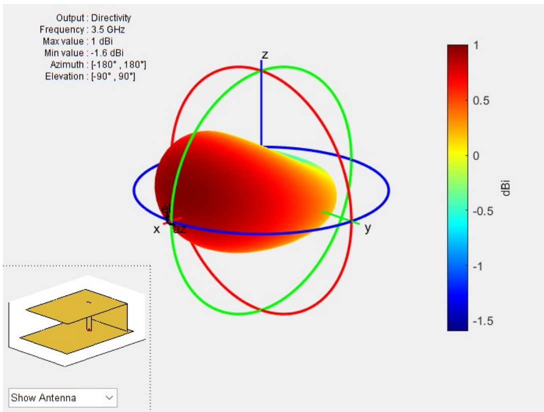

Figure 2.84: Pattern 3D of Optimized PIFA

- **Current distribution**: it can be seen that the current distribution is different since, for example, more current circulates near the open circuit of the optimized antenna than the initial one.

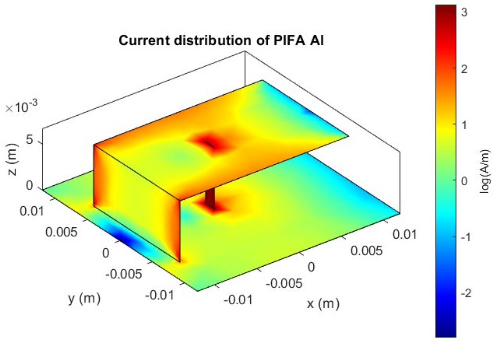

Figure 2.85

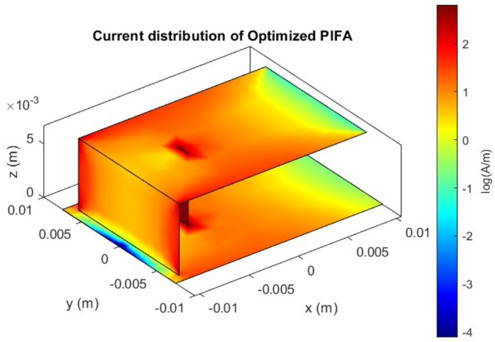

Figure 2.86

- **EH fields e Axial ratio**: From the figures below, it can be seen the distribution of electric and magnetic fields in the various directions. In particular, it can be seen from Figure 2.89 and Figure 2.89 that the polarization of the PIFA AI antenna turns out to be elliptical and constant in the band under consideration, unlike the optimized antenna, which while remaining constant in the band of interest turns out to have more linear polarization.

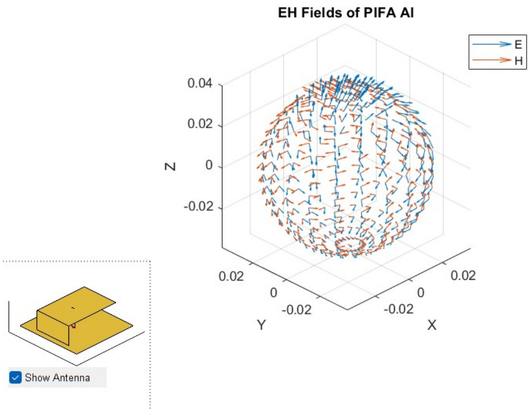

Figure 2.87

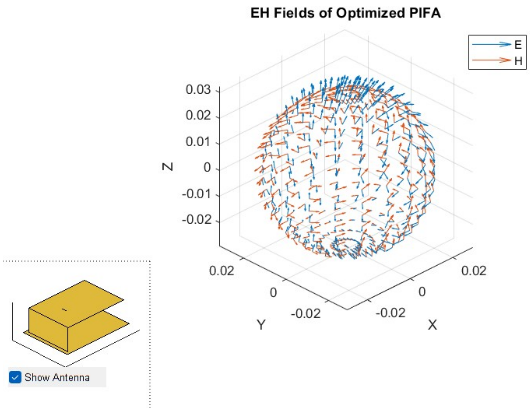

Figure 2.88

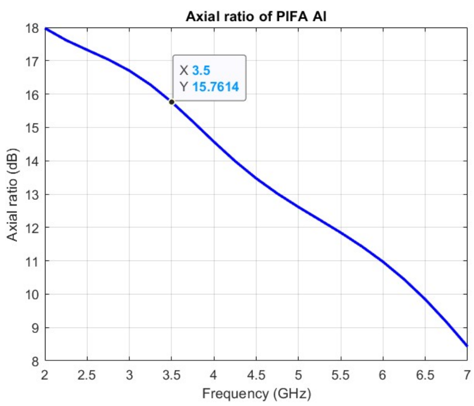

Figure 2.89

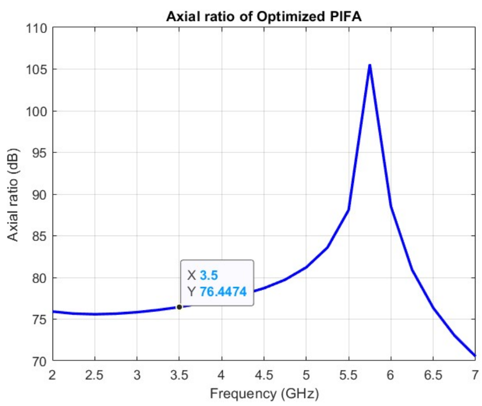

Figure 2.90

Conclusion

The student speakers, through this work on the design, analysis, and optimization of a PIFA antenna, had the opportunity to use the theoretical concepts studied in the previous years, understanding how fundamental these are in the practical design of an antenna as well as closely related to each other. In addition, this project served the students to develop their soft-skills, particularly those related to teamwork and the ability to write an appropriate technical report.

Future Work

The students, having achieved the goal of this project, realized that to increase the resonant frequency of a PIFA antenna cannot be limited to decreasing the size, so the goal of a possible next project may be to design a PIFA antenna with a slot on the top patch, so that the antenna resonates at higher frequencies without decreasing the size beyond the order of millimeters. In addition, a PIFA antenna array could be designed with CST software to improve the performance already discussed in this project.

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