

# **DESIGN AND ANALYSIS AN ARRAY OF PATCH ANTENNA AT 2.4GHZ WITH CIRCULAR POLARIZATION**

**A Degree Thesis**

**Submitted to the Faculty of the  
Escola Tècnica d'Enginyeria de Telecomunicació de  
Barcelona**

**Universitat Politècnica de Catalunya**

**by**

**Ruben Domenech Ruiz**

**In partial fulfilment  
of the requirements for the degree in  
TELECOMMUNICATIONS ENGINEERING**

**Advisor: Sebastian Blanch Boris**

**Pilsen, January 2016**

## **Abstract**

We are in an industry where everything changes very quickly, and if we focus on the design of antennas we see that increasingly we are looking for smaller dimensions with better features.

In this issue we can highlight the antennas with microstrip design that are becoming more and more popular in sectors such as mobile phones, satellite, or more recently as object recognition. Among the advantages of this type of antenna we can emphasize the low cost, small size, low profile, easy to manufacture and easy to implement, among its disadvantages are narrow bandwidth or low gain.

The purpose of this project is design and analysis an array of Patch antenna at 2.45 GHz with circular polarization. We obtain the circular polarization with a single source and upsetting the structure of the patches. This antenna will be part of a system of radio frequency identification (RFID), technology that allows communication over short distances and identify objects bearing an RFID tag.

## **Resum**

Ens trobem en un sector on tot avança de manera molt accelerada, i si ens fixem en el disseny d'antenes, veiem que cada vegada més es busca menors dimensions amb millors característiques.

En aquest tema podem destacar les antenes amb disseny microstrip que s'estan convertint en més i més populars en sectors com la telefonia mòbil, satèl·lits, o ara més recentment en reconeixement d'objectes. Entre les avantatges d'aquest tipus d'antena podem destacar el baix cost, grandària reduïda, baix perfil, fàcil fabricació i fàcil implementació, entre les seves desavantatges trobem un ample de banda estret o un baix guany.

El propòsit d'aquest projecte és dissenyar i analitzar una antena en agrupació d'elements a la freqüència 2.45GHz amb polarització circular. La polarització circular la obtindrem amb una única alimentació i pertorbant l'estructura del conductor. Aquesta antena formarà part d'un sistema d'identificació per radiofreqüència (RFID), tecnologia que permet comunicacions a distàncies petites i identificar objectes que porten etiquetes RFID.

## **Resumen**

Nos encontramos en un sector en el que todo avanza de manera muy acelerada, y si nos centramos en el diseño de antenas, vemos que cada vez más se busca menores dimensiones con mejores características.

En este tema podemos destacar las antenas con diseño microstrip que se están convirtiendo en más y más populares en sectores como la telefonía móvil, satélites, o ya más recientemente en reconocimiento de objetos. Entre las ventajas de este tipo de antenas podemos destacar el bajo coste, tamaño reducido, bajo perfil, fácil de fabricar y fácil de implementar, entre sus desventajas encontramos ancho de banda estrecho o baja ganancia.

El propósito de este proyecto es diseñar y analizar una antena en agrupación de elementos a la frecuencia 2.45GHz con polarización circular. La polarización circular la obtendremos con una única alimentación y perturbando la estructura de los parches. Esta antena formará parte de un sistema de identificación por radiofrecuencia (RFID), tecnología que permite comunicaciones en distancias pequeñas e identificar objetos que llevan una etiqueta RFID.

*If you ever find yourself  
Stuck in the middle of the sea  
I'll sail the world to find you  
If you ever find yourself  
Lost in the dark and you can't see  
I'll be the light to guide you  
  
Find out what we're made of  
When we are called to help our friends in need  
  
You can count on me like one, two, three  
I'll be there  
And I know when I need it  
I can count on you like four, three, two  
You'll be there  
Because that's what friends are supposed to do, oh yeah  
Bruno Mars – Count on me*

## **Acknowledgements**

With this project I finished my first step in the UPC, four-year of Degree in Telecommunications Systems Engineering.

During this time I have learned everything in this world that I love, but also meet wonderful people with whom I could laugh, cry, learn, and fight, all these people, thank you for being part of my life. Of course thank to my family which is what has allowed all this possible, and my close friends, those who are counted on the fingers of one hand, I love you.

Finally to thank all the people I have met in the last five months, especially senior lecturer Jan Mráz of Západočeská Univerzita v Plzni (Pilsen, Czech Republic) that he opened the doors of his office and his country to perform this project. Thanks friend for your friendliness and help, in Spain you always will be well welcome. Also, friends of Waterpolo in Pilsen for letting me be part of their team, you are very great, see you soon in Barcelona.

Anyway, thanks everyone! Everyone that gives me her time, that is so valuable and it is unrecoverable.

A big hug,

Ruben ☺

## Revision history and approval record

Revision	Date	Purpose
0	27/12/2015	Document creation
1	25/01/2016	Document revision

### DOCUMENT DISTRIBUTION LIST

Name	e-mail
Ruben Domenech Ruiz	rudomenech@gmail.com
Sebastian Blanch Boris	blanch@tsc.upc.edu
Jan Mráz	janmraz@kae.zcu.cz

Written by:		Reviewed and approved by:	
Date	20/01/2016	Date	25/01/2016
Name	Ruben Domenech Ruiz	Name	Sebastian Blanch Boris
Position	Project Author	Position	Project Supervisor

## **Table of contents**

Abstract .....	2
Resum .....	3
Resumen .....	4
Acknowledgements .....	6
Revision history and approval record.....	7
Table of contents .....	8
List of Figures .....	9
List of Tables: .....	11
1. Introduction.....	12
1.1. Work Packages, Tasks and Milestones .....	13
1.1.1. Milestones .....	15
1.2. Gantt diagram.....	16
2. State of the art of the technology used or applied in this thesis.....	17
2.1. Microstrip.....	17
2.2. Microstrip antenna .....	18
2.2.1. Characteristic modes .....	22
2.2.2. Obtaining a circular polarization antenna.....	24
2.2.3. Feeding Methods.....	24
2.2.4. Impedance .....	25
2.2.5. Arrays and feed networks .....	26
2.2.6. Matching of Microstrip Lines .....	26
2.2.7. S Parameters .....	27
3. Methodology / project development: .....	28
3.1. First two designs .....	28
3.2. Final design .....	29
4. Results .....	34
5. Budget.....	40
6. Conclusions and future development:.....	41
Bibliography:.....	42
Glossary .....	43



## **List of Figures**

Figure 1.1: Gantt diagram .....	16
Figure 2.1: Structure of microstrip line .....	17
Figure 2.2: Shapes of conductor layer .....	18
Figure 2.3: Structure of patch antenna.....	19
Figure 2.4: E-field in the patch .....	20
Figure 2.5: Linear polarization (a) and circular polarization (b).....	20
Figure 2.6: Circular polarization clockwise (a) and anticlockwise (b).....	21
Figure 2.7: First four characteristic modes .....	23
Figure 2.8: Feeding by transmission line.....	24
Figure 2.9: Feeding by coaxial cable .....	25
Figure 2.10: Array with line feed (a) and array with network feed (b) .....	26
Figure 2.11: Impedance of the twigs of the array .....	26
Figure 2.12: Two-port with incident and reflected waves.....	27
Figure 3.1: Final design of microstrip array antenna. ....	28
Figure 3.2: (a) First design and his (b) gain .....	29
Figure 3.3: (a) Second design and his (b) current distribution .....	29
Figure 3.4: Dimensions of the perturbation .....	30
Figure 3.5: Single patch antenna .....	30
Figure 3.6: Gain (a) and axial ratio (b) of the single patch antenna .....	31
Figure 3.7: Reflection coefficient of the single patch antenna .....	31
Figure 3.8: Near field E of the single patch antenna .....	31
Figure 3.9: Union of two path antenna .....	32
Figure 3.10: Near field E (a) and axial ratio (b) of two patches.....	32
Figure 3.11: Quarter wave transformer .....	32
Figure 3.12: Feed network.....	33
Figure 4.1: Final patch antenna .....	34
Figure 4.2: $S_{11}$ by vector analyzer .....	34
Figure 4.3: $S_{11}$ by FEKO simulation.....	34
Figure 4.4: Anechoic chamber .....	35
Figure 4.5: Horizontal position phi (a) and theta (b) .....	35
Figure 4.6: Horizontal position .....	36
Figure 4.7: Vertical position phi (a) and theta (b) .....	36
Figure 4.8: Vertical position .....	36

Figure 4.9: Theta with FEKO .....	36
Figure 4.10: Phi with FEKO .....	37
Figure 4.11: Gain by FEKO simulation.....	37
Figure 4.12: Gain in anechoic chamber .....	37
Figure 4.13: Polarization pattern.....	38
Figure 4.14: Axial ratio by FEKO simulation.....	38
Figure 4.15: Current distribution in FEKO with (a) $\omega t=0^\circ$ , (b) $\omega t=45^\circ$ , (c) $\omega t=90^\circ$ and (d) $\omega t=180^\circ$ .....	39

## **List of Tables:**

Table 1.1: Values of parameters .....	12
Table 1.2: Five work packages .....	15
Table 1.3: Milestones.....	15
Table 4.1: Axes value .....	38
Table 5.1: Budget .....	40

# 1. Introduction

The objective of this project is fabrication a one antenna with circular polarization using the microstrip technologies at 2.45 GHz with the objective that it will be part of the RFID system that is a wireless technology used for tracking a tag attached to an object and uniquely identifying it.

This type of antenna is very popular now, because it's economic, easy production, low weight and reduced dimensions. The circular polarization is important in our design because regardless of receiver orientation, it will always receive a component of this signal. To obtain circular polarization we have two principal options, the first option is feed the patch with two perpendicular feeds. The second option is truncate the structure of the patch; that usually the complete systems can be smaller than the first option.

To be part of an RFID system I decided that our antenna will must has a gain around 10dBi, good reflection coefficient ( $S_{11}$ ) and of course circular polarization. For this reason, I need know the important parameters and typical values of the microstrips technologies and then, how it's possible make an antenna with microstrip elements. In the next table we can see the objective of the different principal values that I must obtain.

Parameter	Value
Frequency	2.45 GHz
Gain	10 dBi
Polarization	Circular
Range	1 – 3 meters
Reflection coefficient	< - 10 dB at 2.45GHz

Table 1.1: Values of parameters

For design an antenna I was using the FEKO software, FEKO is an electromagnetic simulation software tool for the electromagnetic field analysis of 3D structures. Which FEKO we can obtain different parameters of our design, for example: radiation pattern, reflection coefficient, axial ratio, electrical field,...

### 1.1. Work Packages, Tasks and Milestones

In this section we can see the breakdown of the different step of this project with the description of the important parts and the time that I have been dedicated to each one.

Project: Research Microstrip information	WP ref: 01	
Major constituent: Documentation	Sheet 01 of 05	
Short description: Research and understand information related to antennas polarization, arrays and microstrip.	Planned start date: 14/09/2015 Planned end date: 05/10/2015	
	Start event: 16/09/2015 End event: 19/10/2015	
Internal task T1: Search information about antennas Internal task T2: Search information about antenna polarization Internal task T3: Search information about antenna array Internal task T4: Search information about microstrip antenna.	Deliverables:  Proposal & Workplan	Dates:  05/10/2015

Project: Design array microstrip	WP ref: 02	
Major constituent: FEKO software	Sheet 02 of 05	
Short description: Design a microstrip antenna array with circular polarization with FEKO software.	Planned start date: 13/10/2015 Planned end date: 31/11/2015	
	Start event: 19/10/2015 End event: 27/12/2015	
Internal task T1: Know the tools of the software FEKO Internal task T2: Design a microstrip Internal task T3: Simulation the microstrip Internal task T4: Design a microstrip array Internal task T5: Simulation the microstrip array	Deliverables:	Dates:

Project: Construct the optimization microstrip array.	WP ref: 03	
Major constituent: Fabrication	Sheet 03 of 05	
Short description: Construct the microstrip antenna array with circular polarization that I found in FEKO software.	Planned start date: 10/12/2015 Planned end date: 28/12/2015	
	Start event: 28/12/2015 End event: 18/01/2016	
Internal task T1: Determine if the simulation is physically possible.	Deliverables:	Dates:

Project: Evaluation the antenna	WP ref: 04	
Major constituent: Test	Sheet 04 of 05	
Short description: Evaluate the correct behavior of the microstrip antenna patch	Planned start date: 14/12/2015 Planned end date: 17/01/2016	
	Start event: 18/01/2016 End event: 23/01/2016	
Internal task T1: Tests the antenna in the laboratory	Deliverables: Project Critical Review	Dates: 01/12/2015

Project: Project documentation	WP ref: 05	
Major constituent: Documentation	Sheet 05 of 05	
Short description: Perform a document that containing all information related to the project.	Planned start date: 18/01/2016 Planned end date: 25/01/2016	
	Start event: 27/12/2015 End event: 25/01/2016	
Internal task T1: Write a Final Report Internal task T2: Explain the information that is in the final project.	Deliverables: Final Report	Dates: 25/01/2015

Table 1.2: Five work packages

### 1.1.1. Milestones

WP#		Task#	Short title	Milestone / deliverable	Date (week)
01	01		Antenna information		1/2/3
01	02		Polarization information		4/5
01	03		Array information		6/7
01	04		Microstrip information		7/9
02	01		FEKO software		10/11
02	02		Microstrip	Simulation at 2.45GHz	12/13/14/15
02	03		Microstrip Array	Simulation at 2.45GHz	16/17/18
03	01		Fabrication the microstrip array	Microstrip antenna with circular polarization	19/20
04	01		Test the design		20/21
05	01		Write Final Report	Final Report	19/20/21
05	02		Oral presentation	Exposition	22

Table 1.3: Milestones

## 1.2. Gantt diagram

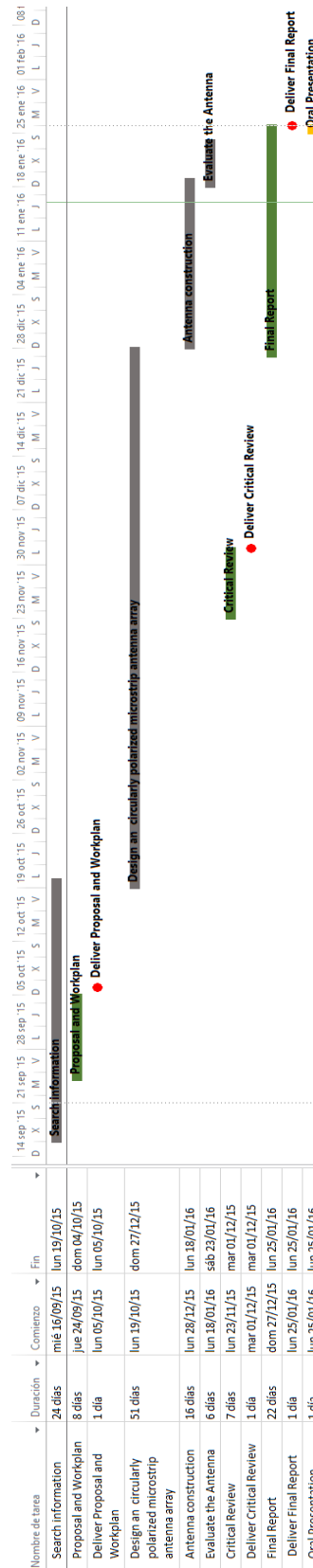


Figure 1.1: Gantt diagram



## 2. State of the art of the technology used or applied in this thesis

In this section, I will expose all the concepts and formulas that it will be necessary for this project. First the concept of microstrip line and then how we can make a microstrips antenna with different variants of the design, finally the concept of S parameters.

### 2.1. Microstrip

[1] Microstrip is a planar transmission line, similar to stripline, but microstrips do not have a substrate in the top. The structure of microstrip transmission line consists of a copper trace separated from a ground plane by an insulating substrate.

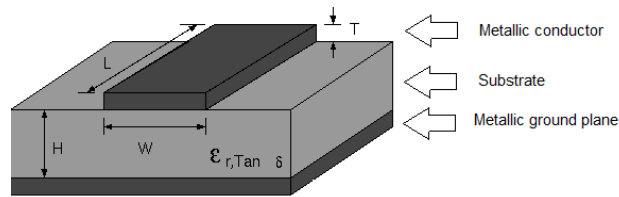


Figure 2.1: Structure of microstrip line

[2] The dimension of the complete microstrip can be determine with width of the line (W), thickness of the line (T) and thickness of the dielectric (H). [3] In this type of structure we don't have a TEM mode, because the electric field is small in left and right of the upper conductor (fringing effect) but not depreciable, for this reason we call them quasi-TEM in which the fields are assumed to be approximately TEM and the effect of the deviation from TEM is taken into account by empirical formulas for the line impedance and velocity factor. If we denote by  $\epsilon_{eff}$  the relative permittivity of the effective dielectric, the wavelength and velocity factor of the line will be given in terms of their free-space values  $\lambda_0$ ,  $c_0$ :

$$\lambda = \frac{\lambda_0}{\sqrt{\epsilon_{eff}}} \quad c = \frac{c_0}{\sqrt{\epsilon_{eff}}} \quad (2.1)$$

And for effective dielectric constant, we use the Hammerstad and Jensen's formulation that is the most accurate:

$$\epsilon_{eff} = \frac{\epsilon_r + 1}{2} + \frac{\epsilon_r - 1}{2} \left(1 + \frac{10}{u}\right)^{-ab} \quad \text{with} \quad u = \frac{w}{h} \quad \text{and} \quad \epsilon_r = \frac{\epsilon}{\epsilon_0} \quad (2.2)$$

$\epsilon_r$  is the relativity permittivity. We define  $a$  and  $b$ , by:

$$a = 1 + \frac{1}{49} \ln \left[ \frac{u^4 + \left(\frac{u}{52}\right)^2}{u^4 + 0.432} \right] + \frac{1}{18.7} \ln \left[ 1 + \left(\frac{u}{18.1}\right)^3 \right] \quad (2.3)$$

$$b = 0.564 \left( \frac{\epsilon_r - 0.9}{\epsilon_r + 3} \right)^{0.053}$$

The accuracy of these formulas is better than 0.01% for  $u < 1$  and 0.03% for  $u < 1000$ . Similarly, the characteristic impedance is given by the empirical formula:

$$Z = \frac{\eta_0}{2\pi\sqrt{\epsilon_{\text{reff}}}} \ln \left[ \frac{f(u)}{u} + \sqrt{1 + \frac{4}{u^2}} \right] \quad \text{where } \eta_0 = \sqrt{\frac{\mu_0}{\epsilon_0}} \quad (2.4)$$

And the function  $f(u)$  is defined by:

$$f(u) = 6 + (2\pi - 6) \exp \left[ - \left( \frac{30.666}{u} \right)^{0.7528} \right] \quad (2.5)$$

The accuracy is better than 0.2% for  $0.1 \leq u \leq 100$  and  $\epsilon_r < 128$ .

## 2.2. Microstrip antenna

[6][11][12] The microstrip antenna was first proposed in 1953 by G.A. Deschamps, but didn't become practical until the 1970s when it was developed further by researchers such as Robert E. Munson, J. Q. Howell and others using low-loss soft substrate materials that were just becoming available. The size of a microstrip antenna is inversely proportional to its frequency, for this reason it's become more popular in the recent years because the frequencies are higher now. Microstrip antenna is becoming very widespread within the mobile phone market. Patch antennas are low cost, have a low profile and are easily fabricated.

We have different design of microstrip antenna with different shape, but all of them have the same structure: on the bottom a ground plane are made of high conductivity metal (typically copper) with similar thickness than the conductor material on the top (typically copper or gold). The thickness of the ground plane or of the microstrip is not critically important. Between these both layers we can find the dielectric material that is typically formed by FR4 and their dielectric constants are usually in the range of  $2.2 \leq \epsilon_r \leq 12$ . The most desirable substrates are those that are at the lower end of the range and also have a high thickness as they provide better results in terms of efficiency and bandwidth. On the other hand, substrates with higher dielectric constant and reduced thickness are more desirable in microwave circuits because the fields are more confined to the structure which minimizes unwanted radiation and coupling, as well as allowing that the devices are more compact. In the Figure 2.2 we can see the different shape of conductor layer:

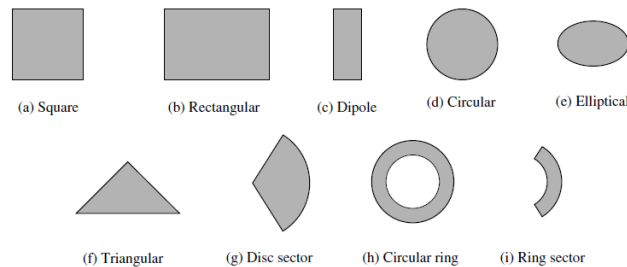


Figure 2.2: Shapes of conductor layer

Square, rectangular, dipole (strip), and circular are the most common because of ease of analysis and fabrication, and their attractive radiation characteristics, especially low cross-polarization radiation. During this document, we will focus just in square antenna.

For design antenna with microstrip technologies we use the same principles than the microstrip line, but we must consider some important things, because we are looking for

that the structure radiate in one direction with circular polarization. The figure below shows the geometry of the rectangular microstrip antenna.

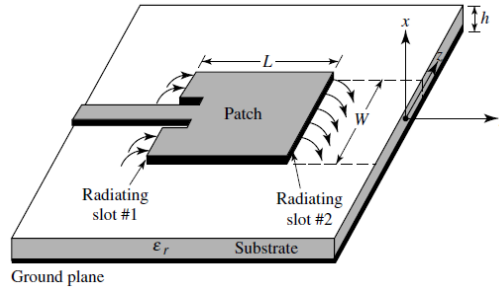


Figure 2.3: Structure of patch antenna

A microstrip antenna consist of a very thin ( $t \ll \lambda_0$ , where  $\lambda_0$  is the free-space wavelength) metallic strip (patch) placed a small fraction of a wavelength ( $h \ll \lambda_0$ , usually  $0.003\lambda_0 \leq h \leq 0.05\lambda_0$ ) above a ground plane. The microstrip patch is designed so it pattern is maximum in normal direction to the patch (broadside radiator). The radiating edges (fringing fields) are at the ends of the L-dimension (usually  $\lambda_0/3 < L < \lambda_0/2$ ) of the rectangle, which sets up the single polarization. Radiation that occurs at the ends of the W-dimension is far less and is referred to as the cross-polarization.

[4] The resonance frequency for the fundamental mode of a rectangular patch is defined as:

$$f_r = \frac{c}{2L_{eff}\sqrt{\epsilon_{reff}}} = \frac{c}{2(L + 2\Delta l)\sqrt{\epsilon_{reff}}} \quad (2.6)$$

$\Delta l$  is a:

$$\Delta l = 0.412h \frac{(\epsilon_{reff} + 0.3) \left( \frac{W}{h} + 0.264 \right)}{(\epsilon_{reff} - 0.258) \left( \frac{W}{h} + 0.8 \right)} \quad (2.7)$$

Where  $\epsilon_{reff}$  is the effective dielectric constant obtained by the quasi-static approximation:

$$\epsilon_{reff} = \frac{\epsilon_{r+1}}{2} + \frac{\epsilon_{r+1}}{2} \left( 1 + 12 \frac{h}{W} \right)^{-1/2} \quad (2.8)$$

Finally obtaining the physical length L of the patch design is:

$$L = \frac{c}{2f_r\sqrt{\epsilon_{reff}}} - 2\Delta l \quad (2.9)$$

The width W is not too critical, with W can be adjust the input impedance and improve efficiency. It can be defined as:

$$W = \frac{1}{2f_r\sqrt{\epsilon_0\mu_0}} \sqrt{\frac{2}{\epsilon_r + 1}} \quad (2.10)$$

In our case, as we want to have circular polarization antenna, it is necessary to design the W dimension equal to L, obtaining a square patch.

[6] The figure below is a side view which attempts to show a snapshot of the E-field under the patch. Note that the fields under the L-edges are of opposite polarity (due to the half-wave nature of the patch) and when the field lines curve out and finally propagate out into the direction normal to the substrate they are now in the same direction (both facing left). In the far field perpendicular to the substrate, the radiation from the two sides adds up because the fields are in phase. As you look out in directions off of boresight, the intensity drops off as the fields of the two edges become farther and farther out of phase. At two angles the fields exactly cancel. Thus the microstrip patch radiation intensity depends on what direction you are facing it from (it has gain and directivity).

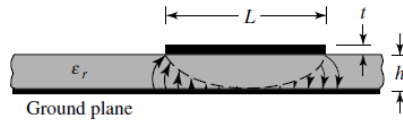


Figure 2.4: E-field in the patch

Normally the microstrip patch antenna has a gain of between 5 dB and 6 dB, have a beamwidth at -3 dB between 70° and 90° and its radiation has a unidirectional character.

Now we know how radiates a microstrip antenna. Let's see what types of polarization we can be found in an antenna.

[4] The polarization indicates how varying the orientation of the electric field vector  $\vec{E}$  at a fixed point in space as time passes. The polarization of a plane wave is geometric figure described, as time passes, by the end of the electric field vector at a fixed point in space in the plane perpendicular to the direction of propagation. For waves with varying time sinusoidal that figure is generally an ellipse, but there are two particular cases of interest: linear polarization and circular polarization.

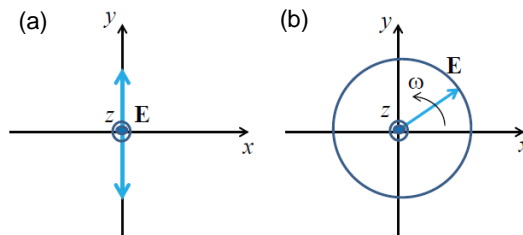


Figure 2.5: Linear polarization (a) and circular polarization (b)

[5] Let's see the formulation. Now consider the superposition of a wave  $\hat{x}$  linearly polarized with amplitude  $E_1$  and a wave  $\hat{y}$  linearly polarized with amplitude  $E_2$ , both of them traveling in the direction  $\hat{z}$  positive. The electric field we can write as:

$$\vec{E} = (E_1\hat{x} + E_2\hat{y})e^{-jk_0z} \quad (2.11)$$

From the above equation, we can have the following possibilities. If  $E_1 \neq 0$  and  $E_2 = 0$ , we have a planar wave with linearly polarization in the direction  $\hat{x}$ . If  $E_1 = 0$  and  $E_2 \neq 0$ , we have a planar wave with linearly polarization in the direction  $\hat{y}$ . If  $E_1$  and  $E_2$  are both reals and different of zero, we have a planar wave with linearly polarized with angle:

$$\phi = \tan^{-1} \frac{E_1}{E_2} \quad (2.12)$$

In the case of  $E_1 = jE_2 = E_0$  with  $E_0$  real, then:

$$\vec{E} = E_0(\hat{x} - j\hat{y})e^{-jk_0z} \quad (2.13)$$

Where the temporal domain of the field is:

$$\vec{E}(z, t) = E_0 \left( \hat{x} \cos(\omega t - k_0 z) + \hat{y} \cos(\omega t - k_0 z - \frac{\pi}{2}) \right) \quad (2.14)$$

This shows that the orientation of the electric field vector changes with time or with distance along the  $z$  axes. One way to look at it is taking a fixed position as  $z = 0$  so that is such that:

$$\vec{E}(0, t) = E_0(\hat{x} \cos(\omega t) + \hat{y} \sin(\omega t)) \quad (2.15)$$

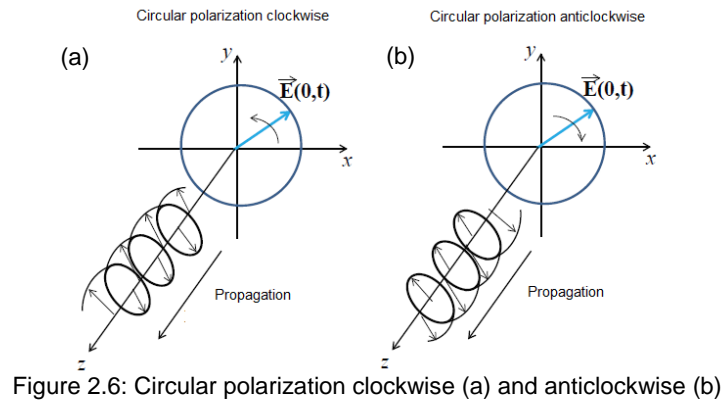
When  $\omega t$  increases from zero, the electric field vector rotates counterclockwise from the  $x$  axes. The resulting angle of the  $x$  axes of the electric field vector with time  $t$ ,  $z = 0$ , is then:

$$\phi = \tan^{-1} \frac{\sin(\omega t)}{\cos(\omega t)} = \omega t \quad (2.16)$$

It is showing that the polarization is rotated at a uniform angular velocity  $\omega$ . Noting the direction of propagation we can say that this wave is circularly polarized clockwise. Just as a field:

$$\vec{E} = E_0(\hat{x} + j\hat{y})e^{-jk_0z} \quad (2.17)$$

It is a counterclockwise circularly polarized wave.



This section also has to talk about axial ratio (AR). The axial ratio is the ratio of the major axes over the minor axes of the ellipse of polarization, which allows assess the circularity of a polarization, and can be calculated as:

$$AR = \frac{V_{max}}{V_{min}} \quad (2.18)$$

The AR for an ellipse is always greater than 1 ( $> 0$  dB), while for a linearly polarized wave AR will be infinite. The concept of axial ratio is widely used in circularly polarized antennas, being 0dB the ideal value of axial ratio to achieve.

### 2.2.1. Characteristic modes

[4][8][9] The theory of the characteristic modes can identify modes of radiation from any antenna.

The formulation of the theory of the characteristic modes of a conductive object begins with the definition of an operator in an equation relating the current  $\vec{J}$  on the surface  $S$  of a conductive object with the electric field incident  $E^i$ .

$$|L(\vec{J}) - \vec{E}^i|_{tan} = 0 \quad (2.19)$$

It is  $tan$  the tangential component on the surface. The linear operator  $L$  is defined as:

$$L(\vec{J}) = j\omega\vec{A}(\vec{J}) + \nabla\Phi(\vec{J}) \quad (2.20)$$

$$\vec{A}(\vec{J}) = \mu \oint \oint_S \vec{J}(r') \varphi(r, r') dS'$$

$$\Phi(\vec{J}) = \frac{-1}{j\omega\epsilon} \mu \oint \oint_S \nabla' \cdot \vec{J}(r') \varphi(r, r') dS'$$

$$\varphi(r, r') = \frac{e^{-jk|r-r'|}}{4\pi|r-r'|}$$

where  $r$  is the field at one point,  $r'$  is a source at one point,  $\epsilon$  is the permeability,  $\mu$  is the permittivity and  $k$  is the wavenumber in free space.

Physically,  $L$  provides the electric field at any point in space due to the current  $J$  on  $S$ . This means that the operator  $L$  has the dimension of impedance:

$$Z(\vec{J}) = |L(\vec{J})|_{tan} \quad (2.21)$$

The operator of impedance  $Z$  is complex and can be defined as:

$$Z(\vec{J}) = R(\vec{J}) + jX(\vec{J}) \quad (2.22)$$

After the development carried out in [8], the current characteristic modes can be obtained as the eigenfunctions of the following equations:

$$X(\vec{J}_n) = \lambda_n R(\vec{J}_n) \quad (2.23)$$

Where  $\vec{J}_n$  are the eigenvalues,  $\vec{J}_n$  are the eigenfunctions, and  $R$  and  $X$  are the real part and the imaginary part of the operator  $Z$ .

According to the above equation, the characteristic modes  $J$ , are real distributions of current on the surface of a conductive object that rely solely on its geometry and dimension, being independent of any specific source or excitation. By definition, modes are related to the power that can be radiated by the conductive object.

In practice, to calculate numerically the characteristic modes of an object, equation 2.23 needs to be reduced to a matrix form by the method of moments and the formation of Galerkin.

$$|X|\vec{J}_n = \lambda_n |R|\vec{J}_n \quad (2.24)$$

Subsequently, the eigenvectors  $\vec{J}_n$  and eigenvalues  $\lambda_n$  can be obtained by solving the problem 2.24 widely using standard algorithms.

The characteristic modes form a complete set of solutions, and therefore the total current in the conductive surface of an object can be expressed as a linear combination of these current modes.

$$\vec{J} = \sum_n b_n \vec{J}_n \quad (2.25)$$

where  $b$  are the coefficients of expansion that are easily derivable:

$$b_n = \frac{\langle \vec{J}_n, \vec{E}^i \rangle}{1 + j\lambda_n} = \frac{V_n^i}{1 + j\lambda_n} \quad (2.26)$$

where  $V_n^i$  is called modal expansion coefficient, and indicating the degree of coupling between the excitation and the characteristic mode. Therefore, the solution for modal current in a surface  $S$  is:

$$\vec{J} = \sum_n \frac{V_n^i}{1 + j\lambda_n} \vec{J}_n \quad (2.27)$$

From the above equation you can extract a set of real eigenvectors  $J$  or characteristic modes of any conductor object to arbitrary geometry, which are the real currents on the surface of the object.

The concept of characteristic modes will be usefully for obtain the circular polarization. [14] If we want a circular polarization is necessary to combine two orthogonal and linearly polarized modes, with the same current amplitude and in phase quadrature ( $90^\circ$ ). In the figure 2.7 [16] we can see the four first modes in a square conductor, for a circular polarization we need the  $J_1$  and  $J_2$  :

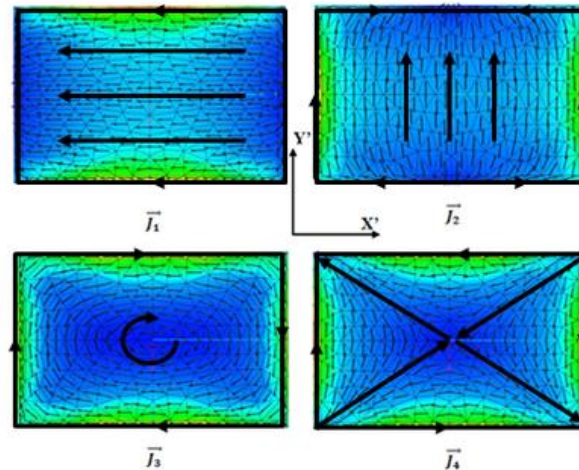


Figure 2.7: First four characteristic modes

### 2.2.2. Obtaining a circular polarization antenna

As we mentioned above, we want to make an antenna with a circular polarization. Circular polarization can be obtained if two orthogonal modes are excited with a  $90^\circ$  time-phase difference between them. This section illustrates the two possible ways to get circular polarization, and for this we use the concept of characteristic modes.

#### - **One feed point**

The main idea of obtaining circular polarization from a single feed point is focused on the introduction of a radiating structure so that the first two degenerate modes ( $J_1$  and  $J_2$ ) change slightly its resonance frequency to each other.

The dimensions of the perturbations introduced together with the proper placement of a feeding point in the structure allow that to an intermediate frequency between the two degenerate modes there is a phase difference of  $90$  degrees between its characteristic angles. This means that the radiated fields of the structure also have this offset and therefore the antenna is circularly polarized.

#### - **Two feed points**

The second method focuses on the use of two in quadrature sources that combine the first two degenerate modes orthogonal of the structure  $J_1$  and  $J_2$ , simultaneously.

It must be ensured that the two feed points are within  $90^\circ$  of each other and ensuring a phase difference between them of  $90^\circ$ .

### 2.2.3. Feeding Methods

[7] [4] We will discuss two methods of feeding a patch antenna.

#### - **By transmission line**

The antenna is fed through a transmission line connected directly to patch for some of the edges of the patch. It is easy to make and the line use the same substrate as the antenna. The disadvantage is that unwanted secondary lobes appear in the radiation pattern.

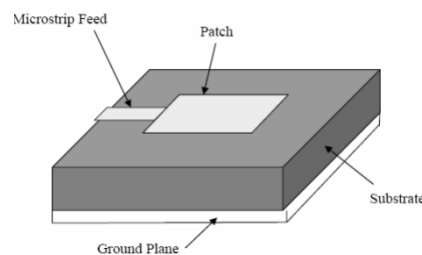


Figure 2.8: Feeding by transmission line



### - By the coaxial cable

The coaxial cable connects directly to the patch from the soil layer through the substrate. The main advantage is that we can optimize separately the patch and feed system to achieving improved efficiency.

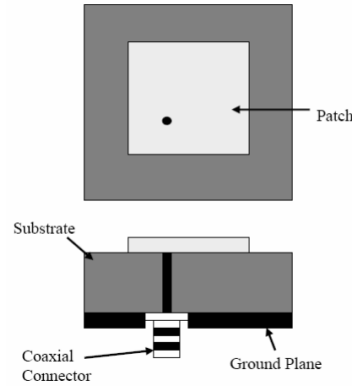


Figure 2.9: Feeding by coaxial cable

#### 2.2.4. Impedance

[10] It is defined as input impedance of an antenna ( $Z_A$ ) the relationship between voltage and current at the input terminals of the antenna. In phasor notation of sinusoidal steady state, the input impedance will have a real part ( $R_A$ ) and an imaginary part ( $X_A$ ). Usually, the current voltage relationship at the entrance of the antenna depends on the frequency, so that  $Z_A$ ,  $R_A$  and  $X_A$  will depend on the frequency).

$$Z_A(w) = R_A(w) + jX_A(w) \quad (2.28)$$

When at a given frequency, the reactance of the input impedance of the antenna is zero, it is said that the antenna is resonant at that frequency.

Typically, the resistive part of the input impedance,  $R_A$ , consists of two components; one R radiation resistance  $R_r$  and a loss resistance  $R_\Omega$ .

$$R_A(w) = R_r(w) + R_\Omega \quad (2.29)$$

We can define the radiation power and power loss:

$$\begin{aligned} P_{\text{radiation}} &= |I|^2 R_r \\ P_{\text{loss}} &= |I|^2 R_\Omega \end{aligned} \quad (2.30)$$

Where  $I$  is the current supplied by a generator hypothetical connected to the antenna and it is defined as:

$$|I| = \frac{|V_g|}{|Z_t|} = \frac{|V_g|}{|Z_A + Z_g|} \quad (2.31)$$

Where  $V_g$  is the voltage of the generator and  $Z_g$  the internal impedance.

Due to that the antenna radiates certain power, and another is lost in the antenna itself, you can define the power delivered to the antenna as the sum of these two:

$$P_{\text{deliver}} = P_{\text{radiation}} + P_{\text{loss}} = |I|^2 R_r + |I|^2 R_\Omega \quad (2.32)$$

The purpose of any antenna is to radiate the maximum power as possible (in the desired direction), so the power losses should be as small as possible, that is, the antenna should be efficient. Efficiency is defined as the power radiated in relation to the power delivered to the antenna.

$$\eta = \frac{P_{\text{radiation}}}{P_{\text{deliver}}} = \frac{R_r}{R_r + R_\Omega} \quad (2.33)$$

### 2.2.5. Arrays and feed networks

[6] Microstrip antennas are used not only as single elements but are very popular in arrays. The arrays are very versatile and are used, among other things, to synthesize a required pattern that cannot be achieved with a single element. In addition, they are used to scan the beam of an antenna system, increase the directivity, and perform various other functions which would be difficult with any one single element.

The elements can be fed by a single line, as shown in Figure 2.10 (a), or by multiple lines in a feed network arrangement, as shown in Figure 2.10 (b).

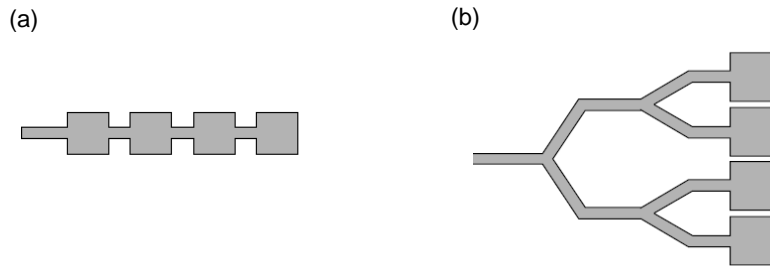


Figure 2.10: Array with line feed (a) and array with network feed (b)

### 2.2.6. Matching of Microstrip Lines

[7] Matching of microstrip transmission lines is done by matching each line to the source, its interconnecting transmission lines, and to the edge of a patch antenna. The patch antenna edge connected to the transmission lines is given an inset to match the radiation edge impedance of the patch antenna to the characteristic impedance of the transmission line.

The characteristic impedance of a transmission line of a microstrip feed patch is designed with respect to the source impedance. The characteristic impedance  $Z_0$  of the transmission line with respect to the source impedance  $Z_s$  is:

$$Z_0 = nZ_s \quad (2.34)$$

where the factor  $n$  is the number of twigs emanating from a node connected to a source. The above equation can be illustrated by considering a 2 x 2 antenna array as shown in Figure 2.11 where an edge feed is matched to a source impedance of 50  $\Omega$ . The transmission lines from the source therefore have an impedance of 100  $\Omega$ . Similarly the characteristic impedance of the transmission line feeding the antennas is 200  $\Omega$ .

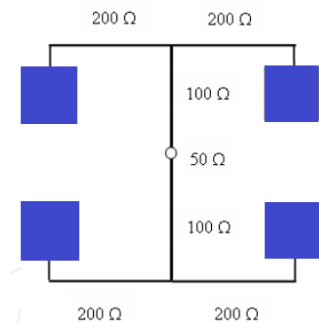


Figure 2.11: Impedance of the twigs of the array

### 2.2.7. S Parameters

[15] S parameters are useful for transmissions lines with  $N$  access, but we will use for measuring the reflection coefficient of the antenna and the axial ratio with the vector analyzer. For this reason I will explain the S parameter of a two-port.

Dispersion S parameters are the reflection and transmission coefficients between the incident (we use  $a$ ) and reflected (we use  $b$ ) waves. These parameters completely describe the behavior of a device under linear conditions in certain frequency ranges. Despite being applicable to any frequency, the S parameters are used primarily for networks operating in radio frequency (RF) and microwave frequencies. Each parameter is characterized by magnitude, gain or loss in decibels and phase.

If we define the two- port with the  $a$  and  $b$  waves:



Figure 2.12: Two-port with incident and reflected waves

The description of the S parameters is:

$S_{11}$ : Reflection coefficient at the entrance

$$S_{11} = \left. \frac{b_1}{a_1} \right|_{a_2=0} \quad (2.35)$$

$S_{21}$ : Direct transmission coefficient

$$S_{21} = \left. \frac{b_2}{a_1} \right|_{a_2=0} \quad (2.36)$$

$S_{12}$ : Reflection coefficient at the exit

$$S_{12} = \left. \frac{b_1}{a_2} \right|_{a_1=0} \quad (2.37)$$

$S_{22}$ : Transmission coefficient

$$S_{22} = \left. \frac{b_2}{a_2} \right|_{a_1=0} \quad (2.38)$$

### 3. Methodology / project development:

In this section I will explain the procedure to design my own antenna. The first step was to know all the important parameters for lines microstrip and patch antennas as mentioned in the previous section. All these concepts will be used in this project.

As I told in introduction section, I was using the FEKO software for this project. FEKO is based on sophisticated numerical methods to solve complex electromagnetic engineering problems. It offers multiple state-of-the-art numerical methods for the solution of Maxwell's equations, enabling its users to solve a wide range of electromagnetic problems encountered in various industries. Which FEKO we can obtain different parameters of our design, for example: radiation pattern, reflection coefficient, Axial Ratio, Electrical field...

#### 3.1. First two designs

In the figure below you can see the final design:

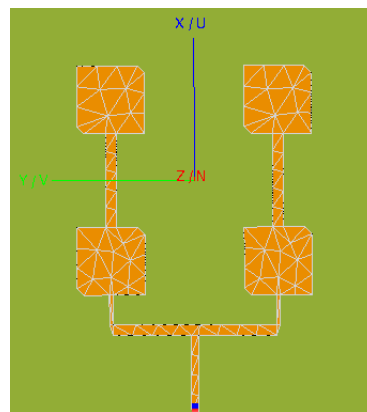


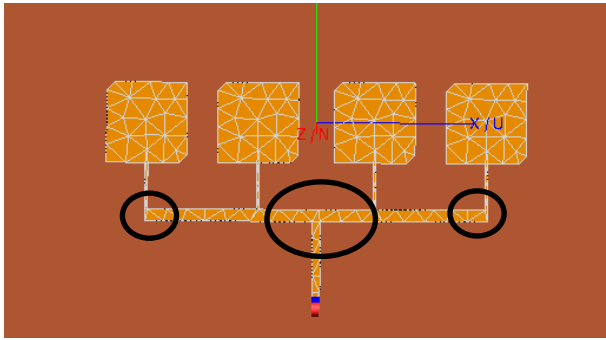
Figure 3.1: Final design of microstrip array antenna.

You can see that is an array with four square elements with two of four corners with perturbation that determine the direction of the circular polarization that I will illustrate later (Figure 4.15). The two top patch are connected with the other part by microstrip straight line, and left and right part are connected between serial network feed to feed all the patches from the same direction.

Before this final design I was studying two other options:

The first one was four patches connected in line. The problem of this design was that due to the design have many corners (you can see in Figure 3.2 (a) the black circles that mark the points of radiation different of the patches), the radiation power in the patches had been very small as you can see in the Figure 3.2 (b) of the gain at the frequency of interest also the radiation was not in normal direction.

(a)



(b)

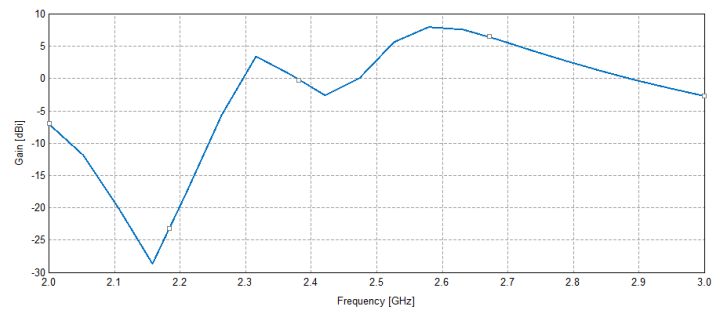
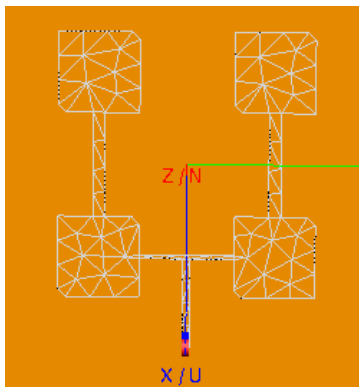


Figure 3.2: (a) First design and his (b) gain

The second design was four patches but the two bottom patch was connected by parallel network that you can see in the Figure 3.3, but with this design we will have problem with the perpendicular radiation because the patches are feeding in opposite directions that you can see the arrows in the Figure 3.3 (b).

(a)



(b)

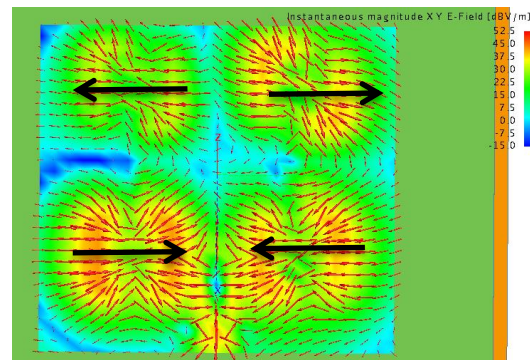


Figure 3.3: (a) Second design and his (b) current distribution

### 3.2. Final design

After these two possible designs I will focus on the final design (Figure 3.1), but note that the same procedure outlined for the final design was used to first design and second design that have been explained above (Figure 3.2 and Figure 3.3).

As I mentioned, to design an antenna array must take into account that all elements have an influence on the other elements. For this reason, I started optimizing a single patch that will form part of the complete system. To determine the optimum dimensions of this first element we use the formulas of microstrip antenna (equations 2.6 to 2.10). Given the established parameters:

$$\left. \begin{array}{l} \varepsilon_r = 4.8 \\ h = 1.6mm \\ freq = 2.45Ghz \end{array} \right\} \quad \begin{array}{l} \varepsilon_{reff} = 4.3 \text{ for patch} \\ L = W = \frac{\lambda}{2} = 30.09 \text{ mm} \end{array} \quad (3.1)$$

After studying the different cases, I decided that the best option to have a circular polarization is perturbing two of four corners of the patch. With this we can excite the two orthogonal modes with a 90° time-phase difference between them. To obtain the correct dimension of the perturbation, I have been modifying slightly for obtain the axial ratio equal to 0 dB.

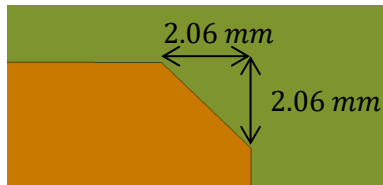


Figure 3.4: Dimensions of the perturbation

But, due to the perturbations of the corners we should modify slightly the length of the edges, for this reason the final length of the edges are:

$$L = W = 28.2mm$$

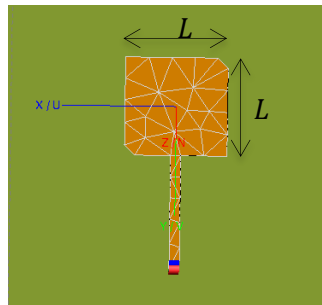


Figure 3.5: Single patch antenna

In the Figure 3.6 (a) we can see the gain of one patch antenna. We see that it's near to 3dB. On the Figure 3.6 (b) we can see the axial ratio (AR), remember that we have circular polarization when the value of AR is 0dB. The blue color corresponds to 0dB.

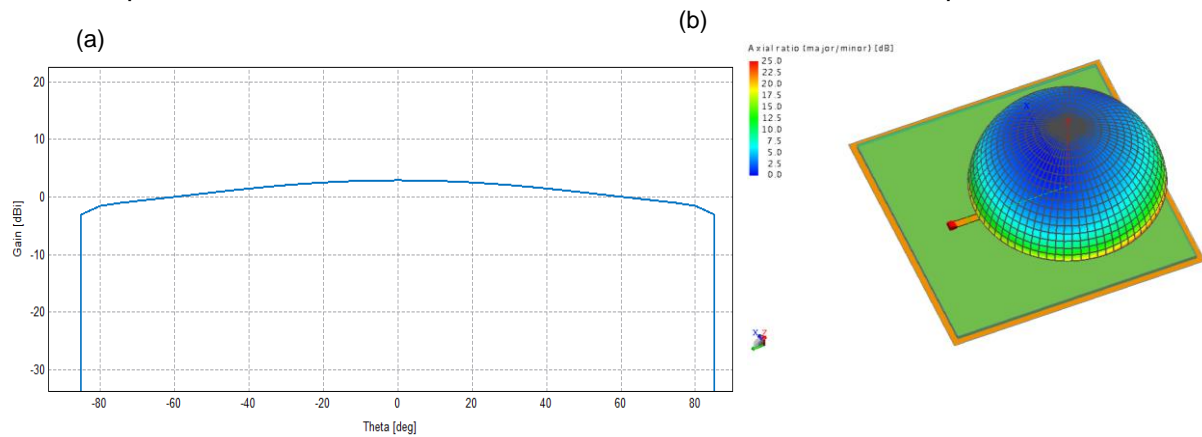


Figure 3.6: Gain (a) and axial ratio (b) of the single patch antenna

In the below Figure 3.7 the reflection coefficient ( $S_{11}$ ) showing the adaptation of the antenna at 2.45GHz with -8,6dB.

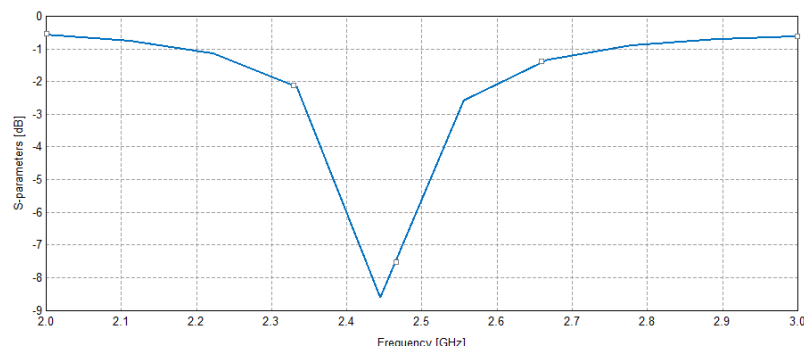


Figure 3.7: Reflection coefficient of the single patch antenna

Finally in the Figure 3.8, we can see the near field E on the top of the surface, with the arrows that produce the radiation in the normal direction of the single patch antenna.

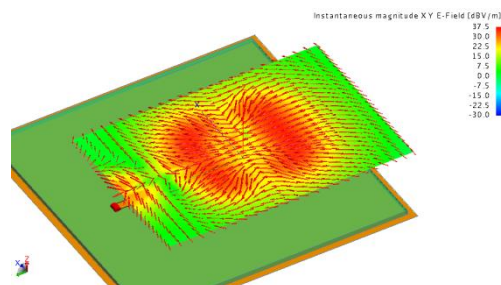


Figure 3.8: Near field E of the single patch antenna

The next step is connect with a microstrip line two patches. The impedance of this line is not so important but I choose a width of 4.5mm for reduce the losses in the line. The distance between both patches line is more important and it must be a lambda half for have both patches in phase and obtain the radiation in normal direction.

With width of 4.5mm we obtain  $D = \frac{\lambda}{2} = 32.24 \text{ mm}$  but due to the perturbations on the cornes we must shift to 39 mm.

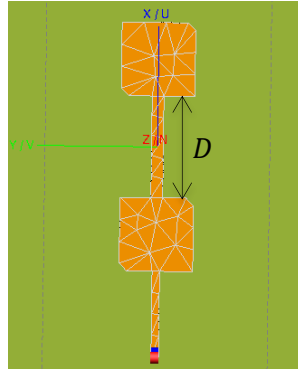


Figure 3.9: Union of two path antenna

In this case we must ensure that we maintain the circular polarization and the radiation in the normal direction.

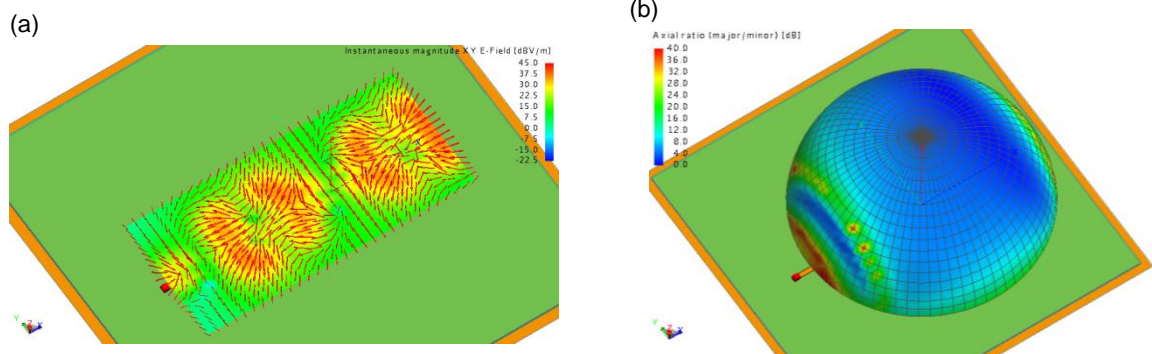


Figure 3.10: Near field E (a) and axial ratio (b) of two patches

When both patches are connected I calculate the impedance of the edge in the feed line to design the impedance of the feed network.

I obtained that the impedance value of the system with two patches is  $63 \Omega$ , I must match the impedance with quarter wave transformer.

$$Z_{in} = \frac{Z_o^2}{Z_L} \quad (3.2)$$

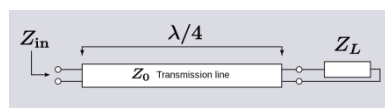


Figure 3.11: Quarter wave transformer



In our case the source is  $50\ \Omega$ , and remember that if we split the microstrip line in two ways (2.34), we have  $100\ \Omega$ .

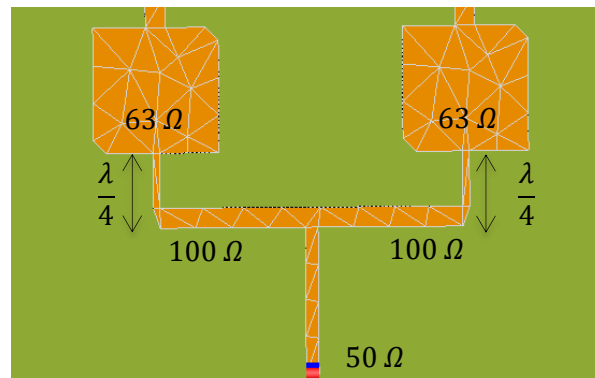


Figure 3.12: Feed network

Therefore, the value of  $Z_o$  is:  $79.37\ \Omega$ . With this value, we obtain that the width of the microstrip lines is 1.305mm. For design the other part of the microstrip network I used width with high value to reduce the losses.

## 4. Results

In this section I will compare the simulations of FEKO with the complete antenna and the results that I obtained in the laboratory after the manufacturing.

In the next image you can see the final prototype:

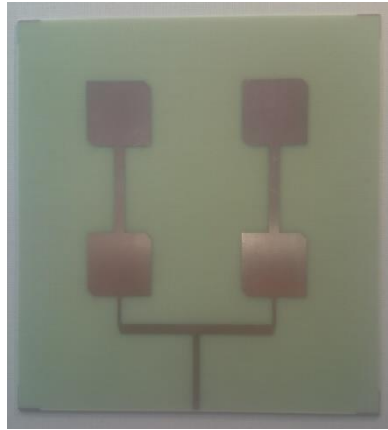


Figure 4.1: Final patch antenna

First of all, I used the Vector Analyzer ZVA8 from Rohde and Schwarz for visualize the  $S_{11}$  parameter. The value that we obtain at 2.45GHz is -19.384dB in linear units means that 1.15% of the power is reflected and 98.84% of the power is useful.

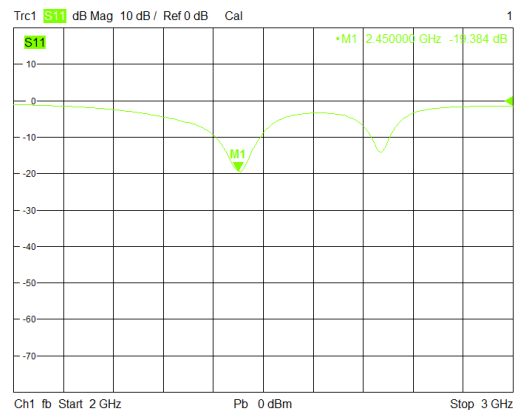


Figure 4.2:  $S_{11}$  by vector analyzer

And by FEKO software we obtain a value of -15.5dB which mean that 2.81% of the power is reflected and 97.18% of the power is useful.

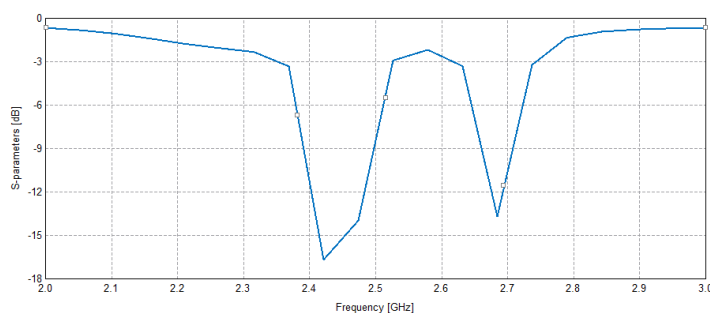


Figure 4.3:  $S_{11}$  by FEKO simulation

The different between this two graphics can be produced because the  $S_{11}$  was computed in a interference environment. Anyway, in both case we obtain a coefficient reflection less than -10dB that it was the objective and determine a good adaptation of the antenna.

If we define the band-width as the range of frequencies with  $S_{11}$  lower than -10dB, we obtain a narrow band-width from 2.39GHz to 2.49GHz

For the next part of the analysis we use a anechoic chamber of the *Západočeská Univerzita v Plzni* for delete the possible interference.

We want to compute the  $S_{21}$  parameter to obtain the radiation pattern in Theta and in Phi degrees. For this, we use the following disposition of the elements: we connect the prototype antenna in vertical position and a broadband horn antenna from Frankonia with linear polarization to the Vector Analyzer and we move the prototype degree by degree from 0° to 360° in vertical and in horizontal position of the horn to compute the phi and theta component, then we change the orientation of the path antenna to horizontal and compute again the power in theta and phi.

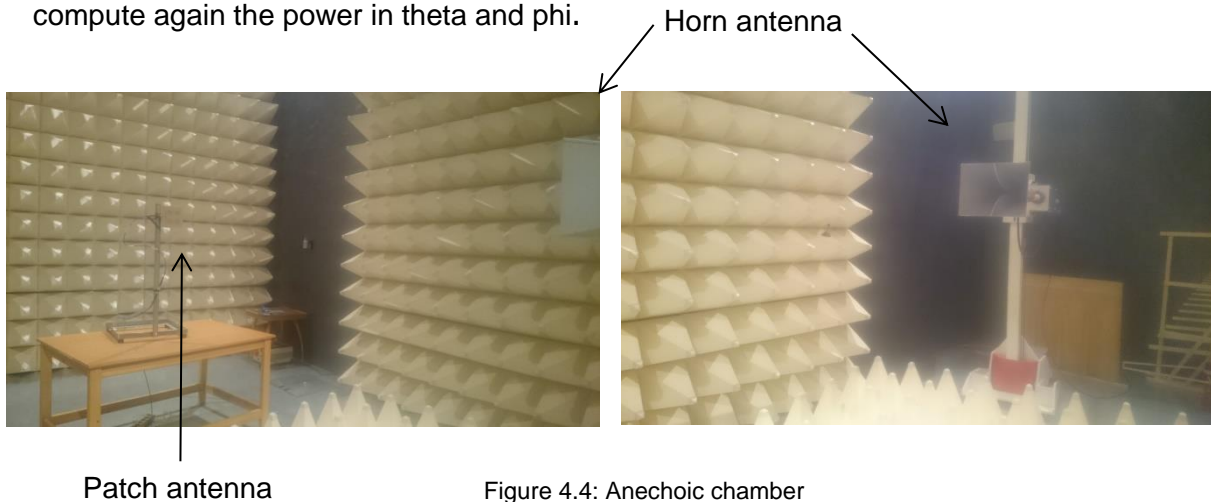


Figure 4.4: Anechoic chamber

Path antenna in horizontal position and horn antenna in vertical and in horizontal:

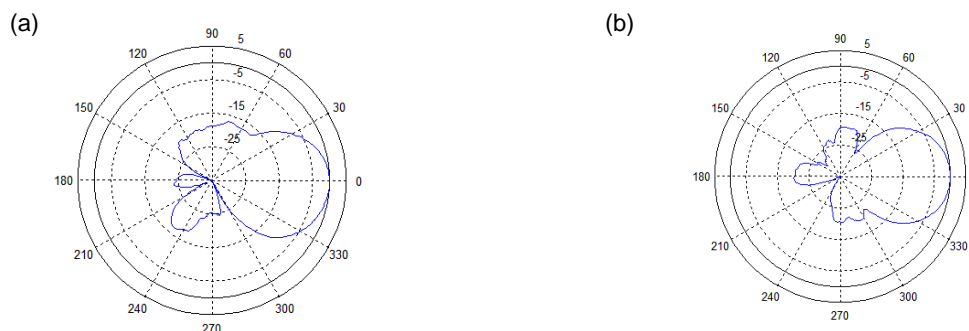


Figure 4.5: Horizontal position phi (a) and theta (b)

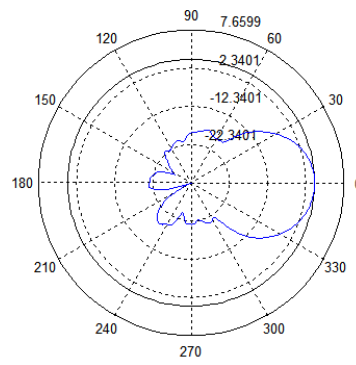


Figure 4.6: Horizontal position

Patch antenna in vertical position and horn antenna in vertical and in horizontal:

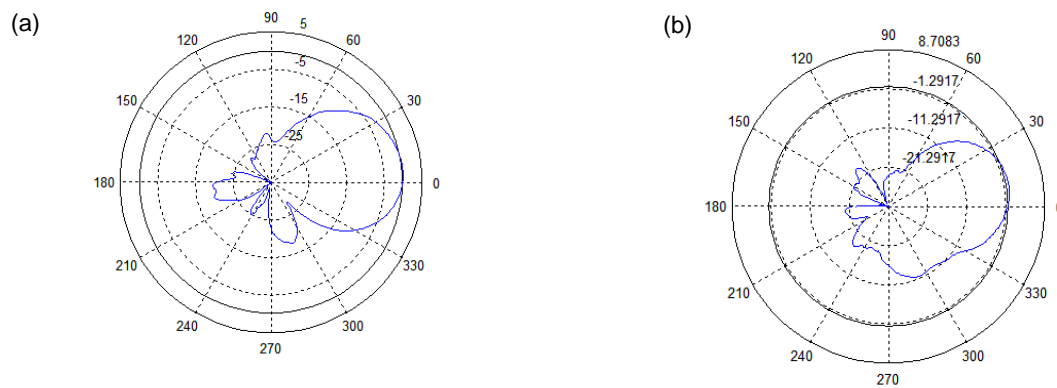


Figure 4.7: Vertical position phi (a) and theta (b)

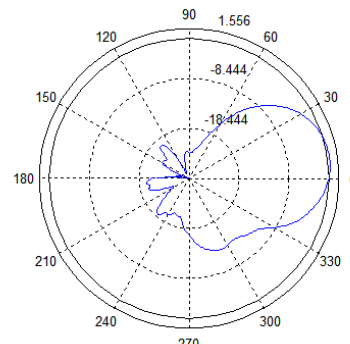


Figure 4.8: Vertical position

If we compare with FEKO software:

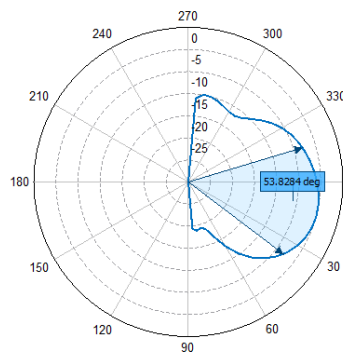


Figure 4.9: Theta with FEKO

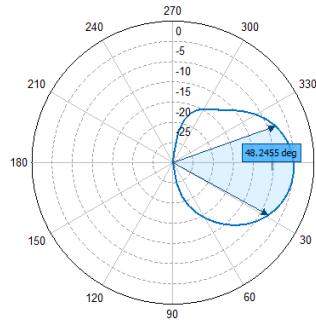


Figure 4.10: Phi with FEKO

In FEKO simulation we can see the beam width ( $\sim 3$ dB of the maximum) of the antenna in phi and theta. We note also that in FEKO we have an infinite ground plane, for this reason we doesn't have secondary lobes and also back lobe. We can see that in the anechoic chamber we obtained a good directivity. If we see the gain:

By FEKO we obtain almost 8dB:

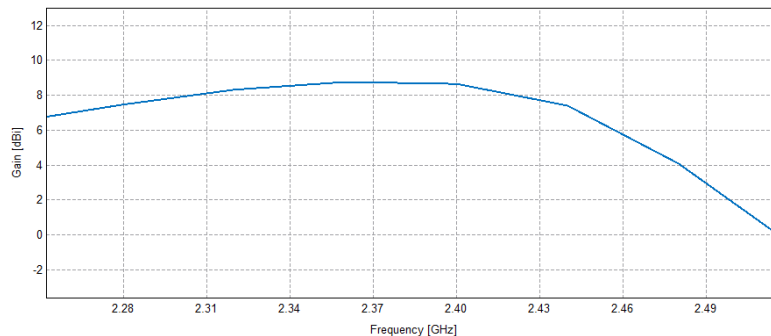


Figure 4.11: Gain by FEKO simulation

And in the anechoic chamber:

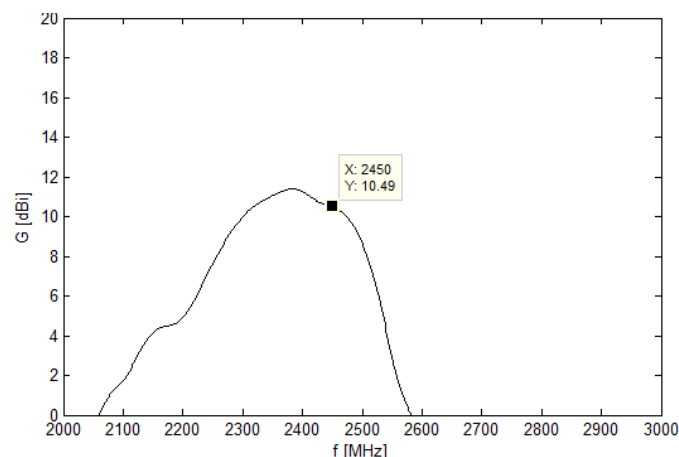


Figure 4.12: Gain in anechoic chamber

The difference between the measurement and simulation can be caused by lack of simulation calculations. If we focus on measurements in anechoic chamber we can see that at 2.45GHz we get a gain of 10.49dBi that it was the objective for this project.

For compute the axial ration we use the concept that due to the horn antenna has a linear polarization, the difference between the  $S_{21}$  when the horn is in horizontal and when the horn is in vertical is the axial ratio. In the next image we can see the concept; the axial ratio is the different between the major and the minor axes: [13]

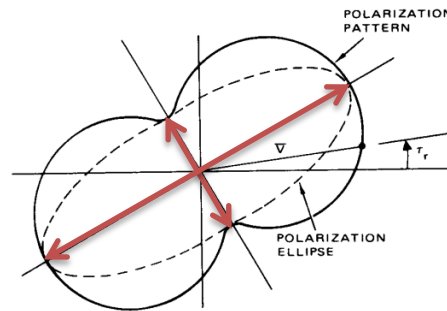


Figure 4.13: Polarization pattern

In our case the value of the axes is:

Axes	Value
Horizontal path phi	-31.5154dB
Horizontal path theta	-30.7669dB
Vertical patch phi	-31.5235dB
Vertical patch theta	-31.2427dB

Table 4.1: Axes value

In all the cases we have less than 1dB of different between the axes. This means that we have a good circular polarization. If we compare with the value provided by FEKO:

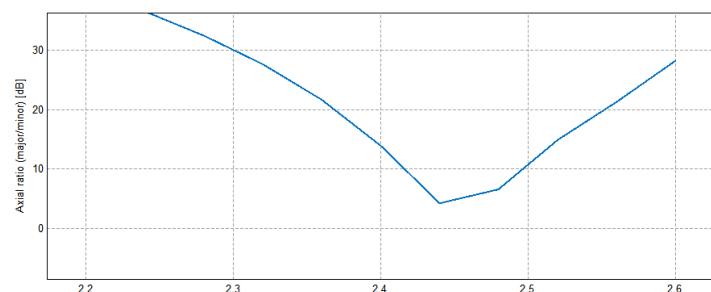


Figure 4.14: Axial ratio by FEKO simulation

At 2.45GHz we have almost 3dB of axial ratio.

Finally, we can see circular polarization if we see the electric current in function of time in the microstrip antenna by FEKO simulation, following the concept of characteristic modes. In the figures below you can see how for different times occurs a rotation in the current distribution.

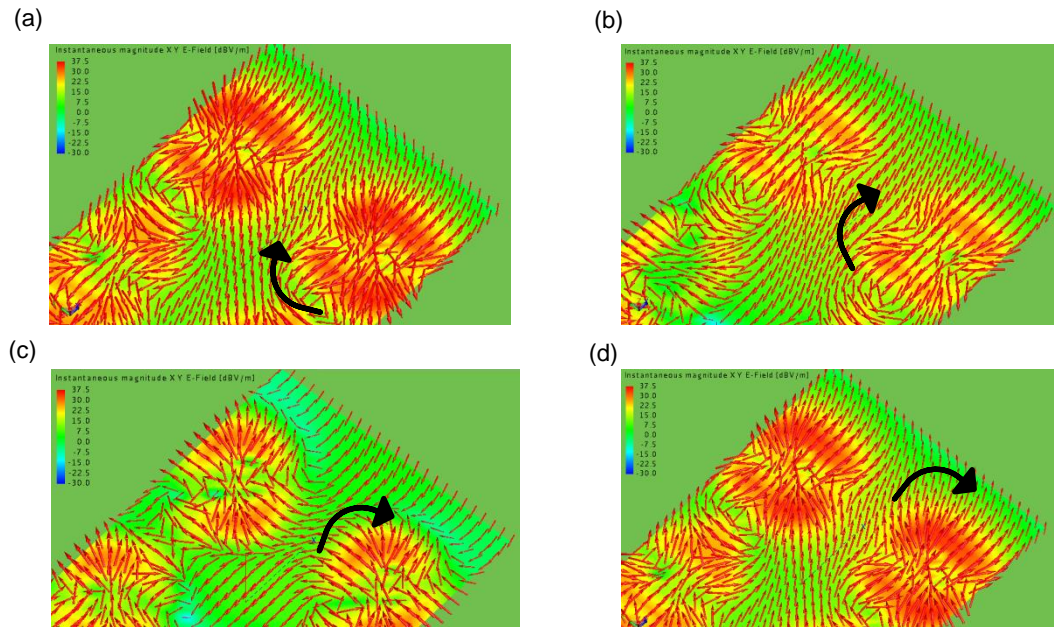


Figure 4.15: Current distribution in FEKO with (a)  $\omega t=0^\circ$ , (b)  $\omega t=45^\circ$ , (c)  $\omega t=90^\circ$  and (d)  $\omega t=180^\circ$

## 5. Budget

	Description	Cost
FEKO software	Education license for one year (no commercial projects)	900 €
Design and prototyping cost(*)	Research microstrip information	120 hours x 7 € = 840 €
	Design array microstrip	270 hours x 7 € = 1890 €
	Construct the optimization microstrip array	5 hours x 7 € = 35 €
	Evaluation the antenna	6 hours x 7 € = 42 €
	Project documentation	150 hours x 7 € = 1050 €
Product	Coaxial connector	1.20 €
	Patch antenna prototype	10 €
TOTAL		4768.2 €

(\*)If the hourly wage is 7€

Table 5.1: Budget



## 6. Conclusions and future development:

After the study the three previous design, our final design of four elements antenna reaches all objectives; have a very good circular polarization in consequently axial ratio near 0dB, good gain, good reflection coefficient ( $S_{11}$ ) and narrow band-width at 2.45GHz that determine a long range of operability. For this reasons, can work efficiently as a reader antenna for a RFID applications. The other two designs will have problem if were part of RFID system because they have problems with the gain or with the radiation.

With the final design the results obtained with FEKO software and in the anechoic chamber are very similar, but we should in mind that in FEKO software we have an infinite ground plane that doesn't allow the secondary lobes and the back lobe.

The next step should be improve the final design and try to make with reduced dimensions and better characteristics. One thing that can be improve is the band-width because we obtained a reduced band-width, that can be improve with increasing the substrate thickness, optimization the impedance matching between antenna and feed network or reducing the substrate effective permittivity.

Despite having the anechoic chamber, for the next test you should dispose of an antenna with a circular polarization to see the direction (clockwise or counterclockwise) of the circular polarization of the antenna under test.

Finally it is noteworthy that we have obtained a low cost antenna with lightweight and has achieved the objectives for our application.

## **Bibliography:**

- [1] Nikola T. "PCB Design". [Online] Available: <http://www.bitweenie.com/listings/microstrip-vs-stripline/>
- [2] Sophocles J. Orfanidis. "Electromagnetic Waves and Antennas". 1999–2014 Rutgers University [Online] Available: <http://eceweb1.rutgers.edu/~orfanidi/ewa/>
- [3] Microwaves101.com *The world's microwave information resource since 2001*. [Online] Available: <http://www.microwaves101.com/encyclopedias/microstrip>
- [4] Mónica Ramírez Acedo. "Antenas Microstrip con Polarización Circular para Sistemas de Posicionamiento por Satélite y aplicaciones RFID". *Thesis Doctoral*, Department of Telecommunications and Engineering Systems, Autonomous university of Barcelona Bellaterra, Spain 2013
- [5] R.J. Garbacz and R. H. Turpin, "A generalized expansion for radiated and scattered fields", *IEEE Transactions on Antennas and Propagation*, vol. AP-19, May 1971.
- [6] Constantine A. Balanis "Antenna Theory Analysis and Design", Wiley & Sons, 2005, New Jersey, USA. ISBN: 978-0471603528
- [7] John R. Ojha and Marc Peters, "Patch Antennas and Microstrip Lines", Germany. [Online] Available: <http://cdn.intechopen.com/pdfs-wm/10307.pdf>
- [8] R.F. Harrington and J.R. Mautz, "Theory of characteristic modes for conducting bodies", *IEEE Transactions on Antennas and Propagation*, vol. AP-19, September 1971.
- [9] E. Antonio-Daviu, "Analysis and design of antennas for wireless communications using modal methods". Thesis Doctoral, 2008
- [10] Eloy Guillem Marti, "Antenas de Polarización Circular para Sistemas RFID", *Engineering of Telecommunications*, Rovira and Virgili University, 10 June, 2010
- [11] M. Yahya and Z. Awang, "Cross Polarization Ratio Analysis of Circular Polarized Patch Antenna," 2010 International Conference on Electromagnetics in Advanced Applications (ICEAA), pp. 442-445, Sep 2010.
- [12] Bhushan Bhimrao Dhengale and Deepak C. Karia, "A high Gain 2-Element Microstrip Array Antenna with Circular Polarization for RFID Applications", *Department of Electronics and Telecommunication Engineering*, Sardar Patel Institute of Technology, India, 2015 International Conference on Advances in Computing. Communications and Informatics (ICACCI). pp. 116-120
- [13] *IEEE Standard Test Procedures for Antennas*. 1979. IEEE Std 149-1965. DOI: 10.1109/IEEESTD.1979.120310
- [14] Cabedo-Fabrés M., Antonio-Daviu E., Valero-Nogueira A. and Fernando Bataller M. *The Theory of Characteristic Modes Revisited: A Contribution to the Design of Antennas for Modern Application*. Universidad Politecnica de Valencia. vol. 49. DOI: 10.1109/MAP.2007.4395295. pp. 52-68. October 2007.
- [15] Ruiz Cruz, J.A. and Masa Campos J.L. "Antenas y circuitos de Alta frecuencia". Department of Electromagnetism and Circuit Theory. *Universidad Politecnica de Madrid*. [Online] Available: [http://arantxa.ii.uam.es/~acaf/Documentacion/Tema\\_II\\_Teoria\\_Circuitos\\_RF.pdf](http://arantxa.ii.uam.es/~acaf/Documentacion/Tema_II_Teoria_Circuitos_RF.pdf)
- [16] FEKO Software. "Characteristic Mode Analysis (CMA)" [Online] Available: [http://www.feko.info/product-detail/productivity\\_features/characteristic-mode-analysis](http://www.feko.info/product-detail/productivity_features/characteristic-mode-analysis)

## **Glossary**

A list of all acronyms and the meaning they stand for.

- UPC: In Catalan: *Universitat Politècnica de Catalunya* (Polytechnic University of Catalonia)
- UWB: In Czech: *Západočeská Univerzita v Plzni* (University of West Bohemia)
- RFID: Radio-frequency identification
- WP: Work package
- TEM: Transverse electric and magnetic mode
- AR: Axial ratio