Master's Thesis

Master in Telecommunication Engineering

Design and construction of a 4G mobile network antenna

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UAB

El sotasignant, *Josep Parrón Granados*, Professor de l'Escola Tècnica Superior d'Enginyeria (ETSE) de la Universitat Autònoma de Barcelona (UAB),

CERTIFICA:

Que el projecte presentat en aquesta memòria de Treball Final de Master ha estat realitzat sota la seva direcció per l'alumne *Samara Hassan Delgado Khalil*.

I, perquè consti a tots els efectes, signa el present certificat.

Bellaterra, *04 de Febrer de 2015*.

Signatura: *Josep Parrón Granados*

Resum:

En aquest projecte es presenta el disseny i la construcció d'una antena de telefonia per a cobertura de 4G, on s'ha pres com a base les investigacions realitzades per Aykut Cihangir en el paper titulat "Integration of Resonant and Non-Resonant Antennas for Coverage of 4G LTE bands in Handheld Terminals". El principal objectiu d'aquesta investigació i desenvolupament és doncs validar els resultats obtinguts en el paper de referència i així buscar millorar el disseny proposant nous mètodes i formes geomètriques de les parts que componen l'antena total. Cal ressaltar que en el disseny de l'antena, donat els requeriments en ample de banda i nivells de reflexió, es fa indispensable desenvolupar xarxes d'adaptació que permetin millorar el funcionament i contribueixin a incrementar la radiació i disminuir les pèrdues per reactàncies en les freqüències de funcionament desitjades.
Finalment, l'antena s'ha fabricat sense xarxa d'adaptació, i s'han realitzat les proves amb l'analitzador de xarxes, comparant els resultats obtinguts en la realitat amb aquells que van resultar de les simulacions en el programari.

Resumen:

En este proyecto se presenta el diseño y la construcción de una antena de telefonía para cobertura de 4G, donde se ha tomado como base las investigaciones realizadas por Aykut Cihangir en el paper titulado "Integration of Resonant and Non-Resonant Antennas for Coverage of 4G LTE Bands in Handheld Terminals". El principal objetivo de esta investigación y desarrollo es pues validar los resultados obtenidos en el paper de referencia y así buscar mejorar el diseño proponiendo nuevos métodos y formas geométricas de las partes que componen la antena total. Cabe resaltar que en el diseño de la antena, dado los requerimientos en ancho de banda y niveles de reflexión, se hace indispensable desarrollar redes de adaptación que permitan mejorar el funcionamiento y contribuyan a incrementar la radiación y disminuir las pérdidas por reactancias en las frecuencias de funcionamiento deseadas.
Finalmente, la antena se ha fabricado sin red de adaptación, y se han realizado las pruebas con el analizador de redes, comparando los resultados obtenidos en la realidad con aquellos que resultaron de las simulaciones en el software.

Summary:

In this project, the design and construction of an antenna for 4G mobile communications coverage is proposed, which has been based on the research performed by Aykut Cihangir in the paper named "Integration of Resonant and Non-Resonant Antennas for Coverage of 4G LTE Bands in Handheld Terminals". The main objective of this research and development is thus to validate the results obtained in the paper of reference and to seek for an improvement on the design by proposing new methods and geometrical modifications of the parts of the overall antenna. It should be noted that in the design of the antenna -given the requirements of the bandwidth and levels of reflection- it is necessary to develop matching networks so as to improve the antenna's performance and to help to increase the radiation and to decrease the reactance's losses in the desired frequencies.

Finally, the antenna has been manufactured without matching network and, has been tested with the network analyser, comparing the results obtained in real performance against those resulting from the simulations in software.

ACKNOWLEDGEMENT

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It is important to me to dedicate my thesis to people I mentioned before and others that always gave their encouragement and strength and were by my side. I felt rather rested on them all this amazing and adventurous time I lived here in Barcelona.

INDEX

ABSTRACT

In this project, the design and manufacturing of a 4G antenna for mobile communications is described. As it is known, since the implausible development of the communications technologies, the boundaries and constraints are limiting the geometry of the devices and, the requirements and features of the services are called to have better and smaller technologies whereas the capabilities of that services are thought to be of a greater performance. From this perspective, it is necessary to reduce the space for the antenna inside the gadgets. Considering 4G frequencies, it is clear that the antenna must operate in the range of 700-960 MHz and 1.7-2.7 GHz taking into account the coverage for 2G, 3G and 4G stated frequencies. Low frequencies often require long or big dimensions of the antenna in order to achieve resonant into the given bandwidth. However, as it is mentioned before, novel technologies need small and reduced space. At that point, this project is based in the new design techniques theories that have been demonstrated in many novel investigations where, in order to satisfy the size constraints, the ground plane –where the electronics of the mobile are located- is used as a tool for non-resonant antenna path to improve the radiation pattern and characteristics. Moreover, to cover the high frequencies, it is necessary to use a small-sized antenna, doing easy to model an ordinary monopole inside the space of the antenna.

In this manner, this project is divided into two main parts. On one hand, we have the design of a non-resonant part of the antenna which has to use the ground plane to help to improve the radiation in the lowest frequencies. On the other hand, we have a single monopole to create another part of the antenna so as to cover highest frequencies.

The former part of this thesis will be referred to a fundamental theory of the mobile communications regarding to 4G technology and, several models of antennas –monopole and dipole- will be presented in order to understand the evolution from the analog to communications to the present. In the latter part of this thesis, the design of the 4G antenna will be presented by explaining the methods and theoretical bases which were used to develop step-by-step the full antenna. It will be depicted several graphics showing the results and comparing with the requirements thus, finally, the constructed antenna will be analysed and some conclusions will be summarized, explaining the results from the comparison between software and real results.

CHAPTER I

INTRODUCTION

Mobile phones were first introduced in the early 1980s, where mobile telephony was limited to phones installed in cars and other vehicles. Then, prior to 1973, Motorola was the first company to produce a handheld mobile phone. In the succeeding years, the underlying technology has gone through many generations. The first generation (1G) phones used analogue communication techniques: they were bulky and expensive, and were regarded as luxury items. Mobile phones only became widely used from the mid-1990s, with the introduction of second generation (2G) technologies such as the Global System for Mobile Communications (GSM). These use more powerful digital communication techniques, which have allowed their cost to plummet, and have also allowed them to provide a wider range of services than before -email and basic access to the Internet-. Third generation (3G) phones still use digital communications and allow to support much higher data rates than before, and hence to provide more demanding services such as video calls and high speed Internet access [1]. Nowadays, with the entrance of fourth generation (4G), phones –called mobile devices- have improved the performance and coverage allowing transferring more data and services, like 3G technologies, even at higher speeds as is shown in Table 1.1.

	LTE
Peak download	100 Mbit/s
Peak upload	50 Mbit/s

Table 1 Data speeds of LTE

As new standards and new frequency bands were introduced and created for better performance of mobile communication systems, wider broadband antennas were needed to be created in order to satisfy the requirements established by the technologies, where the space inside the gadgets remained small and even got smaller. Taking into account those characteristics and the surveys done by many engineers around the world on how to develop and construct well-work antennas –considering new technology capabilities and the new design techniques- this project is just justified in order to obtain a good-performance antenna which will accomplish some requirements through this thesis.

1.1.OBJECTIVES

The main goal of this project is to demonstrate and to validate the results obtained in the design of the antenna for 4G given in [2], as well as to search for the enhancement of the proposed design by making use of new techniques of antenna designs and by changing the form of the structure evaluating the electrical fields and the coupling between the parts of the full antenna.

1.1.1. Specific objectives

The specific goals of this thesis are:

- To evaluate the behaviour of the structures proposed in novel designs of antennas understanding the way they work and how to benefit my design through that.
- To design an antenna for 4G coverage in a designated space of a PCB of a mobile device. Taking into account the new smartphones and gadgets, and the researches, the space used in this project is rectangular 59mm x 114mm.
- To validate the results of the simulations by manufacturing a real prototype of the antenna and, then, to compare the results and make a brief but not superficial analysis underlining the differences of the model obtained to the simulated one.

1.2.METHODOLOGY

Based in novel investigations and once they are studied, the project takes two parts, where the first one is related to the use and manipulation of the software for the computational design of the antenna and the second one is related to the manufacturing of a real prototype of the software’s design.

1.2.1. Software

FEKO 7.0 is a comprehensive electromagnetic simulation software tool for the electromagnetic field analysis of 3D structures. 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 [3]. In matter of antennas, FEKO is capable of doing an analysis of horns, microstrip patches, wire antennas, reflector antennas, conformal antennas, broadband antennas, arrays, and analysis of antenna radiation patterns.

Advanced design system (ADS) is the world's leading electronic design automation software for RF, microwave, and high speed digital applications [4]. In this project, ADS 2011 is used to model and create the necessary matching networks so as to improve the antenna's performance. It is important to notice that ADS and FEKO can share together files .snp to import and to export S-parameters easily.

1.2.2. Laboratory equipment

Basically, it was mandatory to use 2 devices so as to make tests to the real antenna and to fabricate it. N5242A Network Analyser from Agilent Technologies (Figure 1) is used to measure and obtain the S-parameters of the real antenna. This equipment can allow the exportation of the results of measurements so as to display it in the software and compare it with software simulations. It can work from 10 MHz to 26.5 GHz. Also, ProMat S62 drill machine from LPFK Laser & Electronics Spain S.L. is used to manufacture the antenna.

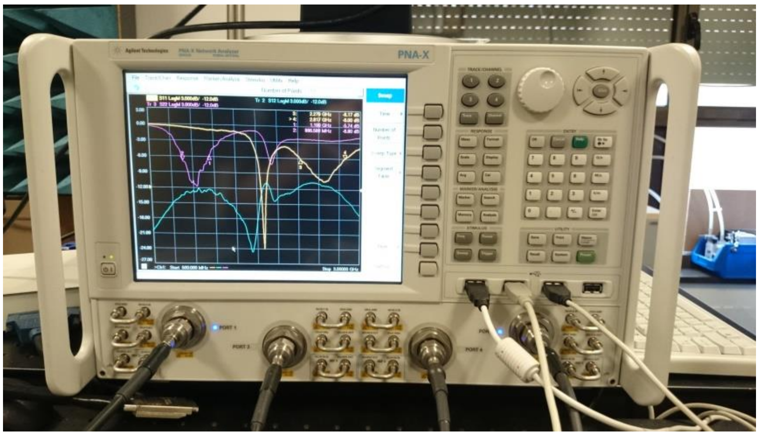


Figure 1 Network Analyser N5242A

1.3.PROJECT'S ORGANISATION

This Master's Thesis is composed of 6 chapters. In Chapter I, it is shown a brief introduction and the objectives of this project are explained detailing the reasons and justifications. As it is important to remark briefly the theory and concepts regarding to 4G developments, in Chapter II it will be introduced the evolution and main concepts of 4G technology and some antennas which are explicitly dedicated to mobile devices and, it will be underlined the importance and value of 4G in the present development. In Chapter III, the design through FEKO software of a non-planar 4G antenna will be explained, indicating the procedures that have been taken into account along the antenna's modelling as well as the results of several tests and designs are depicted. Then some observations must be presented. In Chapter IV, a planar 4G antenna will be depicted indicating the procedures and considerations for the design and explaining the decisions taken and, once the antenna's design is selected, it is constructed. In Chapter V, I will explain briefly the methods used to construct the antenna and the tests done with the laboratory equipment, namely the Network Analyser. A comparison between the software results and real results is presented explaining the main differences and similarities among them and making some conclusions. Finally, in Chapter VI the ultimate conclusions of this project are shown, summarizing the specifications and performance of the final selected design.

CHAPTER II

THEORY OF MOBILE COMMUNICATIONS AND ANTENNAS FOR MOBILE DEVICES

2.1. MOBILE COMMUNICATIONS

Nowadays, mobile communications play a central role in the voice/data network field. From the 80s until now, the mobile communications have changed passing through several protocols and enhancements so as to allow users to receive and make calls, use internet, gps, sensors, and even more services.

Before talking about the evolution of the technology, the concept and principles of mobile systems must be clear. Regarding to the structure of the system, a cellular mobile communications system uses a large number of low-power wireless transmitters to create cells -the basic geographic service area of a wireless communications system. Variable power levels allow cells to be sized according to the subscriber density and demand within a particular region [5] and, as mobile users travel from cell to cell, their conversations are "handed off" between cells in order to maintain seamless service (See Figure 2).

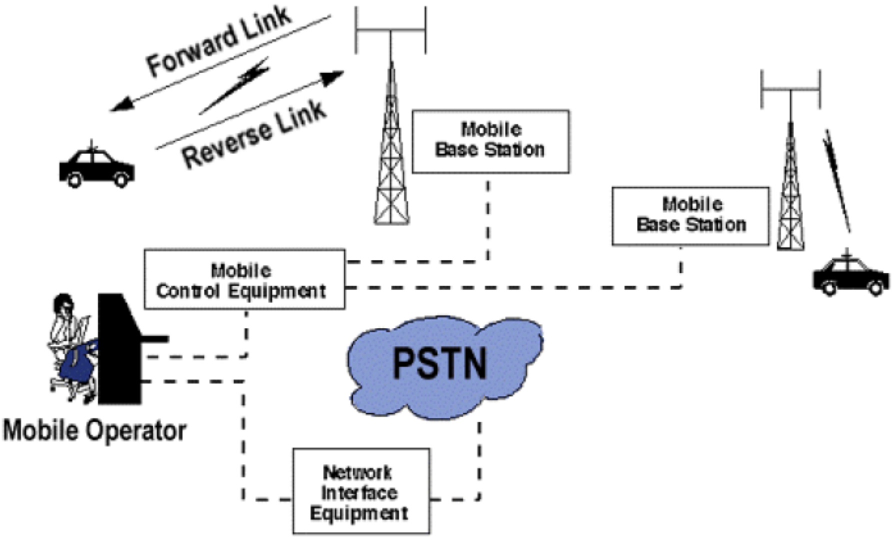


Figure 2 Mobile communication and telephone system [5]

Each mobile device uses a separate, temporary radio channel to talk to the cell site. The cell site talks to many mobiles at once, using one channel per mobile. Channels use a pair of frequencies for communication, one frequency, the forward link, for transmitting from the cell site, and one frequency, the reverse link, for the cell site to receive calls from the users.

Since the development of the wireless communication around 1973, engineers in the world worked to create the protocols and products capable to make workable wireless mobile devices. The first generation of mobiles were analog; it means that these first generation systems provided voice transmissions by using frequencies around 900 MHz and analogue modulation, and were deployed in the Norway in 1981 and was followed by similar systems in the US and UK. The main characteristics of this called first generation (1G) were unencrypted and easily vulnerable, susceptible to cell phone "cloning" and it used a Frequency-division multiple access (FDMA) scheme and required significant amounts of wireless spectrum to support.

Analog systems were eventually superseded by digital AMPS (Advanced mobile phone system) in 1990 [6] and, thus, second generation (2G) emerged. At this point, the next generations are called Digital Networks. In the second generation, the most popular of the 2G standards is the GSM (Global System for Mobile Communications), which uses TDMA for multiplexing and FDD for duplex communication as uplink and downlink. TDMA is a standard that lets multiple users access a group of radio frequency bands and eliminates interference of message traffic, is used to split the available 25MHz of bandwidth into 124 carrier frequencies of 200 kHz each. The important advantage of digital networks is that they allow improving the voice data transferring and expanding the range of applications to some basic ones such as fax and messages, even though those systems are not implemented at all for web browsing. For solving that issue, it was created the 2.5G which adds the IP identification and support so as to aggregate packet data transferring to 2G. The main protocols in this technology are GPRS and WAP.

All 2G wireless systems are voice-centric. GSM includes short message service (SMS), enabling text messages of up to 160 characters to be sent, received and viewed on the handset. Most 2G systems also support some data over their voice paths, but at painfully slow speeds usually 9.6 Kb/s or 14.4 Kb/s [7].

After that, mobile communications were thought to be related to videocall and complex services, while improving the bandwidth and the capacity of the mobile services, 3G generation emerged, searching for covering the user services mentioned. Nevertheless, along the development of this technology, it was realized that the service needed by the users was internet. So from this part, technologies were dedicated to cover internet services among other services such as videocalls and complex multimedia transferring.

3G technologies make use of Time Division Multiple Access (TDMA) and Code Division Multiple Access (CDMA) and, these technologies have value added services like mobile television, GPS (Global Positioning System) and video conferencing and the basic feature of 3G Technology is fast data transfer rates [8]. 3G speeds are 144 Kb/s while the user is on the move or in a vehicle, 384 Kb/s for pedestrians, and up to 2 Mb/s for stationary users.

In this technology, mobile devices are capable to connect to internet at new high speeds and cover operability as phones and internet access devices. Since now, the main objective of enhancement of technologies turns around from voice services to complex data transfer services.

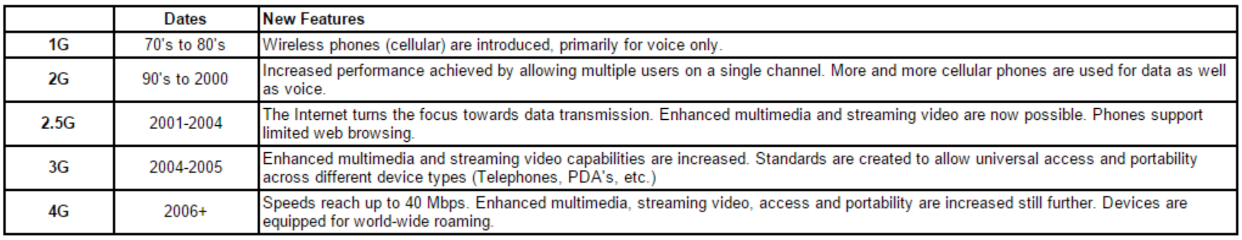
2.2. 4G TECHNOLOGIES

It has been shown that through the years, since the very first mobile phone device (1G), the cellular mobile networks have had several changes in order to cope with the increment of users, the coverage, the necessity to transfer different kind of data such as voice, video and data packets, and also the desire to make the human-machine interface more amenable. At the same time, 3G technology was reaching its limit boundary and getting full of users. The necessity for create a new technology which increments the bandwidth and the data transfer rates was compulsory. 4G technology appears as a framework to be established to try to accomplish new levels of user experience and multi-service capacity by also integrating all the mobile technologies that exist [7]. The modulation schemes of QPSK, 16QAM and 64QAM are used to obtain peak data rates of up to 1Gbit/s for a low-mobility user in downlink (100Mbit/s for high mobility) and 500Mbit/s for uplink. OFDMA is used for multiple accesses in the downlink whereas SC-FDMA is used for uplink [9].

Even though 4G technologies cover a certain range of frequencies, every gadget or mobile device must be capable of working in the 3G frequencies. This is because exists the risk of lacking of the 4G signal or there are some countries and cities that haven't implemented 4G coverage base-stations. Figure 3 shows the range of frequencies that current devices must work in in order to cover 3G and 4G services.

Figure 3 Frequencies for 4G services [9]

In figure 4 it is presented a brief chart summarizing a comparison between all generations of mobile communications.



	Dates	New Features
1G	70's to 80's	Wireless phones (cellular) are introduced, primarily for voice only.
2G	90's to 2000	Increased performance achieved by allowing multiple users on a single channel. More and more cellular phones are used for data as well as voice.
2.5G	2001-2004	The Internet turns the focus towards data transmission. Enhanced multimedia and streaming video are now possible. Phones support limited web browsing.
3G	2004-2005	Enhanced multimedia and streaming video capabilities are increased. Standards are created to allow universal access and portability across different device types (Telephones, PDA's, etc.)
4G	2006+	Speeds reach up to 40 Mbps. Enhanced multimedia, streaming video, access and portability are increased still further. Devices are equipped for world-wide roaming.

Figure 4 Chart of summary of all generation's features

2.3. ANTENNAS FOR MOBILE DEVICE

At the first generation, the antennas were situated in the top portion of the mobile devices as a monopole. This monopole was designed to work as a quarter length of the operational frequency. Therefore, knowing the operational frequencies, miniaturization techniques were proposed to reduce the size of the monopole. One example of this miniaturization was to compress the antenna by making it helix type and, when working in multiband services a little whip was introduced into the helix so as to cover the two bands required (Figure 5). When the PCB was of the quarter length size these devices worked even better because PCB plus monopole worked as a dipole.

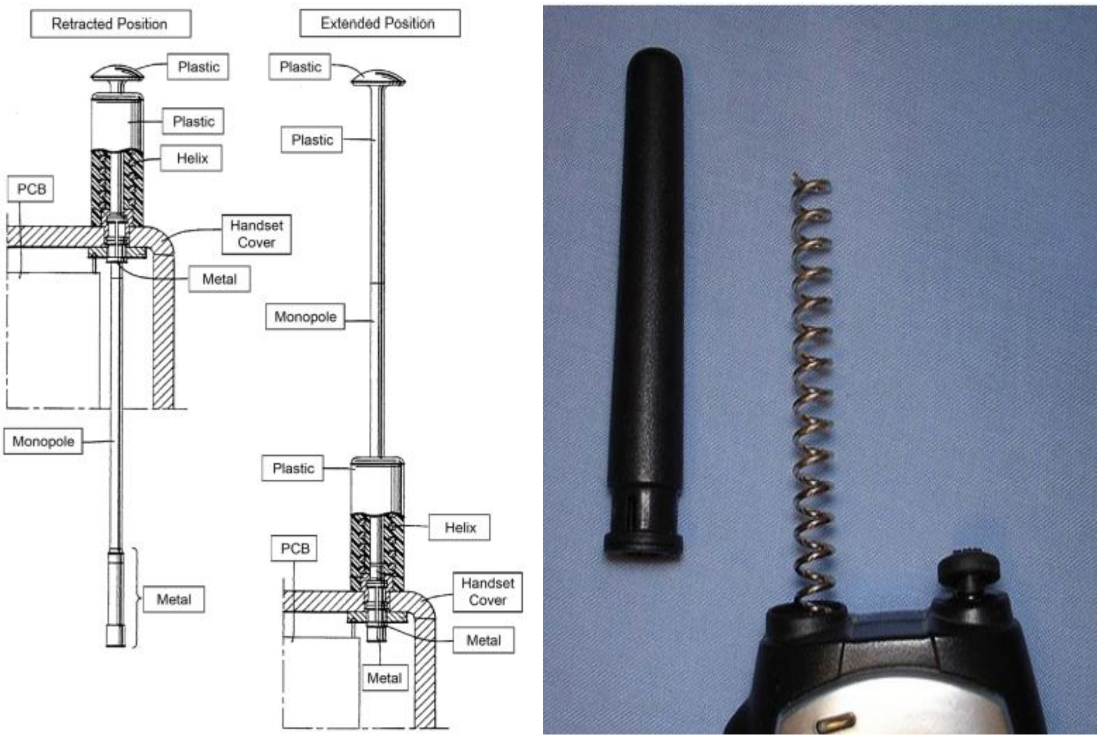


Figure 5 Monopole plus helix antenna [9]

The main disadvantage of this monopole-helix antenna was the external discomfort and even the good radiation pattern it had, this antenna also had a high Specific Absorption Rate (SAR). So, in the 1990’s were developed internal antennas so as to avoid the trip of having discomfort. These internal antennas were called PIFA (planar inverted F antenna) and they had a ground plane connected to a physical point of the antenna and, for multiband behaviour, they also had a slot in the main plate to disturb the current distribution (Figure 6).

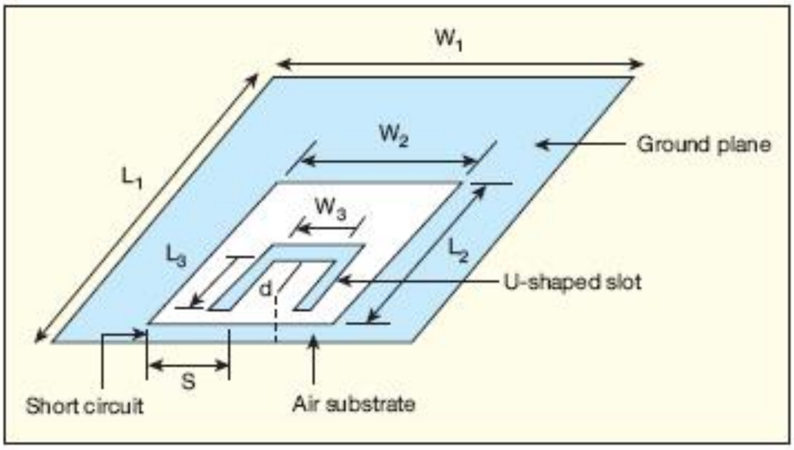


Figure 6 Dual-band PIFA [8]

In addition, in comparison to the conventional whip antennas showing omnidirectional radiation, such PIFAs have the advantage of relatively smaller backward radiation toward the mobile phone user. This suggests that the possible electromagnetic energy absorption by the user's head can be reduced [10].

Another kind of internal antenna used was a simple planar monopole which were not connected to the ground plane. This type of antennas may require a ground clearance region in the vicinity (generally on one edge of the PCB) for acceptable performance. Techniques like adding parasitic elements or adding parallel branches to the radiating element can be used for multiband operation [9]. Currently this antenna is used for GSM coverage. In most cases the monopole requires miniaturization so as to be inside the antenna's housing. For instance, a 900 MHz operation frequency device must require an antenna with a straight planar monopole of a height of about 83 mm. The mainly designs techniques to reduce the antenna are the bending, the folding, or the wrapping two-dimensional planar monopoles into three-dimensional structures. An example of those techniques is given in Figure 7.

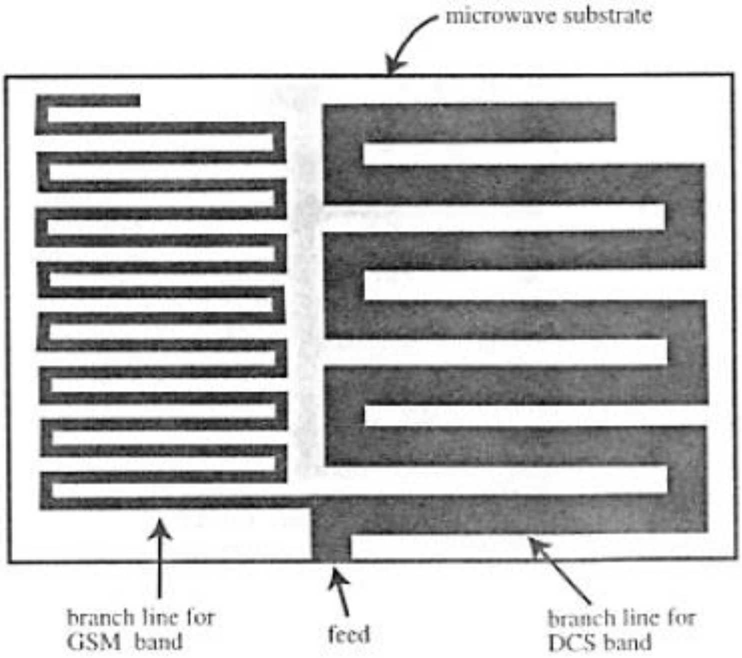


Figure 7 Geometry of a GSM/DCS dual-frequency planar monopole [10]

From this point, the technology evolution and the new concept designs change the way mobile devices were thought to be. It means, it has been a change in the technical requirements due to new services proposed and a change in the geometrical form of the devices which required new sizes of antennas and the specific space for their location inside the devices had change asking for the creation of new miniaturization techniques.

As it is mentioned in [11], techniques like etching slots or meandering were used to alter the currents on the antenna element and/or the PCB, called inductive loading and capacitive loading was also used for this purpose, this time to manipulate the electrical near fields (like bending the antenna closer to the ground plane).

Currently, another important requirement in the mobile systems is the bandwidth. As it is known, for the 3G and 4G technologies it is required antennas to work in band frequencies greater than 200 MHz. One essential technique for bandwidth enhancement is the use of Matching Networks (abbreviated as MN) which can either be distributed along the antenna or introduced directly at the feed for arranging the antenna input impedance for cover the requirements. The use of a matching network will be discussed later in the design of the antenna.

2.4. COUPLING ELEMENT ANTENNAS

Low-volume antenna structures for mobile devices might require the reducing of the volume of the antenna elements –due either to the location into the PCB or the specifications-. A way to do that is to efficiently use the radiation of the currents in the ground plane or mobile PCB. As it is explained in [12], essentially non-resonant coupling elements (called CE) are used to optimally couple to the dominating characteristic wavemodes of the chassis. The antenna structures are tuned to resonance with matching circuits. However, there are no systematic feasibility and performance studies of the coupling elements, and it is all reduced then to a practical-laboratory designs and tests. As it is stated in [12], the ground plane of the printed circuit board (PCB) in a mobile terminal plays the major role for radiation especially in the lower-frequency bands, where 90% of the total radiation comes from the PCB at 900MHz.

The coupling element based antenna structure consists of three main parts. The first part is the mobile terminal chassis, which is meant to work as the main radiator of the antenna structure. Coupling elements are used to excite the primary wavemodes of the chassis as efficiently as possible. Impedance matching to the transceiver electronics is produced with a matching circuitry. In order to couple to the chassis wavemode efficiently (Figure 8), the location and shape of the coupling element have to be chosen correctly. The strongest coupling (and largest bandwidth) can be achieved by bending the coupling element over the shorter end of the chassis [13].

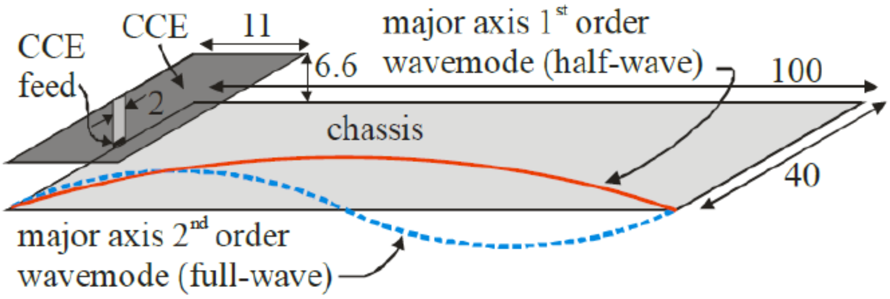


Figure 8 Effect of the coupling element on the ground plane [13]

Since the results and effects of the coupling element are pretty interesting for designing, this kind of development has been proposed in many novel investigations and researches, where this technique is widely used to cover the cellular communication band in the mobile devices. The main drawback of the technique is that despite the high obtainable bandwidth potential, it is almost necessary the use of a complex matching network in order to improve the adaptation near the resonant frequencies, thus to improve the bandwidth. Even a matching network is a solution; it must take into account that introduces losses due to the SMD components. In Figure 9 is depicted a design using CE for covering GSM bands.

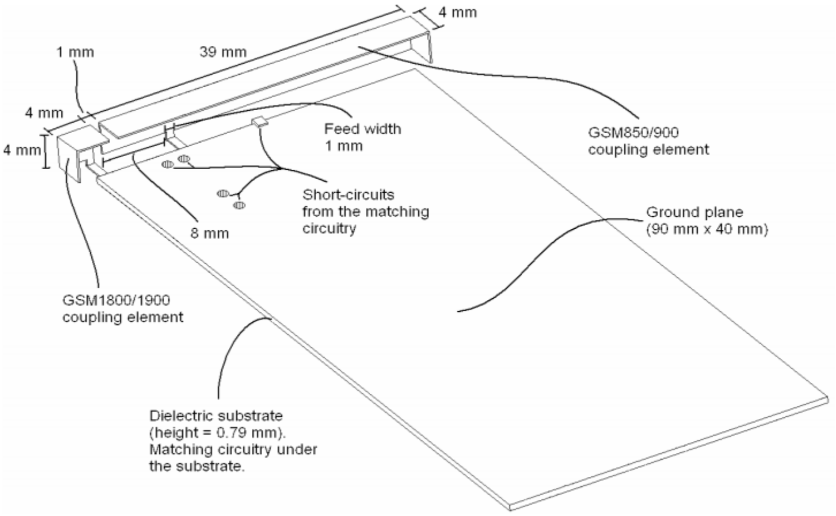


Figure 9 A quad-band prototype which consists of a ground plane, matching circuitry, and two separate coupling elements for the GSM850/900 and GSM1800/1900 bands [14]

Another disadvantage of this CE technique is the necessity of keep the region between the coupling element and the PCB clear from any component or metal, because these materials can cause a distortion in the Electric Field and, therefore, losses in the total bandwidth.

Due to the fact that the allocation for the antenna in the mobile PCB is straitened and in lower frequencies the antenna has an element part that is bigger than the PCB geometry, in this thesis, in the modelling of the antenna, it will be used this technique to develop the first part of the antenna regarding to low-frequency band, that is to say, from 700 MHz to 960 MHz.

2.5. MATCHING NETWORKS

As a significant part of the design of any kind of antenna and knowing the new requirements and technology development, it is almost necessary in any mobile device to implement a matching network so as to accomplish the requirements, especially in bandwidth and reflection coefficient. Nevertheless, the use of a MN is almost restricted to certain parameters; it means that a matching network must be selected carefully because it introduces losses in the radiation characteristics even though a MN improves another performance properties. In lower frequencies where antennas get big sizes a MN is a solution to reduce the antenna element’s size. So, a good selection is always necessary. In the case of mobile devices, where the antennas need to work in a considerable bandwidth range, a simple matching network cannot be considered. Conversely, it is required one that can cover all the bandwidth; it means the use of a complex broadband matching network. Though several surveys indicate that the order improves the adaptation, it is preferred to use at maximum two-order network so as to avoid the trip of introducing losses into the antenna.

2.5.1. Broadband Matching Network

A conventional matching network is called L-Network and it consists of an inductor and capacitor and, depending on the application required the network can be low-band or high-band filter. As it is known, in antenna designs a complex matching network is required and, one technique to obtain it is cascading two or more L-networks (Figure 10) with each section having a lower Q for improving the bandwidth.

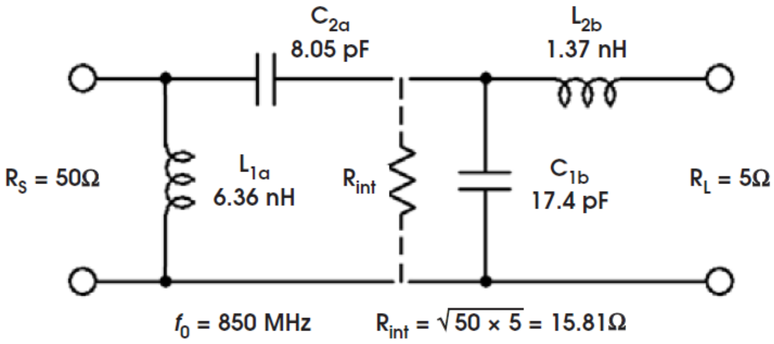


Figure 10 Example of a broadband matching network [15]

In Figure 10 it is depicted an example of a broadband matching network where two L-networks -second order- have been cascaded in series. With cascaded sections, the lowest Q (and widest bandwidth) is achieved when the intermediate impedance is the geometric mean of the source and load impedances [15]. Wider bandwidths and flatter impedance curves can be achieved by cascading more sections with the additional intermediate impedances creating smaller impedance ratios, and correspondingly lower Q for each section. However, the losses introduced by the increment of components can decrease the energy radiated by the antenna because part of the energy could be absorbed by those components, so it is not recommended to use more than two or three L-networks.

It should be noticed that, in this work, the load –resistance of the antenna- includes reactance. Thus, it is mandatory to add another component to the MN to cancel the load resistance. In Figure 11 are depicted two methods to cancel that reactance.

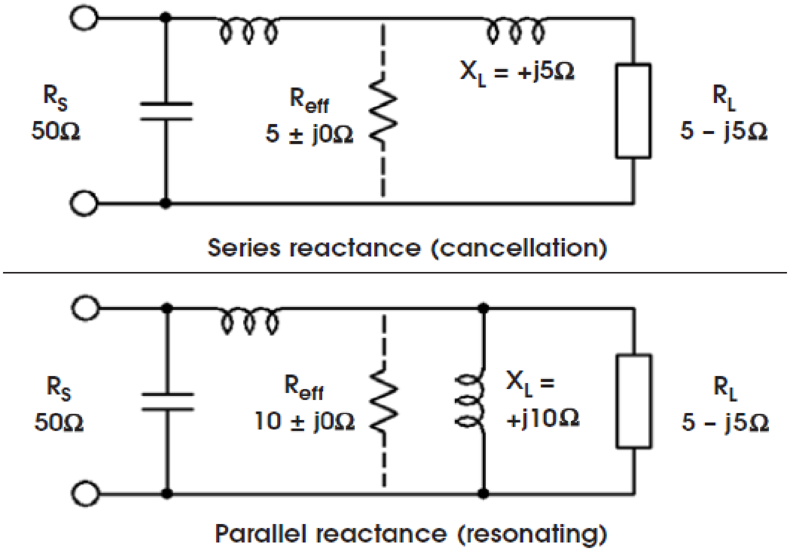


Figure 11 Two methods to cancel the load reactance [15]

Clearly, in this project, the design includes some matching networks in order to achieve the given specifications. So along the next chapters it will be explained the topology and the calculations of the matching networks that are used in this thesis.

2.6. SINGLE-FEED AND MULTI-FEED OPTIONS

In most antenna designs it is just necessary to have one feed point because with the aggregation of a duplexer, the device then is capable to switch in RF front-end and to work as transmitter-receiver (transceiver) so as to cover all the standard frequency ranges for 2G and 3G. Now, with the emergence of 4G technology the situation has changed. In 4G scheme, it is possible to receive voice data and traffic data over the two bands, meaning that it can be two data packets at the same time trying to get into the devices. So, for example, trying to send some data in 900 MHz and in 2.2 GHz will not be possible because the single-feed point cannot activate the two elements of the antenna -each one regarding to each frequency- and the duplexer can just select either transmission or reception.

The solution to overcome this drawback is to implement a multi-feed point for the antenna (Figure 12). Each element of the antenna must be connected to one single point to cover each frequency band and to avoid the problem of 4G multi-sent data. However, this can derivate into another problem, the port-to-port isolation. The isolation is needed to dodge the port-to-port coupling and to evade the efficiency losses. Thus, obtaining a good isolation depends on the position of one antenna’s element respect to the other one and -considering the small space reserved for the antenna-that is a parameter to be considered and analysed in the design of the full antenna.

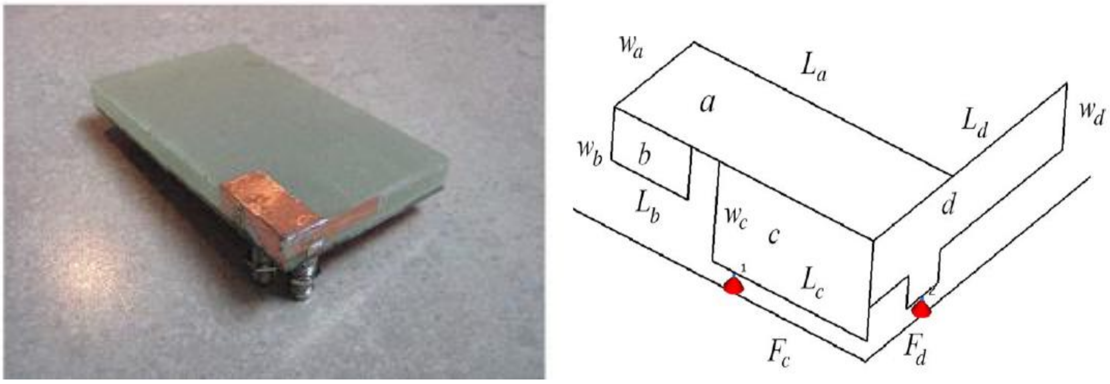


Figure 12 Example of a two-feed point antenna [16]

CHAPTER III

NON-PLANAR 4G ANTENNA DESIGN

3.1. SPECIFICATIONS

Today, with the inclusion of 4G in the mobile devices, they should be able to cover the frequencies corresponded to all the generations, that is to say GSM, WCDMA, WLAN, DCS and LTE (4G). So, considering all the frequency ranges of those technologies, it can be summarized two groups into dual-band coverage: 700-960 MHz and 1.7-2.7 GHz [2]. But, the space reserved for the antenna is smaller than the operating wavelength. The antenna behaves as an electrically-small radiator in the low frequency band and it is difficult to it to work as a wideband antenna's element. On the other hand, in the high-frequency band due to the required size for cover that frequencies, it is easy to model a simple monopole to cover the central frequency and by using some techniques, it can be turned in a wideband antenna's element.

Thus, the design will be developed in two parts. Two antenna's elements must be modelled so as to cover the two frequency ranges mentioned above. One element is designed as a coupling element because of the effect produced in the PCB ground plane and, to take this advantage for reducing the size of the element and cover the required frequencies. The other element is designed as a single monopole (probably to be folded because of the space) to cover higher frequencies. Nevertheless, it is also considered and analysed the position of the antennas and the coupling between them to enhance the bandwidth and to accomplish with the technical specs.

In terms of the device's size, as is mentioned in [2], considering new technologies on mobile devices like smartphones and, as is mentioned in several literatures, the total PCB size of common devices is between 10-12 cm large and 5-7 cm width. In this thesis as in the reference paper [2], an 11.4x5.9 cm PCB dimensions have been used with a FR4 material of a height of 1.5mm with a clearance reserved for the full antenna of 1.4x5.9 cm where the two antenna's elements must be placed on.

Summarizing the specs for this project:

- Dimensions of the device PCB: 11.4x5.9 cm (Figure 13).
- Material of the PCB: FR4 with a height of 1.5 mm.
- Space reserved for the antenna: 1.4x5.9 cm.
- First element to cover 700-960 MHz (low-frequency range): coupling element.
- Second element to cover 1.7-2.7 GHz (high-frequency range): single monopole.
- Type of the final design to be constructed: non-planar.
- Maximum reflection coefficient level allowed in the operating frequencies: -6dB.
- Maximum matching network order: two.
- Type of feeding: two-feed points, one for each element.

Once the specs are given, it is going to be explained the procedures and considerations taken to design the full antenna.

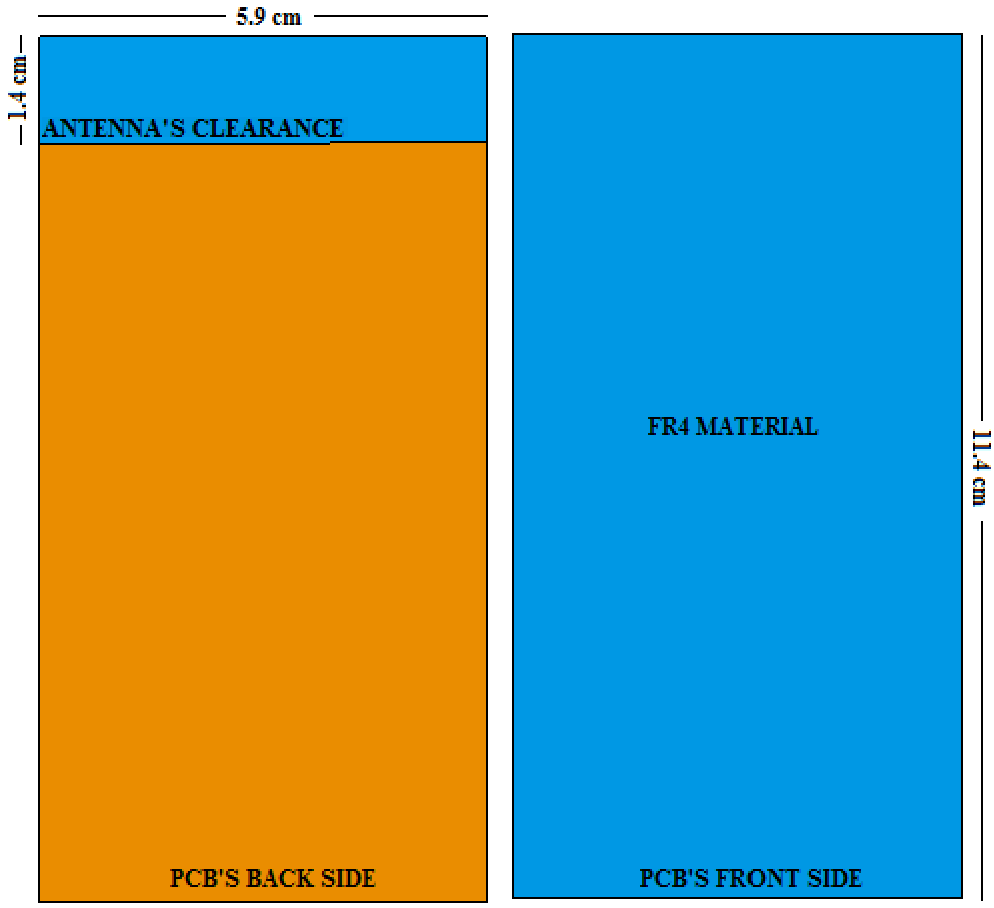


Figure 13 PCB (mobile device) dimensions

3.2. ANTENNA'S LOW-FREQUENCY BAND ELEMENT DESIGN

The first element to be implemented is a non-resonant element; i.e. due to the space reserved for the antenna, the element cannot achieve resonance in the frequency range of 700-960 MHz (low-frequency range). It is introduced then the concept of coupling element, which is a non-resonant element, specifically designed to excite proper currents on the PCB ground plane [17]. In this scheme, the currents are induced into the ground plane by the capacitive effect of the coupling element making those currents stronger near to the resonant frequencies of the ground plane where the frequencies are either into the frequency range required or near to it.

As is shown in Figure 13, there is often a small space located in the top part of the PCB for the antenna in a mobile device. One technique known to achieve the strongest possible coupling to the chassis wavemode within the used volume is to shape and locate optimally the coupling element at the end of the ground plane. The strongest coupling (and largest bandwidth) can be achieved by bending the coupling element over the shorter end of the chassis [14]. The modularity of the idea enables the use of several coupling elements to cover several separate frequency bands, e.g. those of GSM900 and GSM1800. A typical coupling element could be a plate that induces the currents by its capacitive effect; this plate is well known as plain coupling element, or simply plain CE (Figure 14).

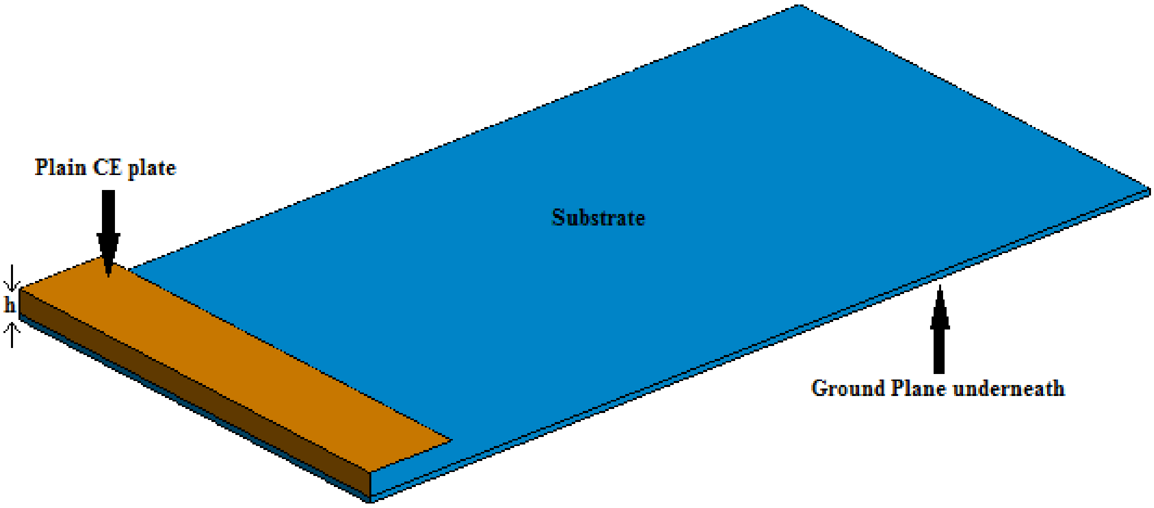


Figure 14 Bended-plain coupling element plate for bandwidth improvement

It must be noticed that the plate has a height "h" of 3 mm from the PCB in order to obtain the bended property. As well as the coupling element is not in the same plane with the PCB, the gain space in this situation can be used, for instance, to locate the other element of the antenna, i.e. the element for high-frequency coverage.

It can be seen -if the substrate were removed and the plain CE plate were connected to the ground plane- that the union of both elements is working as a non-symmetric dipole (Figure 15) and then, the impedance of that union at resonant frequency will depend on the independent impedance of each one.

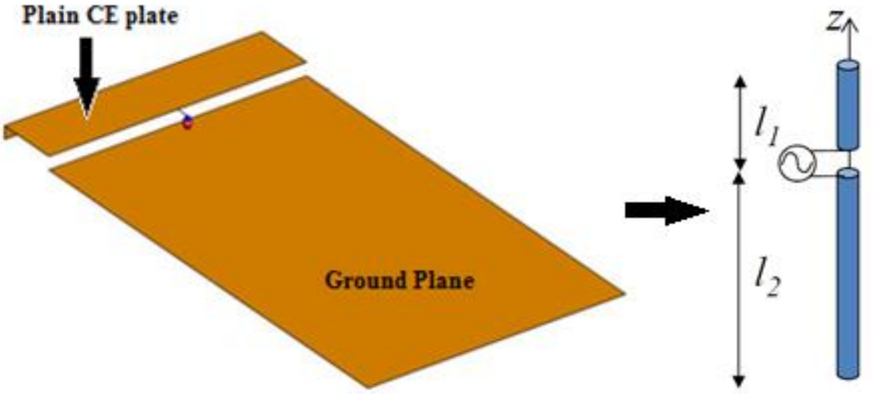


Figure 15 Asymmetric dipole obtained from the design

As shown in Figure 15, the structure works as an asymmetric dipole where the structure resonates near to the resonant frequency of the ground plane, which adaptation impedance is [19]:

$$Z_{in\_l1+l2} \approx \frac{Z_{in\_2l1} + Z_{in\_2l2}}{2}$$

3.2.1. Hollowing the plain CE plate

The plain CE plate is a good technique to introduce currents in the PCB and thus, to use an element smaller than the wavelength in the frequency range described before. In principle, the structure of the Figure 15 is a design that resonates at about 1 GHz (Figure 16). Nevertheless, the structure is using all the reserved space for the full antenna and, this is not practical for the purpose of the project. In [9] it has been done a technique called Hollow

Plain CE where the traditional plain CE has been modified geometrically so as to obtain a more spaced-efficient structure keeping the characteristics and performance of the new structure equal to the original one. In this part of the project I will apply that technique and evaluate the results of doing it in the design of the low-frequency element.

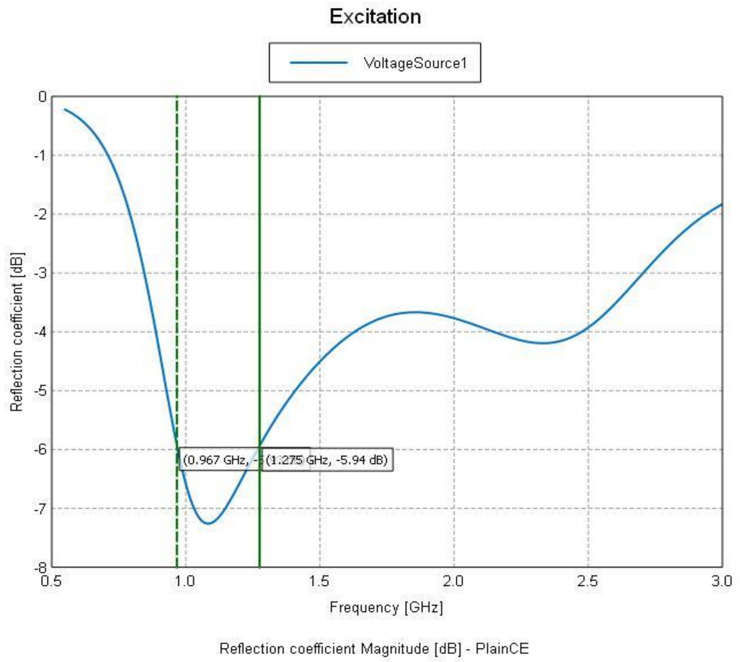


Figure 16 Reflection coefficient of plain CE plate and ground plane structure with substrate

By evaluating the current distribution in the plain CE plate and structure (Figure 17), it is observed that the central part of the plate and of the ground plane has small influence of the currents at 1.04 GHz, near resonance frequency.

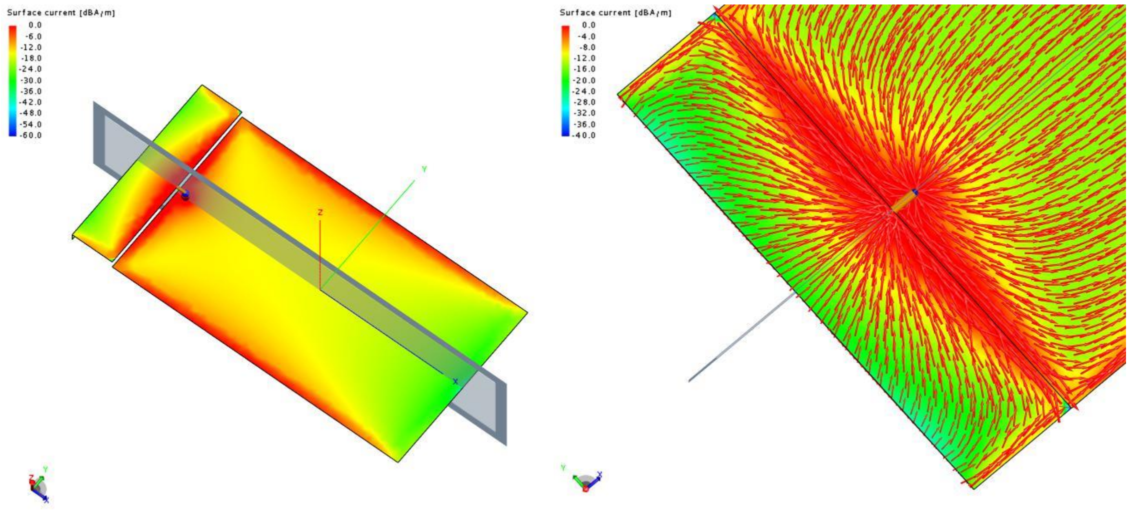


Figure 17 Currents of the structure at 1.04 GHz

The influence of the currents is small in the central part of the plate and the ground plane at 1.04 GHz and near to the resonances of interest. Given this situation and applying the hollowing in the geometry of the structure, the central part of the plain CE plate is removed so as to gain space for the rest of the antenna and the edges have a width of 0.1 cm. The ground plane remains equal because it is impossible to modify it, given the specs; the only part that can be modified is the one that is reserved for the antenna. In Figure 18 we can see the modification and the resulted reflection coefficient measurement is shown in Figure 19.

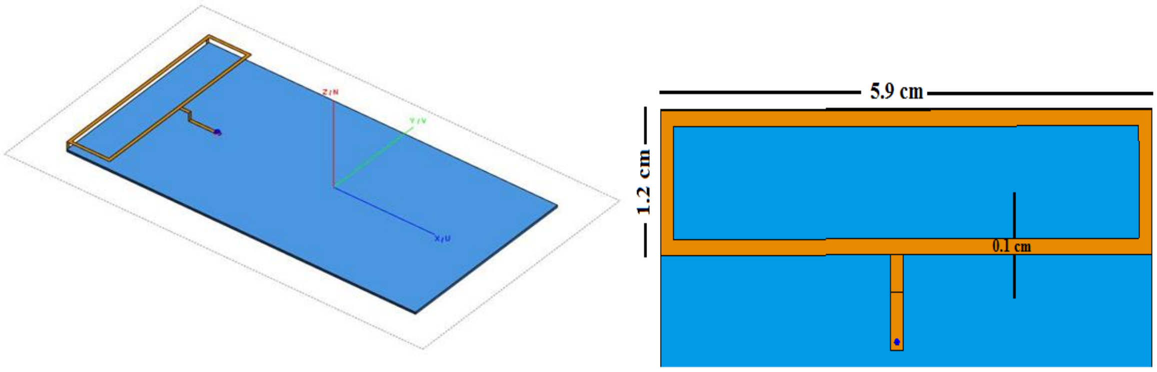


Figure 18 Hollow modification on the structure

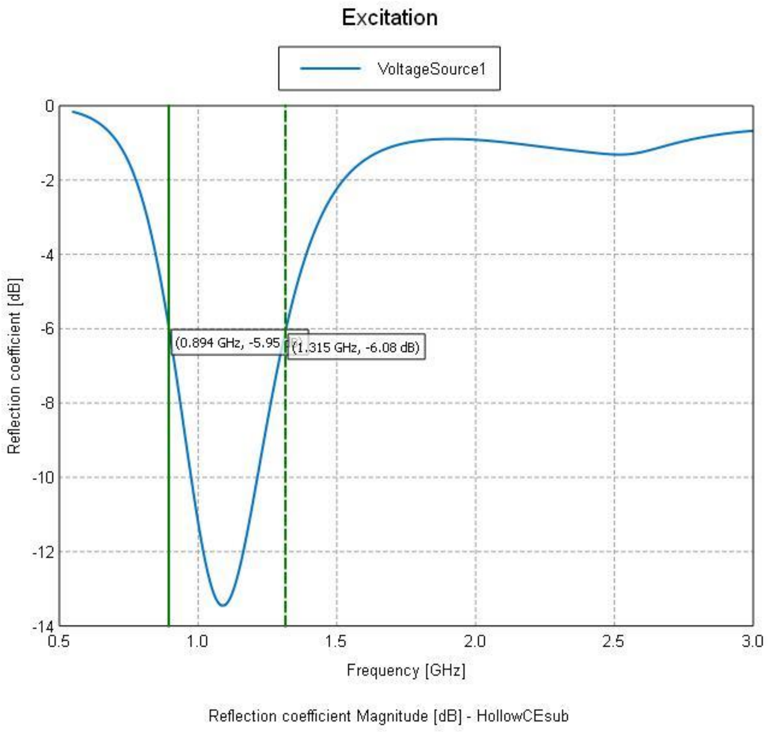


Figure 19 Reflection coefficient of the hollow CE plate connected to the ground plane

It is shown in Figure 19 that the bandwidth at -6 dB is 421 MHz pretty enough for the specs even though the structure does not work at that level in the required low-frequency band. And since the performance of the antenna's element has not changed and there is no a trade-off due to the new geometry, it is mandatory to make new modifications in the new structure so as to accomplish with the cover of the given frequencies. Considering the fact that we want to keep the asymmetric dipole functionality, a modification on the bottom edge of the hollow plate has been done by moving up and down that edge (Figure 20), resulting that moving the edge up gives a right displacement of the resonant frequency and, moving the edge down gives a left displacement of the resonant frequency. Clearly, this technique does not work since it is wanted to cover 700-960 MHz band.

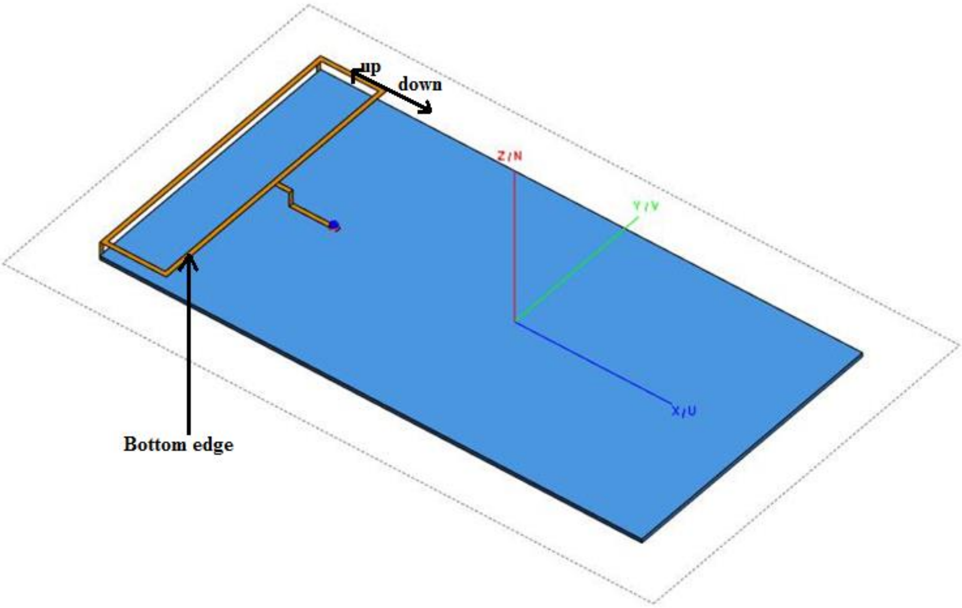


Figure 20 Bottom edge displacement technique

Another software experiment results such as meandering and incrementing the width of the edges from 1mm to 2 and 3 have not had essentials effects in the behaviour of the structure, the only effect seen by the modifications was the frequency displacement without achieving the bandwidth and band required. And, several tests have not changed the performance of the hollowed structure. The ground plane and the FR4 substrate must not be modified because the specs of the project. Another solution, as was mentioned in Chapter II, is to implement a matching network. The design of it to accomplish the low-frequency band requirements will be detailed in section 3.5.

3.3. ANTENNA'S HIGH-FREQUENCY BAND ELEMENT DESIGN

To cover the high-frequency band located in 1.7-2.7 GHz range, it is necessary the introduction of a new element into the previous design. The fact that we have space gained because of the hollowing in the plain CE plate and the influence of the currents in that zone indicates that the free region can be used to insert the new element (high-frequency element) and thus, the element can be directly designed (printed) on the substrate. As the central frequency of the range is 2.2 GHz, a simple dipole antenna for this frequency would be 6.8 cm which is also a big dimension for the given space. So, considering just a monopole working at ¼ of lambda, that monopole must resonate between 3.2 and 3.5 cm.

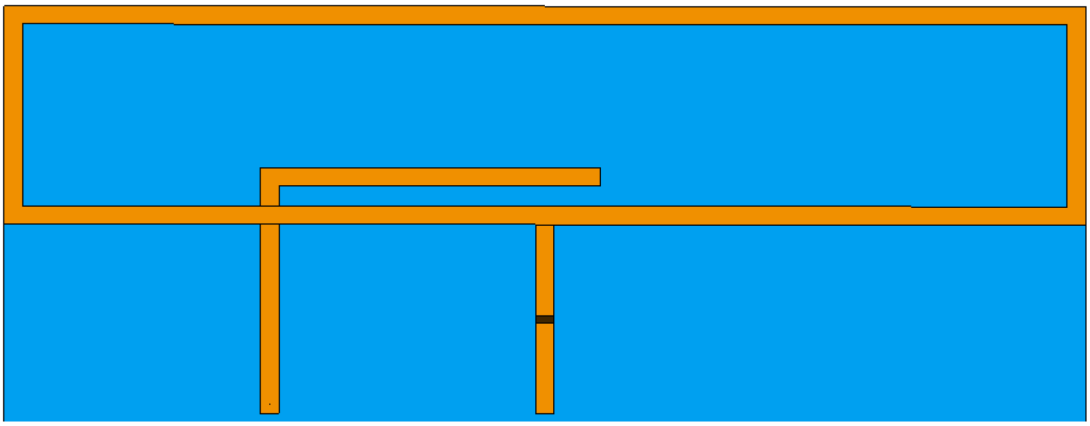


Figure 21 General structure, high-frequency band element's location

As it can be seen in Figure 21, the monopole has been inserted into the region surrounded by the low-band element. This location is chose because the structure gives a small electric field due to the low currents effect in that region (Figure 22). Nevertheless is important to choose correctly the position of the monopole to obtain a high port-to-port isolation avoiding the introduction of the currents when one element is working and when the other one is not. Clearly, the monopole cannot be situated as monopole geometry and must be folded so as to allow its allocation inside the area mentioned before. Notice, as mentioned before, that the monopole must have a total size between 3.2 and 3.5 cm.

Though Figure 21 depicts the model to simulate to obtain the full antenna, several tests over the alone monopole were done. However the evaluation of that monopole must be done always considering the boundaries established by the edges of the low-band element (hollow coupling element).

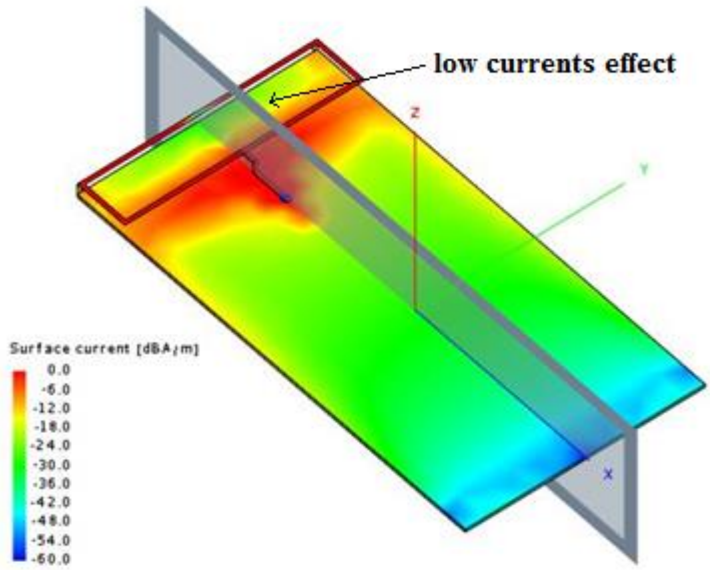


Figure 22 Currents effect at higher frequencies of the low-band alone structure

3.3.1 Monopole Tests

The monopole presented before was tested alone in the PCB. The resonance frequency is 2.08 GHz as is expected due to its size and to the presence of the substrate. Before the introducing of the monopole inside the low-frequency band element, several tests were done in order to observe the position where the monopole gives its best performance. For the spaces given in Figure 23, the monopole presents a reflection coefficient level of -13 dB and a bandwidth of 1.854 to 2.394 GHz at -6dB, obtaining 540 MHz of bandwidth (See Figure 24).

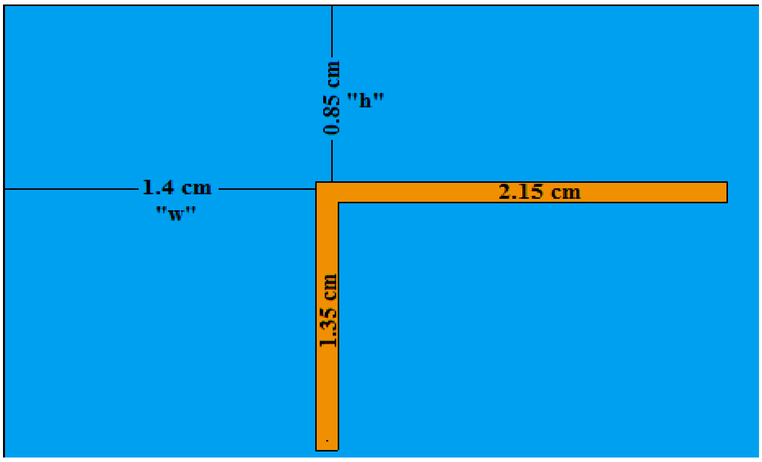


Figure 23 Distances of testing

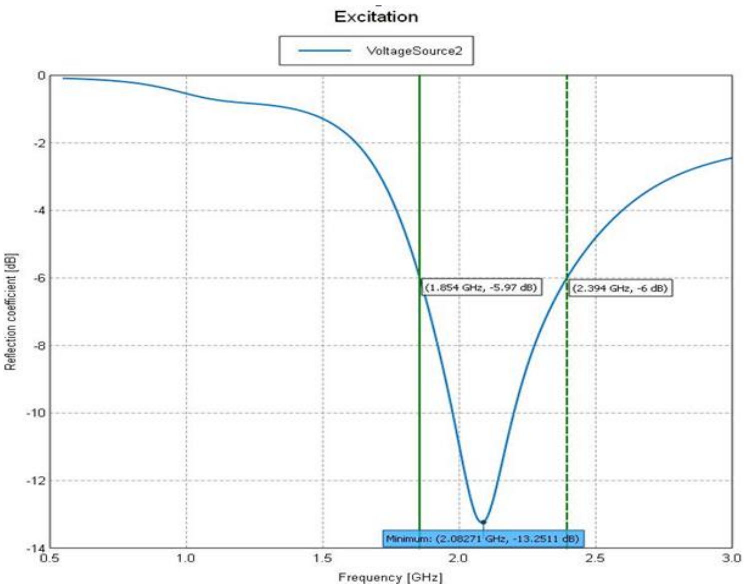


Figure 24 Reflection Coefficient of the given monopole

So as to look for a good performance, it has been tried to move the monopole along the area reserved for the full antenna. The distances or parameters to be modified to move the monopole are the "w" and "h" indicated in Figure 23 while the size of monopole remains the same to not to affect the central frequency of the high-frequency band (1.7-2.7 GHz). When displacing the element until the distance "w" is 0.9 cm, it is obtained a bandwidth of 614 MHz from 1.827 to 2.441 GHz and -13.06 dB of reflection as well as, when moving the element until the distance "h" is 0.55 cm it is obtained a little increment in the bandwidth but a displacement of the central frequency from 2.1 to 1.8 GHz (Figure 25).

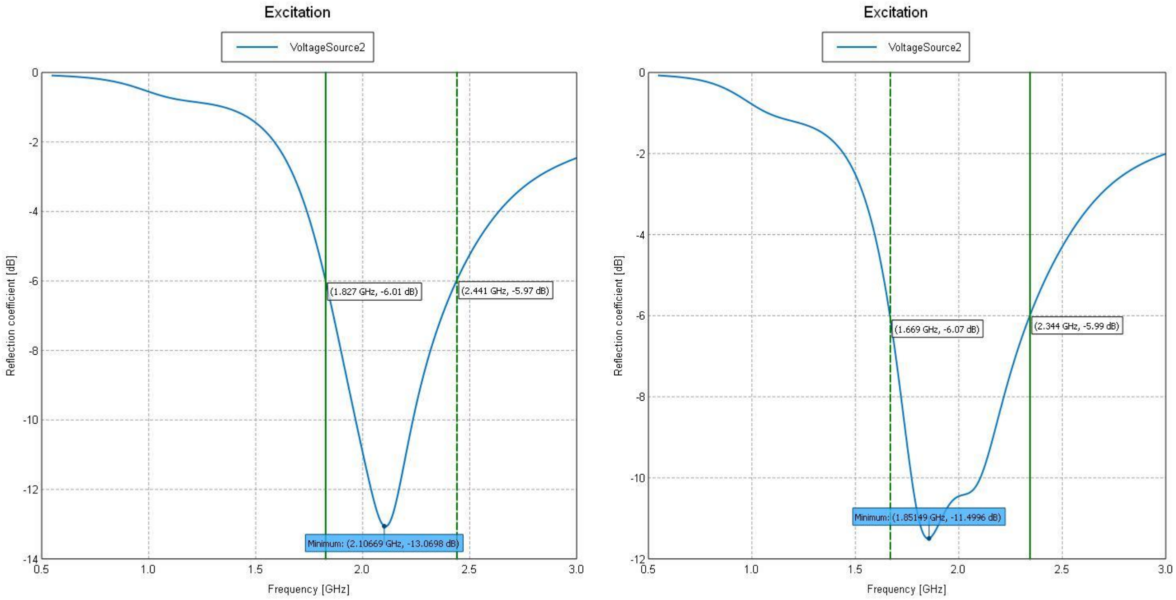


Figure 25 a) When w is 0.9 cm b) When h is 0.55 cm

Another test carried out with simulations was the modification of the length of the monopole. As it is seen in Figure 23, the folded monopole has a height of 1.35 cm and a length of 2.15 cm and, for reasons of comfort it is decided to modify only the length to see the effect on the reflection coefficient. Increasing the length to 2.55 cm, the resonant frequency displaces to 1.87 GHz (Figure 26 a) while decreasing the length to 1.95 cm produces a displacement on the resonant frequency to 2.28 GHz (Figure 26 b). It is underlined that the smaller the length of the folded monopole the greater the bandwidth.

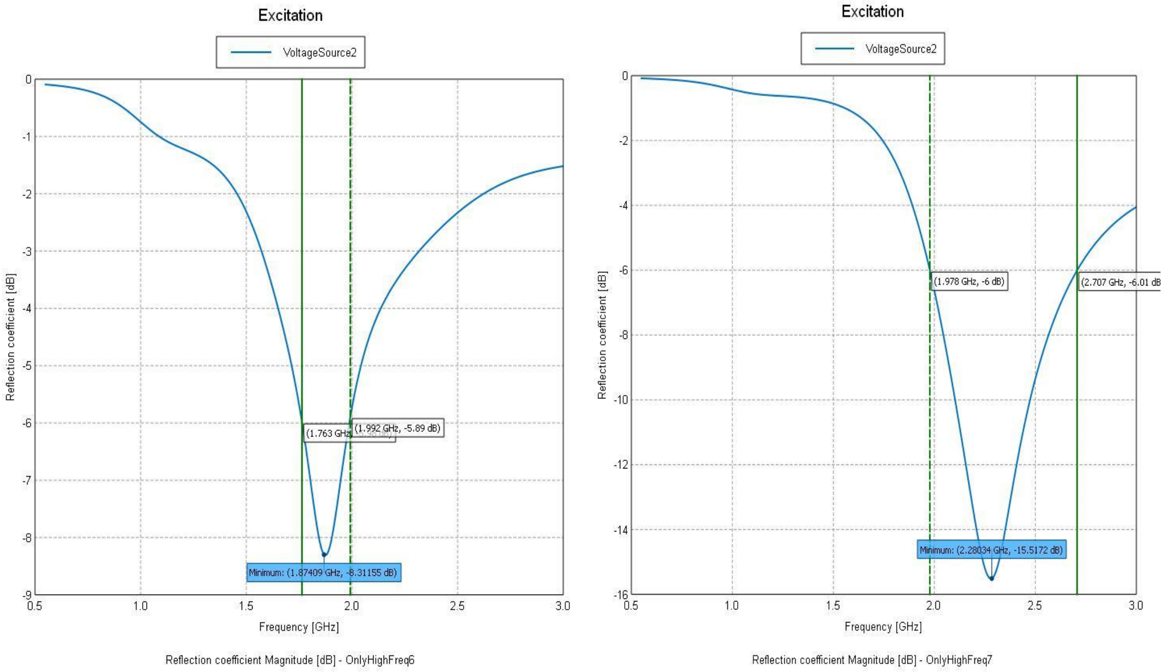


Figure 26 a) Monopole’s length of 2.55 cm b) Monopole’s length of 1.95 cm

Thus, it is concluded that the changes in the position which produce clear effects in the behaviour of the monopole are the locations regarding the top and bottom of the reserved area for the antenna. The modifications on the length of the folded monopole improve the bandwidth when that length tends to be smaller and the resonance frequency tends to be logically greater. And, finally some elementary tests changing the thickness of the elements were done obtaining few variations in the bandwidth. Those variations make the bandwidth a little greater than the ones when the thickness is 0.1 cm (original).

Nonetheless, to verify the real effect produced in high-frecuency band it is necessary to locate the monopole with the hollow coupling element (low-band element) to evaluate the real behaviour of the full antenna when the two elements are together.

3.4. FULL ANTENNA

As was mentioned in part 3.3 and as was planned from the beginning, the folded monopole is placed inside the area surrounded by the hollow coupling element to take advantage of the small effect of the currents in that region and to benefit the antenna by using the reserved space (antenna's clearance). It must be reminded that the tests realised in parts 3.2 and 3.3 have revealed that the folded monopole tends to have a better performance when is closer to the bottom edge of the antenna's area.

Sundry tests have been done, as the hollow coupling element cannot be modified and relocated, the folded monopole has been tested by moving it inside the area underneath the hollow CE. The design that almost accomplish with the requirements of the antenna is shown in Figure 27. Clearly, as the proofs demonstrated before the monopole has a better behaviour near the bottom edge of the hollow CE, giving an acceptable bandwidth due to the large of the folded monopole and to the beneficial coupling between the two elements of the antenna.

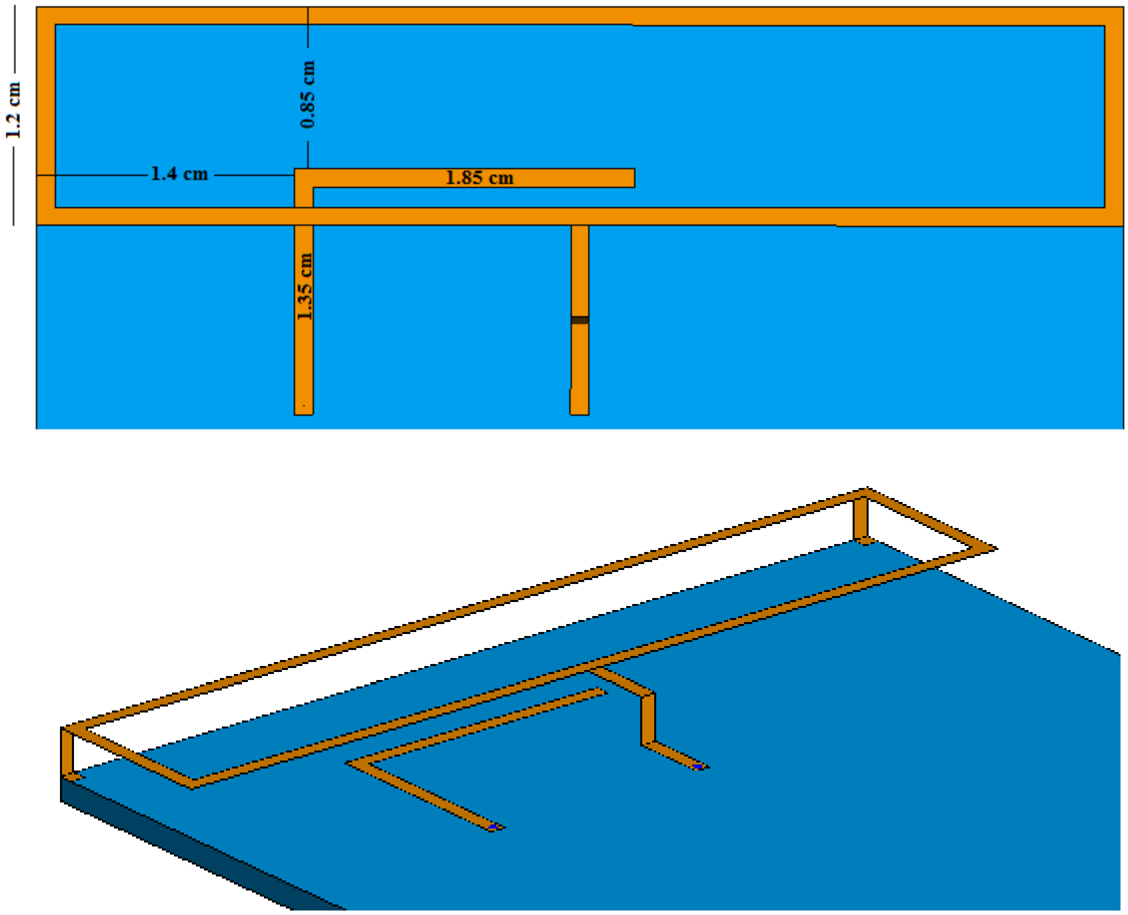


Figure 27 Antenna's full design

First of all, the high-frequency band behaviour has been simulated by turning on the high-band feed point and turning off the low-band one. The results show, as is mentioned in [2] and the proofs have demonstrated that the hollow coupling element is also affecting the performance of the monopole helping it out to improve the bandwidth in the high-band as it is shown in Figure 28.

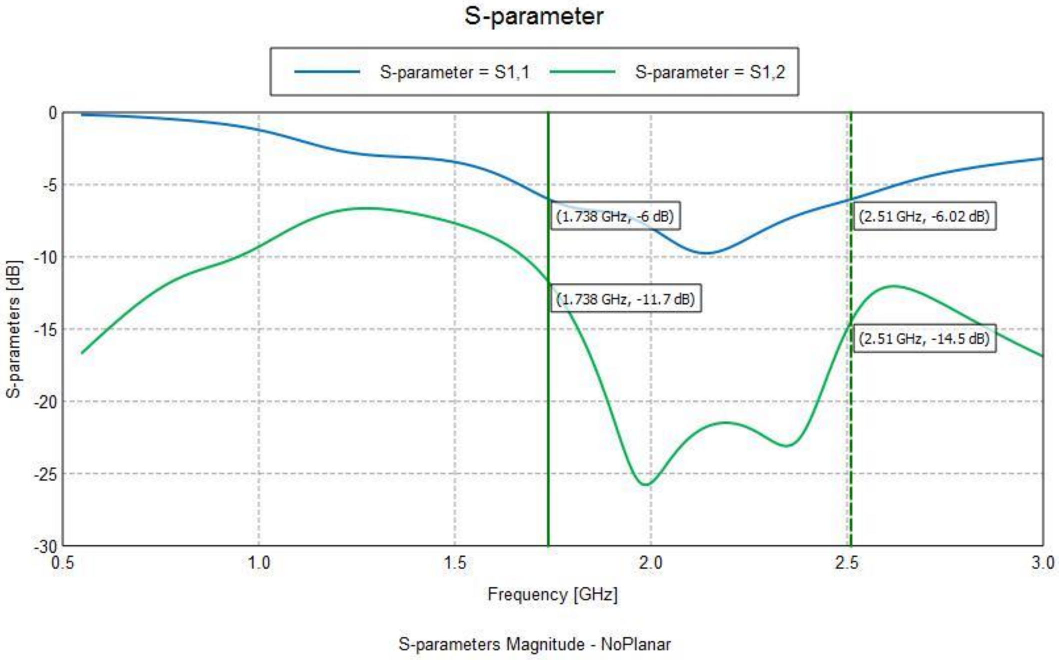


Figure 28 Reflection coefficient in the high-frequency band

It is also observed that in high frequency the antenna has a bandwidth of 772 MHz at -6dB, improving the bandwidth obtained when the monopole was working alone in the PCB. Another advantage is the high port-to-port isolation (green line in Figure 28) which is the responsible for the beneficial coupling of the monopole with the higher modes of work of the hollow CE.

Despite the good results obtained in high-frequency band, when turning on the low-band feed point and turning off the high-band one, it can be realised that there is no affection in the behaviour of the antenna at low-frequency band, it means that the monopole is not affecting in the performance of the hollow coupling element at all. In fact, the bandwidth and the levels of the reflection coefficient remain the same or, at least, very close the values obtained in part 3.2. The results of the simulation are depicted in Figure 29 where it is shown that the bandwidth is 295 MHz and the level of the reflection around -9 dB.

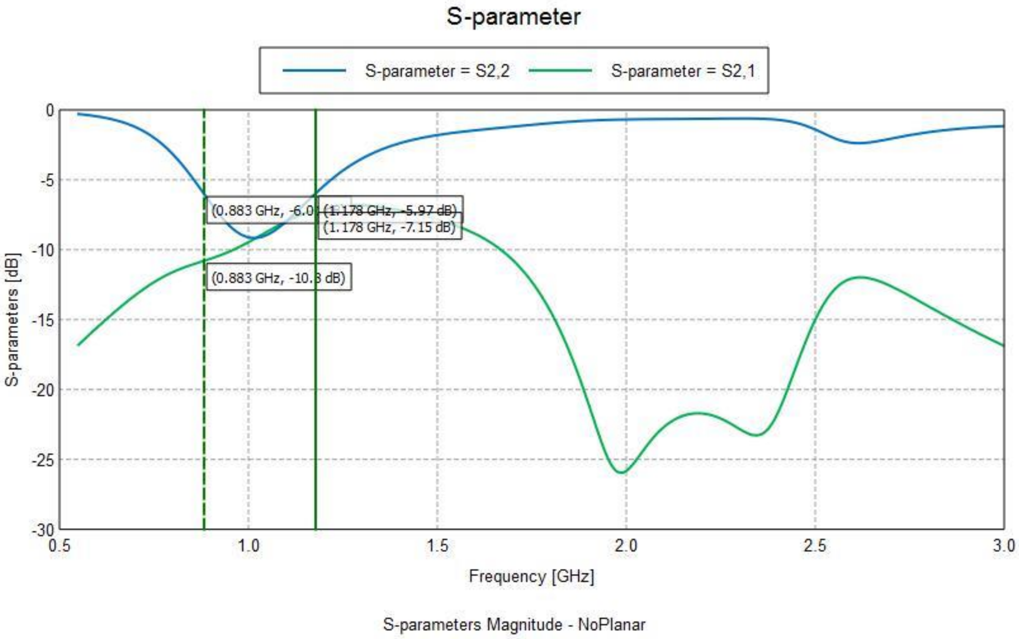


Figure 29 Reflection coefficient in the low-frequency band

Comparing to the results shown in Figure 19 where the bandwidth is 421 MHz and the level of the reflection coefficient is around 13.5 dB, clearly the effect of the monopole over the hollow CE is negative because of the little reduction of the bandwidth and the amplitude of the reflection coefficient also decreases. It might be seen that the result is not good enough; this is because as it is seen in line green (Figure 29) the port-to-port isolation is not the expected one which suggests that some currents are flowing from one port to the other one. Nevertheless, for the purposes of this project it results rather comfortable given the specifications and taking into account that it has not been developed a matching network yet.

3.5. MATCHING NETWORK

At this point, it has been seen that an antenna which is non-planar with a hollow coupling element and a folded monopole can cover almost all the requirements established for this part of the project. However –as we saw in the introduction- almost all the time it is required to design a matching network to enhance the performance and the precision of the full antenna. As this antenna has two-port feed points, each for the low-frequency and high-frequency bands, it is clear that it will be necessary to create two matching networks in order to satisfy the specifications given for each band.

As it was stated, in the low-frequency band it is desired to cover from 700 to 960 MHz meanwhile in the high-frequency band from 1.7 to 2.7 GHz. It is shown in the previous Figures 28 and 29 that the full modelled antenna covers from 883 to 1178 MHz and from 1.738 to 2.51 GHz respectively. Despite the fact that it was designed by trying several tests to enhance the behaviour and to achieve the requirements along the design part of the elements of the antenna –namely the folded monopole and the hollow coupling element- the elements has been developed as good as possible in the simulator. The ground plane and the FR4 substrate must not be modified because the specs of the project. Another solution, as was mentioned in Chapter II, is to implement a matching network. It was mentioned before in section 3.2 that it will explain the creation of a matching network. Due to time issues, the reach of this project and the achievements obtained in sections 3.3 and 3.4, it will be explained the design of a matching network for covering the frequencies in the low-frequency band.

3.5.1. Low-frequency band matching network

The main reason for the coverage obtained in the previous sections is that the antenna has not reached the impedance matching at certain frequencies. Those frequencies are between 700 to 883 MHz, 1.7 to 1.738 GHz and 2.51 to 2.7 GHz ranges. The impedance matching is often an important part of a larger design process for a microwave component or system. The basic idea of impedance matching is illustrated in Figure 30, which shows an impedance matching network placed between a load impedance and a transmission line. The matching network is ideally lossless, to avoid unnecessary loss of power, and is usually designed so that the impedance seen looking into the matching network is Z0 [18].

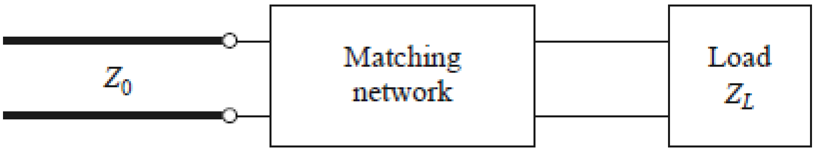


Figure 30 General scheme of a matching network [18]

One disadvantage of the use of a matching network is that it requires many lumped components to achieve relatively large bandwidths therefore a high order of the MN, which introduces relevant losses due to the insertion of those components to the network, namely inductances and capacitances, and their inner resistances attenuate the signal. However, a good impedance matching will help out to achieve the requirements in low-frequency band.

On the other hand, as stated in [18], an impedance matching is important because:

- Maximum power is delivered when the load is matched to the line (assuming the generator is matched), and power loss in the feed line is minimized.
- Impedance matching sensitive receiver components (antenna, low-noise amplifier, etc.) may improve the signal-to-noise ratio of the system.
- Impedance matching in a power distribution network (such as an antenna array feed network) may reduce amplitude and phase errors.

Factors that may be important in the selection of a particular matching network include complexity, bandwidth, implementation and adjustability. In terms of this thesis the three first factors are demanding important and will be considered in the design of the matching network.

Despite the Chapter II refers to the design of a broadband matching network with cascaded L-networks, at first tests, in this project I tried to enhance the low-band behaviour by making a simple L-network with lumped elements. There are two possible configurations for the L-network as shown in Figure 31. If the frequency is low enough and/or the circuit size is small enough, actual lumped-element capacitors and inductors can be used. This may be feasible for frequencies up to about 1 GHz or so, although modern microwave integrated circuits may be small enough such that lumped elements can be used at higher frequencies as well [18].

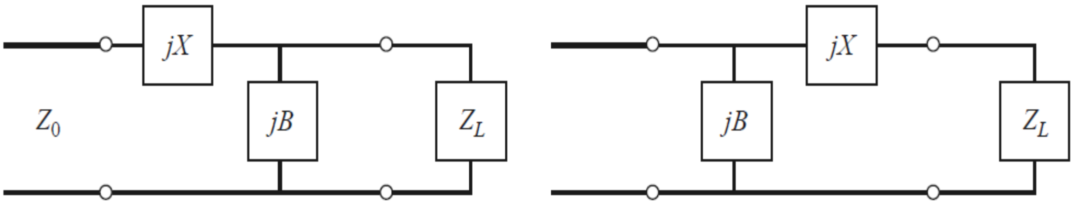


Figure 31 General scheme for L-network [18]

If we define the load impedance as $Z_L = R_L + jX_L$ and the impedance of the generator or the feeding point as Z_0, it might be considered that the circuit on the right of Figure 31 must be applied when $R_L > Z_0$ and the circuit on the left of Figure 31 when $R_L < Z_0$. Since the impedance of the antenna (Load impedance) is 11.18 – j16.53 at 830 MHz (central frequency of low-frequency band) shown in Figure 32, all the computations are done related to that frequency.

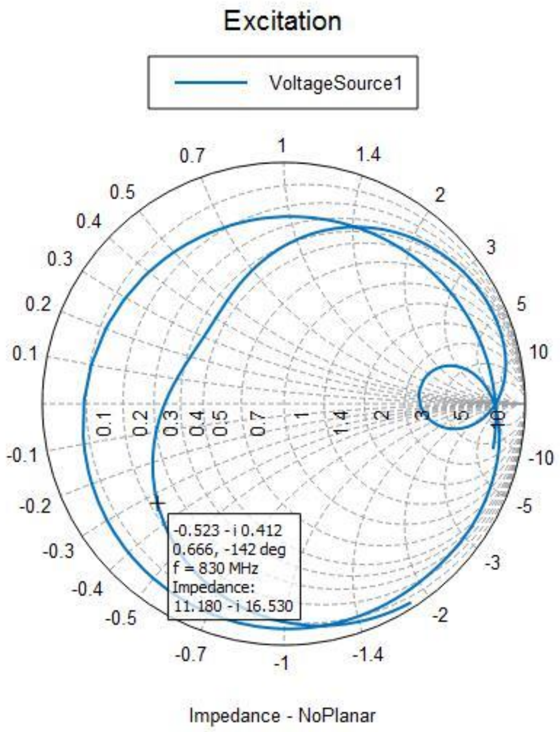


Figure 32 Antenna impedance at low-band performance (830MHz)

After the calculations were done easily by means of MATLAB the circuit was constructed in Agilent ADS as we can see in Figure 33. Taking into account the theory described before the L-network consists in two inductor elements. Then, the S-parameters of the matching network are imported to FEKO and connected to the antenna. The simulation results are illustrated in Figure 34. At first sight, ADS showed a good resolution of the bandwidth, however when simulating in FEKO with the antenna the results showed a reduction of the bandwidth up to around 120 MHz even though that bandwidth now is inside the low-frequency band.

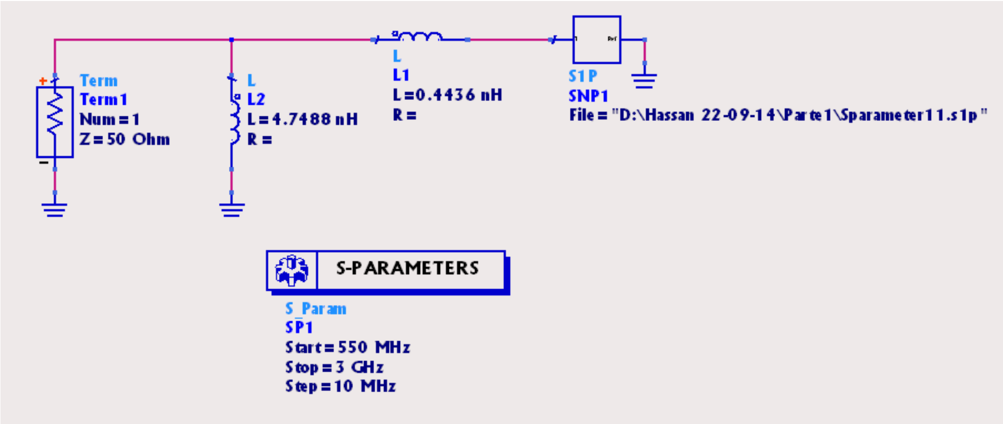


Figure 33 L-network for low-band

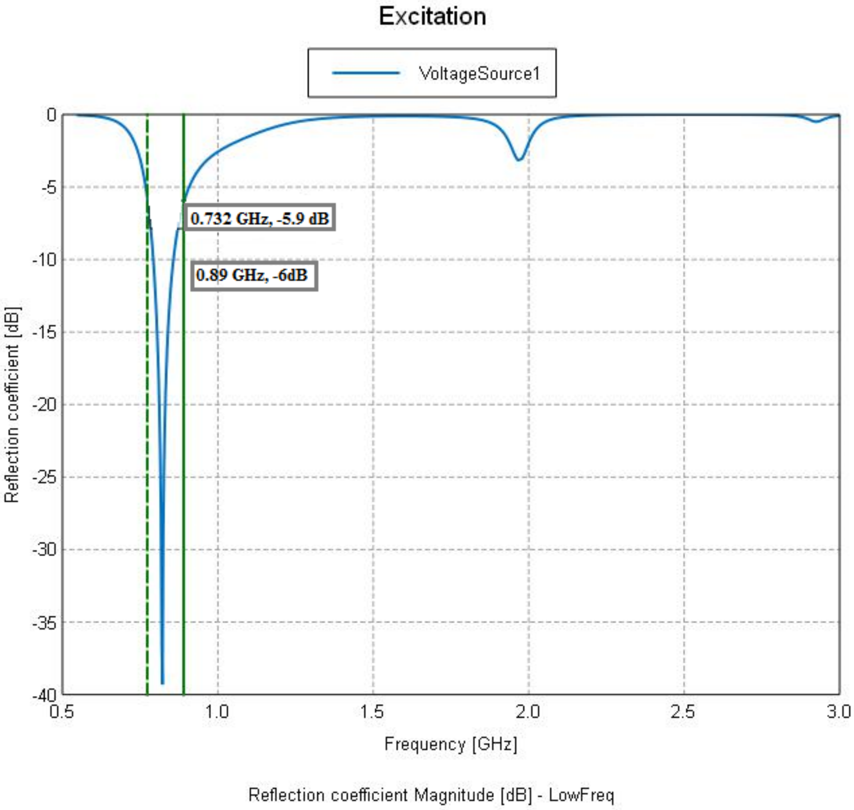
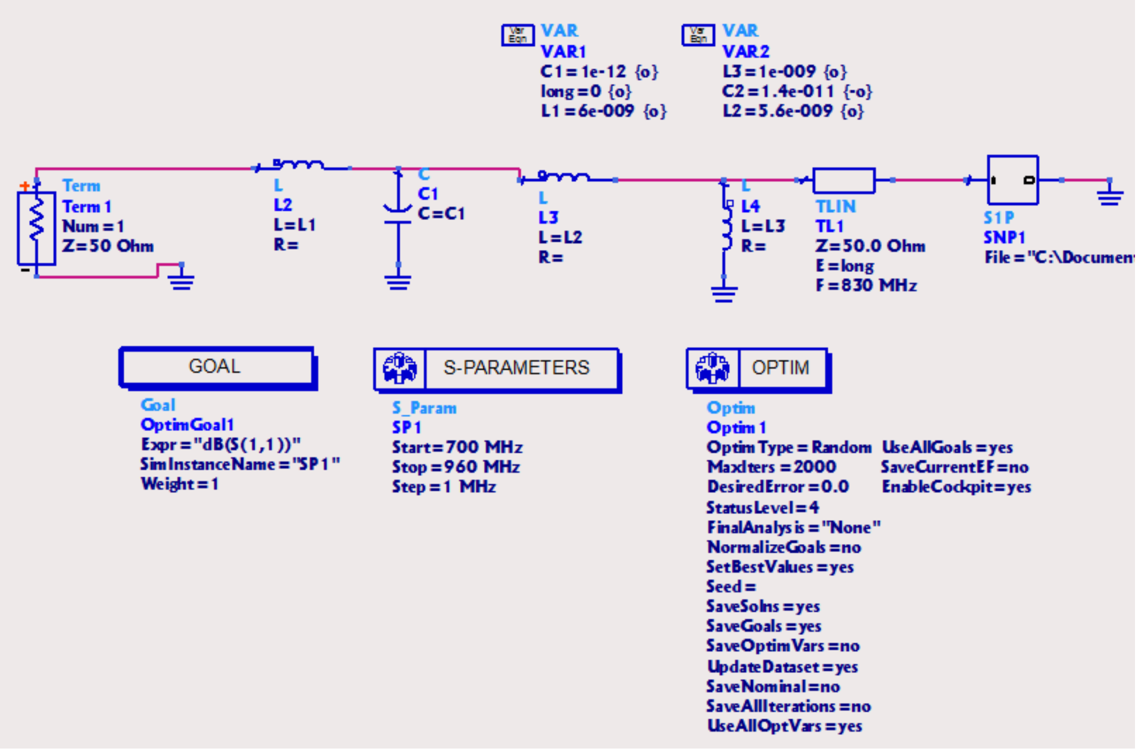


Figure 34 New response of hollow coupling element due to the matching network

Though the results shown in Figure 34 are not good as it was expected, it is also the alternative to use a complex broadband matching network as mentioned in Chapter II so as to try to achieve the specifications for the low-band coverage.

3.5.2. Low-frequency band broadband matching network

For a complex matching network it was indicated in Chapter II the solution of the use of a cascaded L-network. Nevertheless, the tests done in the simulator gave vague results and they did not help to achieve the specs and, several types of circuit models were designed following the rules and the theory established before. The solution to obtain a wideband matching network was to use a T model network with a shunt inductance next to the antenna to eliminate the reactance. The model is shown in Figure 35 where the simulation has been done with the help of the parameterization and the optimization routine in ADS. The circuit is composed of a T model L-C-L though the values of the inductors are not the same. A third inductor is introduced and shunted to eliminate the reactance of the load. Then a transmission line is added to ensure that the impedance matching will not affect the union between the feeding point ports and the elements of the antenna. The values obtained for the final low-band matching network can be seen in Figure 36. Notice that these values are not commercial and they are used only for simulations purposes.



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long=0 {o}
L1=6e-009 {o}

VAR
VAR2
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C2=1.4e-011 {-o}
L2=5.6e-009 {o}

Goal
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SimInstanceName="SP1"
Weight=1

S_Param
SP1
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Stop=960 MHz
Step=1 MHz

Optim
Optim1
OptimType=Random
MaxIters=2000
DesiredError=0.0
StatusLevel=4
FinalAnalysis="None"
NormalizeGoals=no
SetBestValues=yes
Seed=
SaveSolns=yes
SaveGoals=yes
SaveOptimVars=no
UpdateDataset=yes
SaveNominal=no
SaveAllIterations=no
UseAllOptVars=yes
UseAllGoals=yes
SaveCurrentEF=no
EnableCockpit=yes

Figure 35 Design of a broadband matching network – ADS optimization program

It is important to highlight that in the optimization program, the requirements such as amplitude of reflection coefficient and bandwidth were introduced, that is to say, a coverage from 700 to 960 MHz at -6dB.

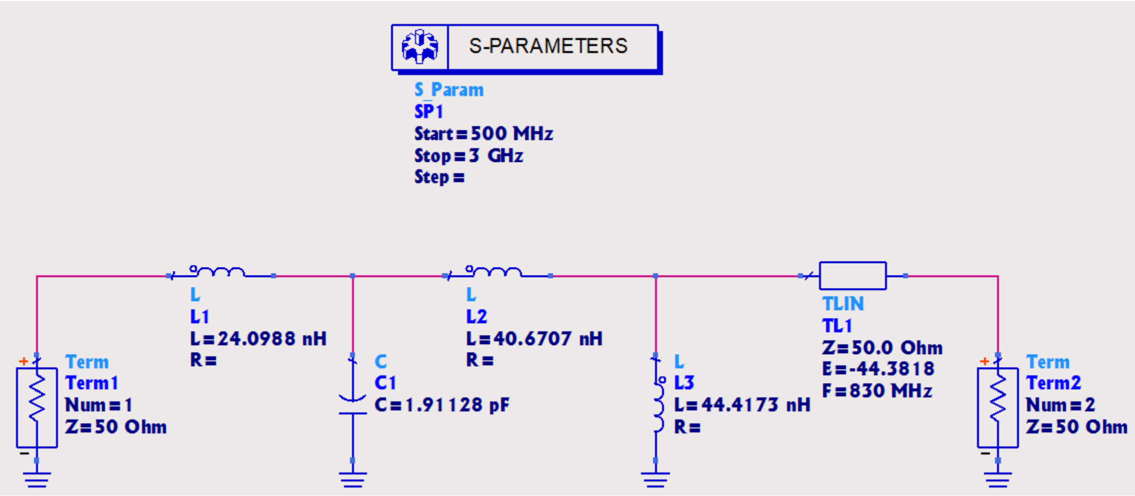
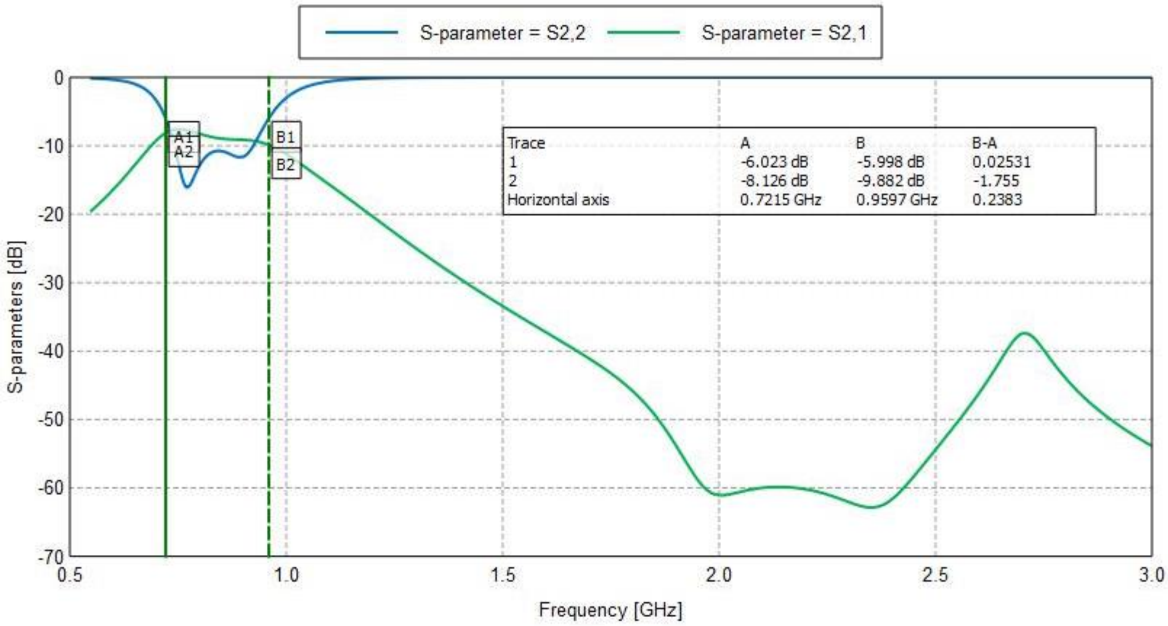


Figure 36 Final low-band matching network

Consequently, the network obtained in Figure 36 was exported in .snp file to FEKO to simulate the S-parameters of the full antenna, including the two elements and the matching network and, therefore the low-band behaviour is depicted in Figure 37.



Trace	A	B	B-A
1	-6.023 dB	-5.998 dB	0.02531
2	-8.126 dB	-9.882 dB	-1.755
Horizontal axis	0.7215 GHz	0.9597 GHz	0.2383

Figure 37 Low-band reflection coefficient due to the final matching network

It is observed from Figure 37 that the bandwidth is covered from 721 to 960 MHz at -6 dB –almost the full bandwidth required-. The simulation indicates the utility of the use of a matching network for helping to achieve the specs. It is also remarkable that there is no affection in the behaviour of the high-band range and the antenna keeps its performance from 1.738 to 2.51 GHz (See Figure 28).

3.6. FULL ANTENNA RADIATION PATTERN

Finally, I will present the radiation pattern of the full antenna including the low-band matching network. Figure 38 shows an interesting radiation patterns where in low-band operation the pattern is a dipole-type radiation as it was expected since the main radiator is the ground plane and as was mentioned in Section 3.2 (See Figure 15) the functionality of the low-band structure is like a asymmetric dipole. In Figure 39 are depicted the radiation patterns for high-band operation. Though in high-band the shape is not defined it can be seen that in the operating frequencies the pattern has some wide-angle deep nulls which is important fact for mobile communications, given those patterns we can see the design in matter of radiation has a poor one because it is always expected to cover 360°. This is a drawback for the transmission and reception functions of the antenna.

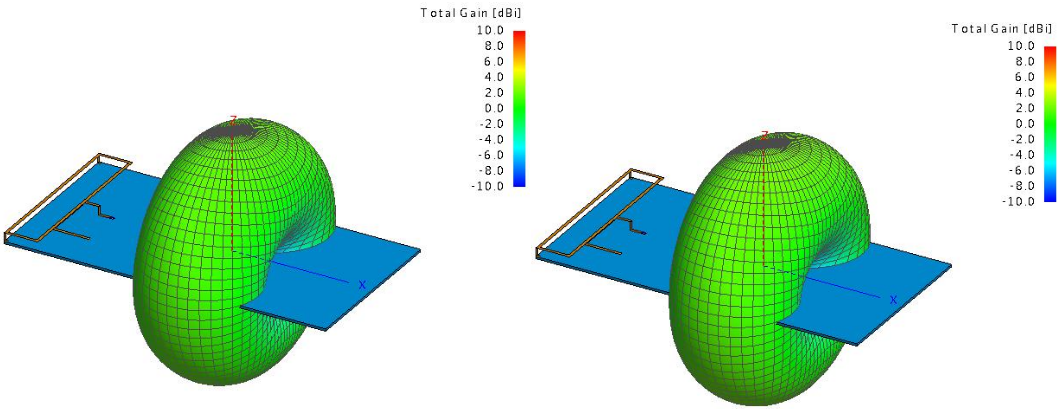


Figure 38 Radiation pattern at a) 754 MHz and b) 958 MHz

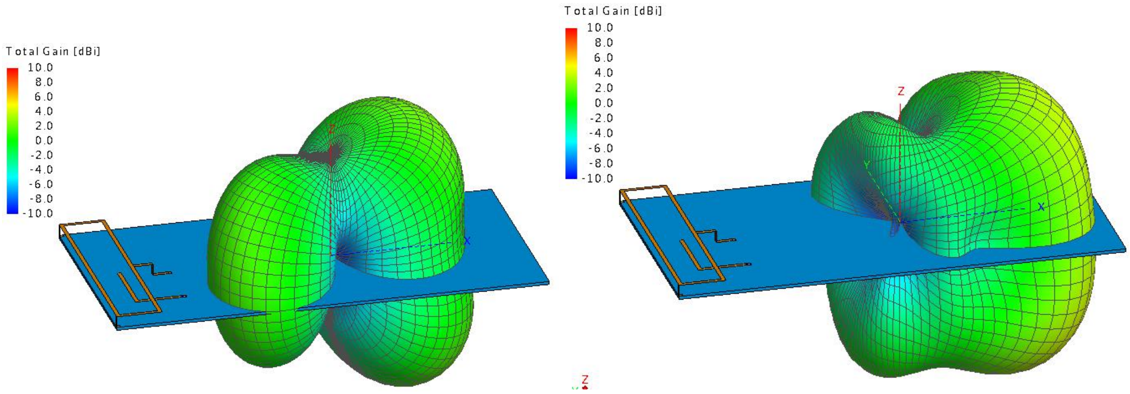


Figure 39 Radiation pattern at a) 1.775 GHz and b) 2.63 GHz

3.7. SUMMARY

A non-planar antenna for 4G mobile communications coverage was designed based on the main reference mentioned throughout this work. This antenna have been passed for several tests since the initial point in order to achieve the requirements of 4G technologies and current mobile devices. In this chapter:

- For the coverage of the low-frequency band it has been design a hollow coupling element located 3mm above the substrate, where a plain CE is made hollow by removing the metal in the central part of the plate to gain space and without a performance trade-off. For coverage of the high-frequency band a single monopole resonating at ¼ of lambda is folded to be located into the central part of the hollow CE where the currents are weak and have not effects over that zone. The coverage obtained is from 883 to 1178 MHz and from 1.738 to 2.51 GHz respectively. To try to enhance the poor low-band performance, a T-type matching network was designed, so the full antenna covers from 721 to 960 MHz and from 1.738 to 2.51 GHz at -6 dB. These facts remark the important impact of a good-designed matching network which adapts perfectly the impedance in the require frequencies.

- All the element's tracks are made of 0.1 cm of thickness and the proofs that have been done demonstrate that a small variation on the width of the tracks has no relevant effect in the behaviour in both the low-frequency and the high-frequency bands. And also it was demonstrated the importance of the geometric shape of the hollow CE which is has an essential effect in the behaviour of the folded monopole by making the monopole to work as a broadband element in high-frequency band.

- As is shown in section 3.6, the radiation patterns are quite coherent to the reality because their shape is like it was expected. For the hollow CE we have a dipole-type shape and for the folded monopole there is no a perfect geometrical form and it is seen that the patterns have nulls in some directions in the bands of interest.

CHAPTER IV

PLANAR 4G ANTENNA DESIGN

In Chapter III, it was designed a non-planar structure with a hollow coupling element located 3mm above the FR4 substrate. Despite the good results the previous design has two disadvantages:

- The non-planar antenna is susceptive to shocks and damages due to its position above the substrate plane and due to its thickness of 0.1 cm, it can be possible modify geometrically.
- As long as the design is non-planar, the space for its location inside the mobile device tends to be bigger and since the current devices are slimmer than before, it is mandatory to obtain structures as thins as it is possible.

Therefore, in this part of the thesis I have developed a planar antenna to satisfy the prevailing technology conditions and it must be considered now that one antenna would not be integrated inside the other one because they both are going to be printed directly over the PCB and also is important to take into account the specifications which are rather the same as the non-planar design.

4.1. SPECIFICATIONS

Considering that the antenna is designed for 4G, it should be able to cover the frequencies corresponded to all the generations by considering all the frequency ranges of actual technologies, that is the two groups selected before for dual-band coverage: 700-960 MHz and 1.7-2.7 GHz. The space reserved for the antenna is the same 11.4x5.9 cm. The antenna behaves as an electrically-small radiator in the low frequency band but now must be printed in the PCB. In the high-frequency band due to the required size for cover that frequencies, it is easy to model a simple monopole, analysing the new effect of the planar element of low-frequency band.

Thus, this design will be developed in two parts. Two antenna's elements must be modelled so as to cover the two frequency ranges mentioned above. One element is designed as a printed coupling element because of the effect produced in the PCB ground plane and, to take this advantage for reducing the size of the element and to try to achieve the requirements. The other element is designed as a single monopole (to be folded because of the space) to cover higher frequencies. Nevertheless, it is also considered and analysed the position of the antennas each other to avoid couplings and to accomplish the specifications. Due to factors of spacing in the reserved area and considering the effects of the edges of the PCB over the elements and the fact that the two elements must be now printed on the substrate; it is stipulated in this planar design to locate the low-band element in the top portion of the reserved area for the antenna and the high-band element in the bottom portion (Figure 40).

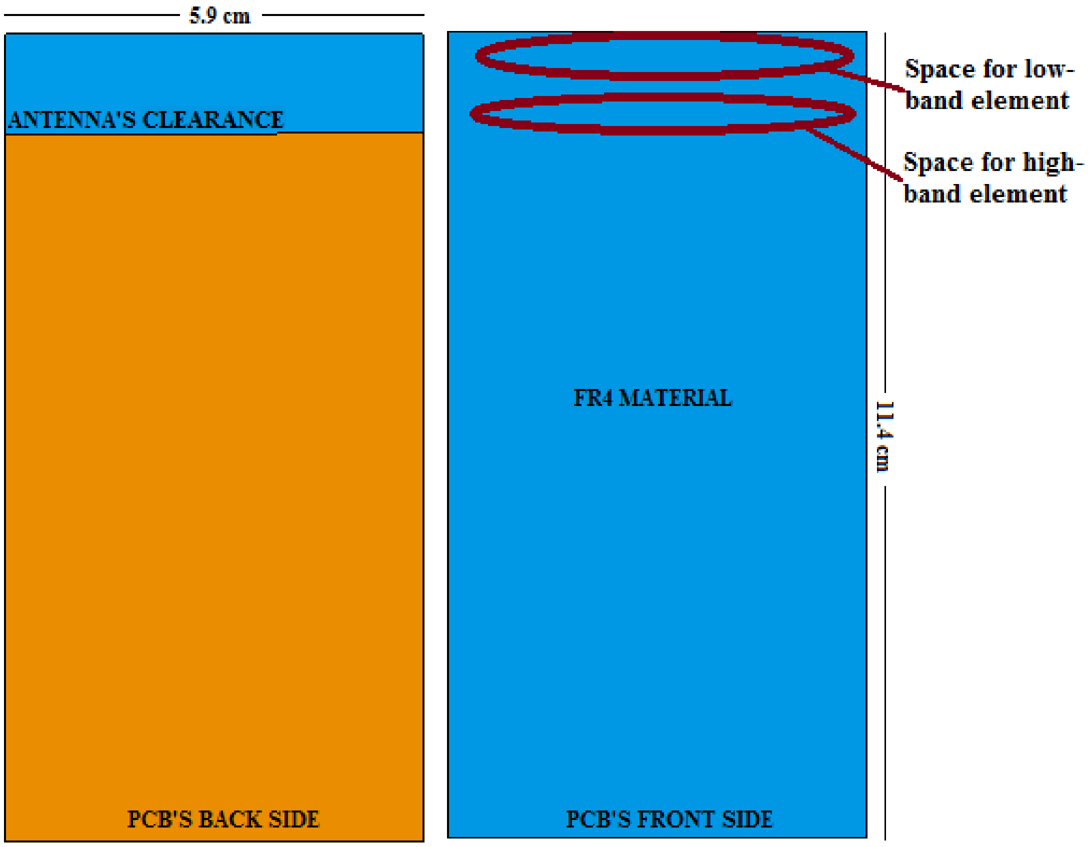


Figure 40 Considerations for antenna's planar design

Summarizing the specs for this project:

- Dimensions of the device PCB: 11.4x5.9 cm (Figure 13).
- Material of the PCB: FR4 with a height of 1.5 mm.

- Space reserved for the antenna: 1.4x5.9 cm.
- First element to cover 700-960 MHz (low-frequency range): printed coupling element.
- Second element to cover 1.7-2.7 GHz (high-frequency range): printed single monopole.
- Type of the final design to be constructed: planar.
- Maximum reflection coefficient level allowed in the operating frequencies: -6dB.
- Maximum matching network order: two.
- Type of feeding: two-feed points for each element.

Once the specs are given, it is going to be explained the procedures and considerations taken to design the full antenna.

4.2. ANTENNA'S LOW-FREQUENCY BAND ELEMENT DESIGN

It was explained before in Chapter III that for the coverage of low frequencies (element size relatively big) is more suitable to use a coupling element which induces the proper currents in the ground plane to work together as a dipole-type antenna where the radiation is characterised by the asymmetric dipole function (See Figure 15). In this case, the modelling keeps going the coupling element but printed on the substrate or PCB. It might be looked like that the plate would occupy all the available space for the full antenna but actually, the plate is reduced as small as possible in the top edge of the PCB (Figure 41). Then the bottom part of the reserved area will be available for the positioning of the high-frequency band element which will be a folded monopole as in the non-planar design.

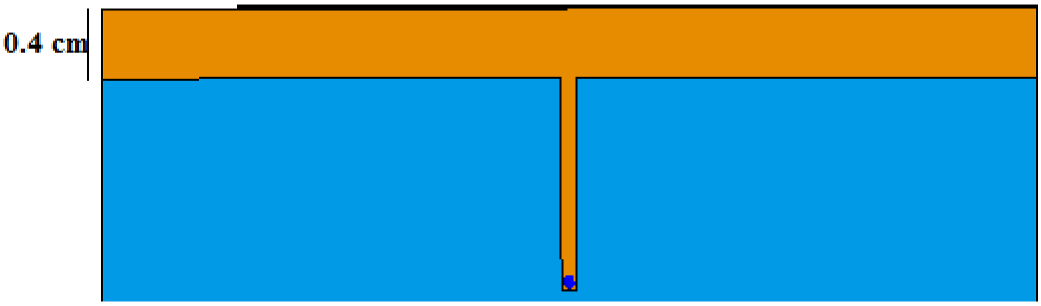


Figure 41 Printed coupling element

In Figure 41 we can see a coupling element occupying around 30 percent of the total area reserved for the antenna and it has a height of 0.4 cm. Despite the fact that it would not be necessary to remove the central part of the coupling element, it is going to be shown that removing it can help to enhance the performance of the high-frequency band element when it is implemented.

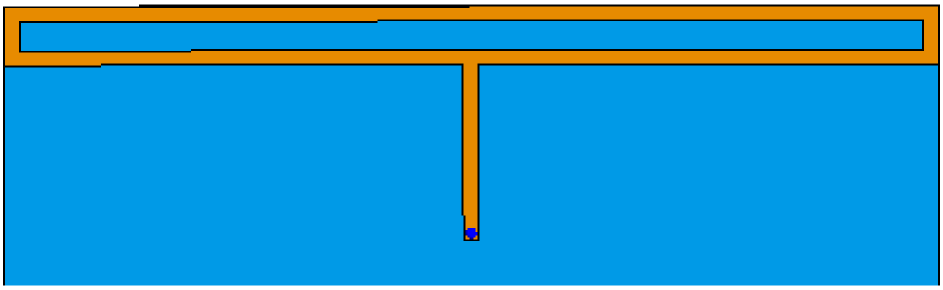


Figure 42 Printed hollow coupling element

The “Printed hollow coupling element” is shown in Figure 42. At first sight, it might be seen that there are no differences between the printed CE and the printed hollow CE in the sense that they produce the same behaviour. In fact, this is totally wrong. It has been simulated both structures and the reflection coefficients are depicted in Figure 43. Clearly, by hollowing the coupling element and keeping the tracks in 0.1 cm produces an enhancement in both the bandwidth –decreasing the resonant frequency of it- and the amplitude of rejection which reaches -22 dB. Therefore it is suggested the use of the hollowing as it improves the element’s behaviour benefiting the total response.

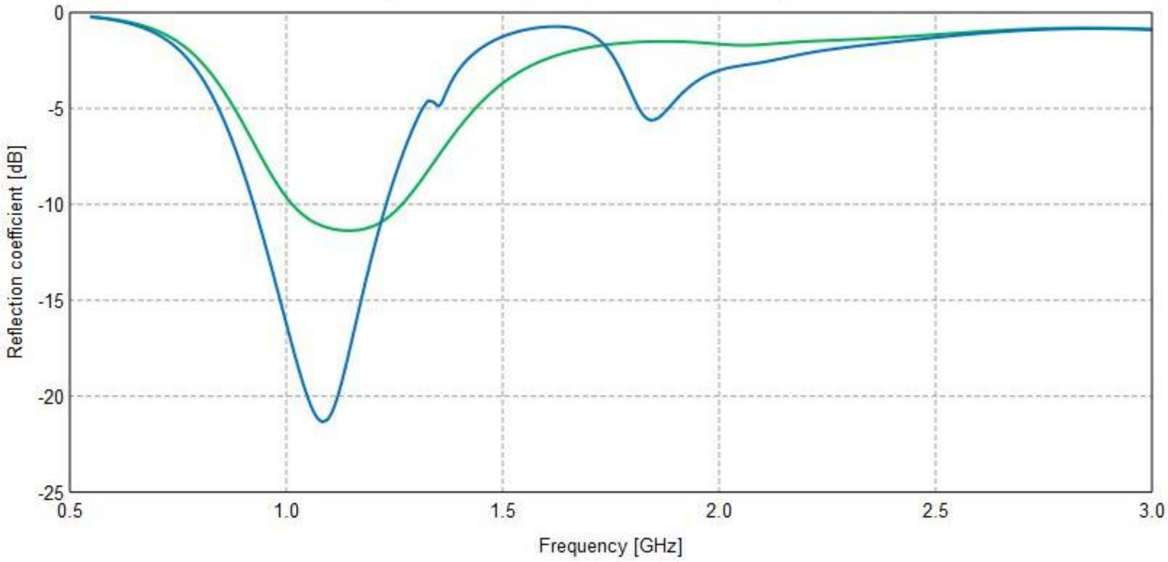


Figure 43 Reflection coefficients of printed CE (green line) and printed hollow CE (blue line)

Now that we saw the hollowing helps to improve the bandwidth out and the amplitude of the rejection, we must prove that the height of the element (See Figure 41) when is 0.4 cm is the appropriated for the expected behaviour. By increasing and decreasing this height it will be shown the perfect value to my design. As is depicted in Figure 44, the blue line indicates a height of 0.4 cm, the green line 0.6 cm and the red one indicates 0.8 cm. It seems that the best rejection is obtained by the small height of the printed hollow CE structure.

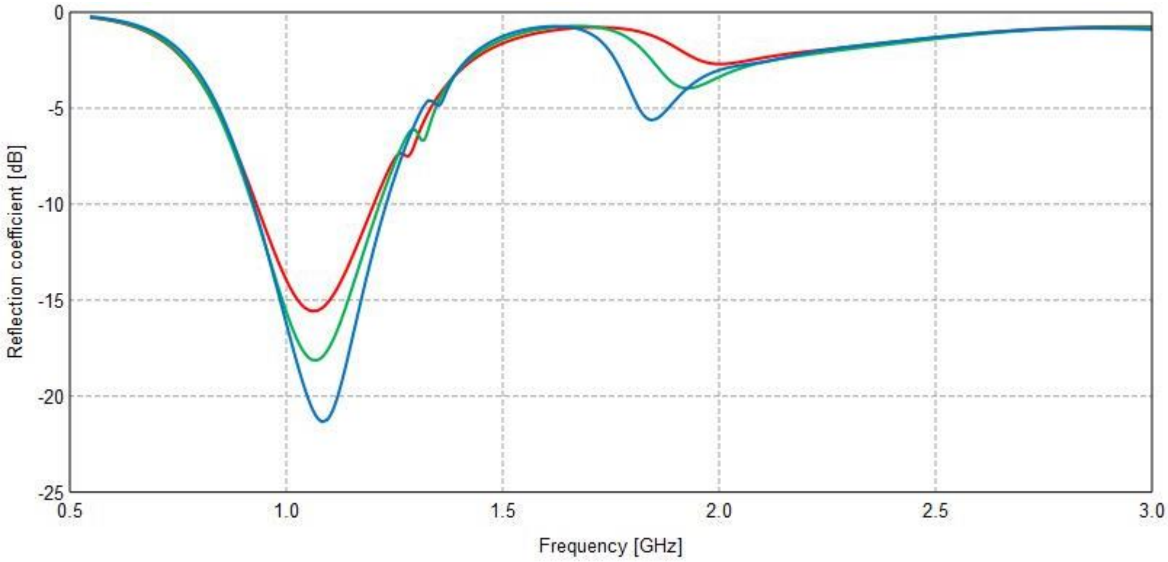


Figure 44 Reflection coefficient of the printed hollow CE for heights of 0.4 cm (blue), 0.6 cm (green) and 0.8 cm (red)

The results demonstrate that 0.4 cm of height for the printed hollow coupling element gives a good performance and, as it is expected the resonance frequency has a reflection level better at the smaller height. As the substrate and the PCB geometry cannot be changed, all the tests done to obtain the model that accomplish with requirements must be focus on the geometry changes and location of the high and low band elements. Since the low-frequency band element -the printed hollow coupling element- is bigger than the high-frequency band element and, as mentioned in the previous chapter, the antenna works better near the edges of the PCB; this antenna is considered to be located as is indicated in Figure 42 with a height of 0.4 cm. Nevertheless, in order to assure this geometry is suitable, one simulation is done with a height of 0.3 cm. In Figure 45 is shown the reflection coefficient of the printed hollow coupling element with a height of 3mm. Notice that the new response is similar to the element with 0.4 cm, both present a sharped second resonance frequency around 1.7 GHz which can later considered for a good effect over the monopole element.

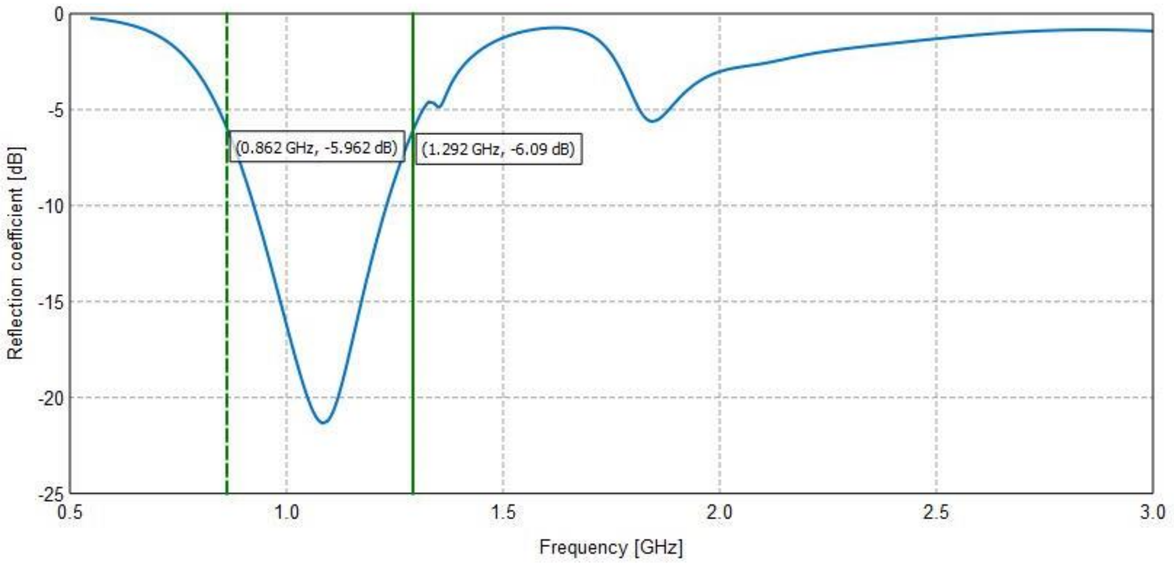


Figure 45 Reflection coefficient of the printed hollow CE of 0.3 cm of height

Despite the responses of the 0.3 cm and 0.4 cm are suitable for the design and the bandwidths are rather useful to cover the requirements, 0.4 cm is considered to this design because there is no performance trade-off in the change of the height. The printed hollow coupling element has a resonance frequency around 1.1 GHz and a bandwidth of 430 MHz. Apparently, the effects of the alone element are pretty interesting for this part of the project; nevertheless, in order to see the real behaviour of the element, it is mandatory to put it with the high-frequency band monopole to observe the mutual couplings and the produced effects of each other. Again, we have gained spaced because the reduction of the antenna, in this case, logically, the monopole has not to be located inside the low-frequency band structure but it is remaining a big space in the area reserved to locate it.

4.3. ANTENNA’S HIGH-FREQUENCY BAND ELEMENT DESIGN

To cover the high-frequency band located in 1.7-2.7 GHz range, it is necessary the introduction of a new element together with the printed hollow CE. The fact that we have space gained because of the reduction of the low-band element –namely the printed hollow CE- and again, the influence of the currents in the gained space (Figure 46) indicates that the free region can be used to insert the new element (monopole-type high-frequency element) and thus, the element can be directly design (printed) on the substrate. As the central frequency of the range is 2.2 GHz, a simple dipole antenna for this frequency would be 6.8

cm which is also a big dimension for the given space. So, considering just a monopole working at ¼ of lambda, that monopole must resonate between 3.2 and 3.5 cm.

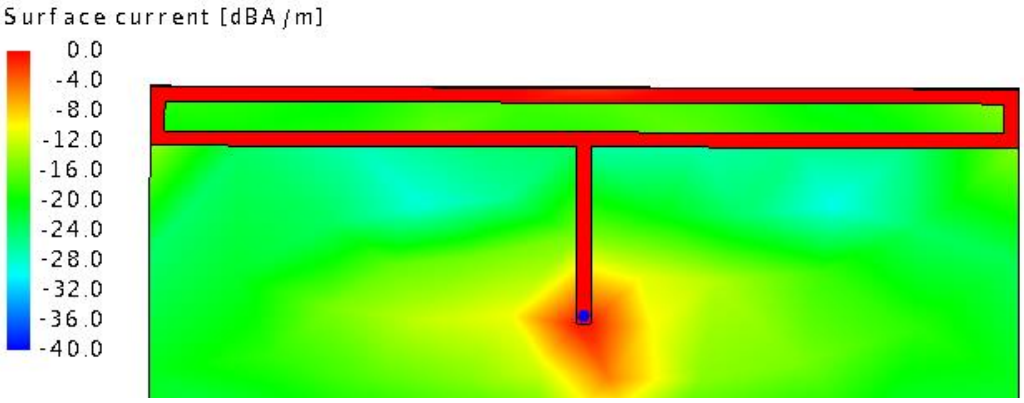


Figure 46 Current influence of the low-band element at 2.2 GHz

In this case, the design of the monopole cannot be elaborated by the alone element in the reserved area. Indeed, so as to demonstrate the effect produce over the monopole from the low-frequency band element, it is necessary to put together both elements and analyse the produced effects due to the relative position of the monopole in the remaining free region. So, in the following sections it is going to be demonstrated those effects and it will be presented the final design.

4.4. FULL ANTENNA

As was mentioned in part 4.3, the monopole is going to be placed in the free area left by the printed hollow coupling element to take advantage of the small effect of the currents in that region and to benefit the antenna by using the reserved space.

Several tests have been done, as the printed hollow coupling element cannot be modified and relocated, the monopole –which is folded due to the space- has been tested by moving it inside the area left by the low-frequency band element and changing the form of the monopole so as to create effects of enhancement of the bandwidth. First of all, it is simulated a design proposed by the main paper on reference in this work, namely [2], where the monopole has been changed in shape to cover the requirements. And finally, after the tests realised in the laboratory and the simulator, I will introduce my own design with its results.

4.4.1. First Approach

In [2], it is presented a new novel design of a Printed Hollow Coupling Element Antenna with the introduction of a folded monopole in the bottom-left part of the whole PCB. In this scheme, the design was replicated and simulated to evaluate the performance of the antenna. In Figure 47, the full structure on reference is depicted.

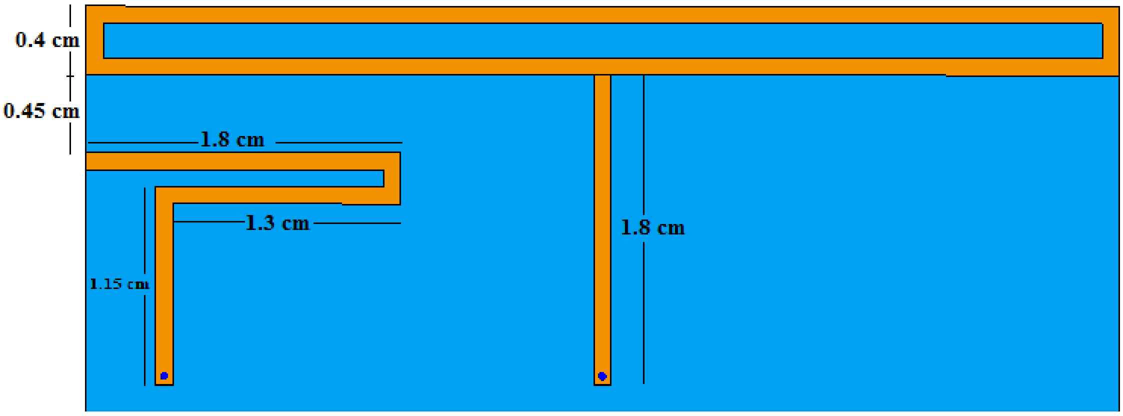


Figure 47 Paper's design approach

The structure looks like pretty logic and in agreement with the specifications for the design and the monopole has a total size of 4.25 cm. As mentioned in [29], since the high-band element could not be integrated inside the printed hollow CE, it is placed at the left side of the PCB, where the E-field was simulated to be the weakest. The PCB and ground plane dimensions are the same as well as the reserved area for the antenna is also the same and, with the tracks or strips thickness of 0.1 cm.

In Figure 48 are depicted the responses of the antenna in mention. It is remarkable the good performance of each element of the antenna. The low-frequency band element (Figure 48 b) covers from 909 to 1118 MHz at -6dB reflection coefficient amplitude, as it would be expected because of the total length the resonance frequency is located around 1.1 GHz causing the coverage of the indicated bandwidth which is 209 MHz. The high-band element (Figure 48 a) covers from 1.973 to 2.5 GHz at -6dB, this is because of the influence of the low-frequency band element's position relative to it. It is underlined the wideband behaviour of the monopole because of the mutual coupling with the higher order modes of the printed hollow CE.

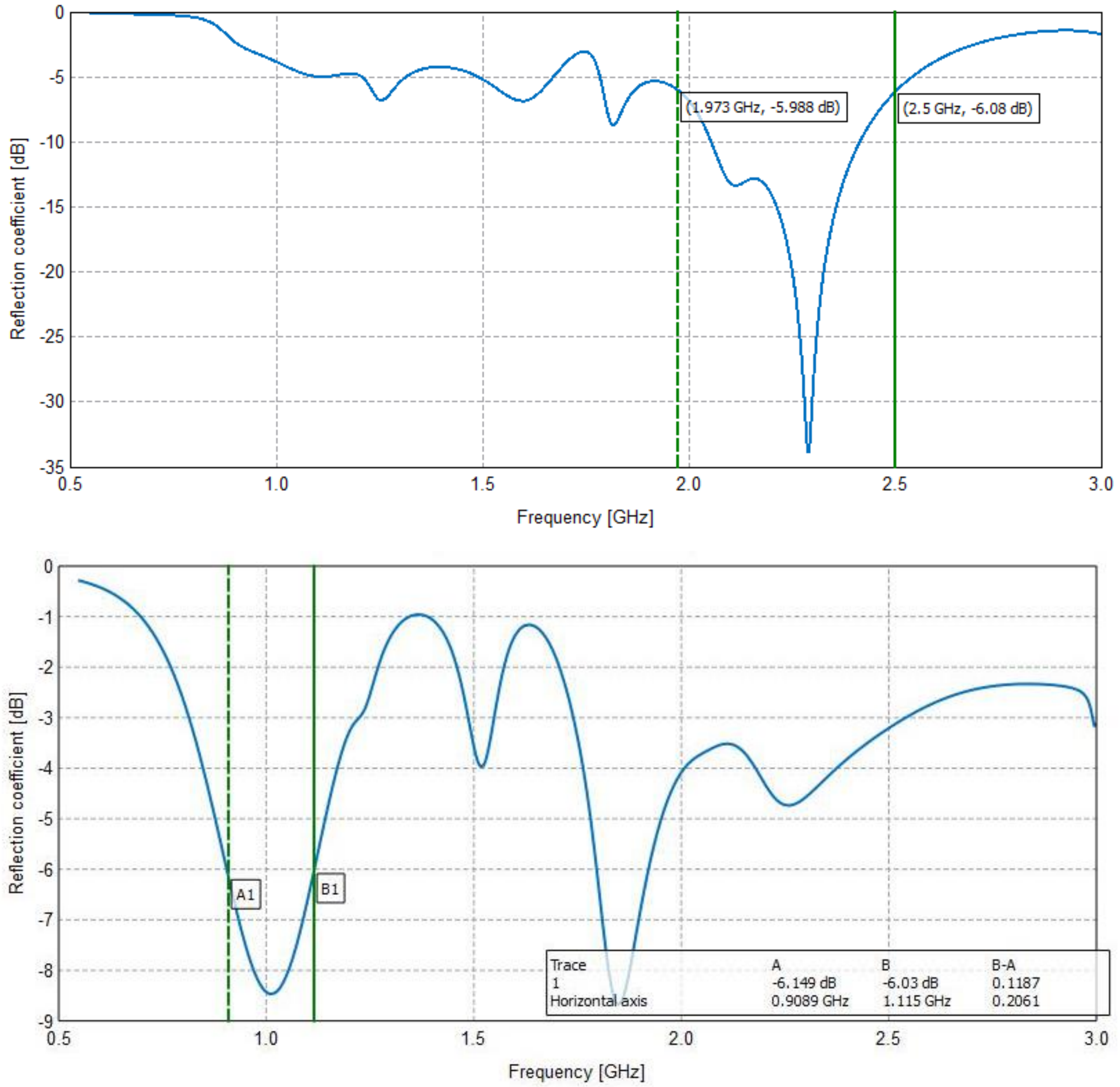


Figure 48 Reflection coefficient of a) high-frequency element and b) low-frequency element

It is mentioned in the reference and it is proved in the tests done throughout this project that the low-frequency band element is suitable for the design due to its position in the reserved area and, in order to achieve the specs, it is required the design of a matching network –like the one designed in Chapter III- for the improvement in the coverage of low-frequency band. It was proposed in the consulted literature a model for the MN suitable for this design which has not been analysed because is out of the scope of this project. So, it is decided –based in the design presented and the results obtained- to design a new model of the structure where the single folded monopole will be introduced in the free area and moved to find out a good position to the achieve the required coupling to enhance the high-frequency band bandwidth even more than the obtained in Figure 48. Then a matching network for coverage of the low-frequency band will be presented.

4.4.2. New design of the full antenna

After several tests done in the simulator, it is found that the structure that accomplish with the desired bandwidths and levels is that which is illustrated in Figure 49.

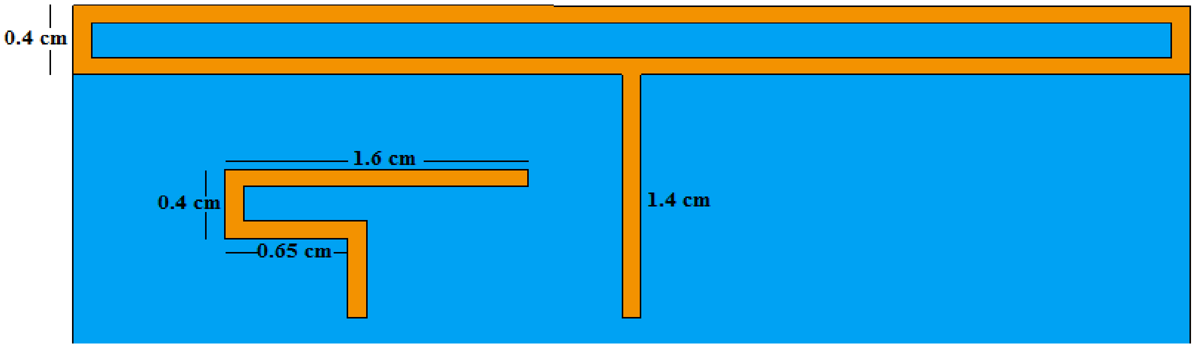


Figure 49 Final proposed design for the planar antenna

Again, as the tests done in the non-planar antenna, it is found that the monopole has a good coupling with the higher modes of the low-frequency band element when it is located near the bottom edge of the reserved area and, it is also demonstrated that the location of the monopole far from the edges of the printed hollow coupling element influences in the behaviour of the high-frequency band. In principle, it is seen (Figure 50) a better performance of the low-frequency band element which covers from 859 to 1238 MHz, increasing the bandwidth from 209 to 379 MHz. It is appreciable also (See Figure 48) an increment of the rejection level up to -14dB.

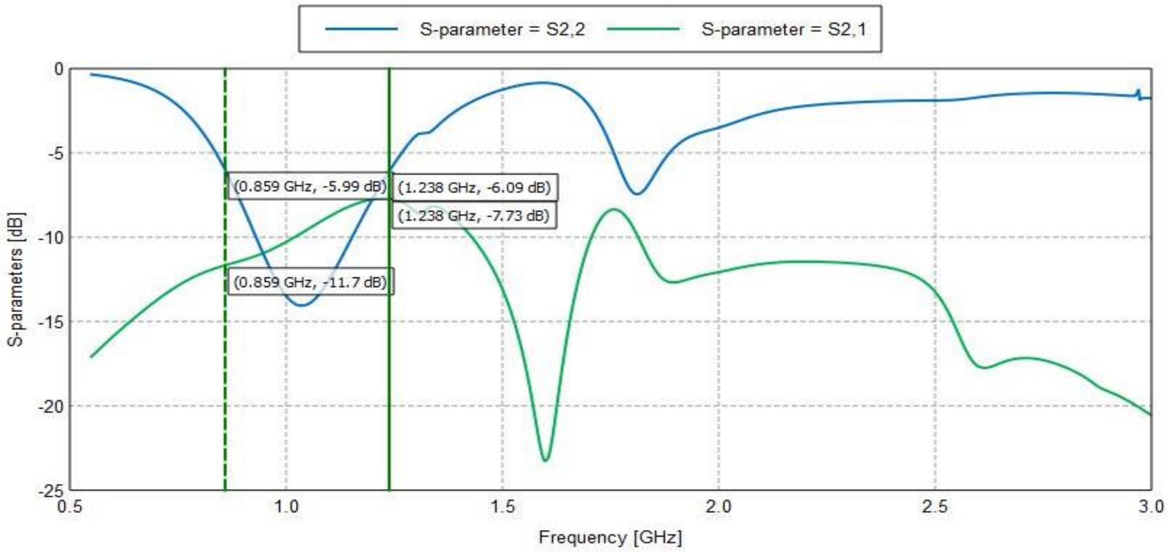


Figure 50 Reflection coefficient of low-band element (blue line)

In Figure 51 is depicted the behaviour of the monopole in the high-frequency band. Here it is also observed an improvement of the behaviour of the element which covers from 1.681 to 2.641 GHz at -6 dB –almost all the bandwidth required-. Comparing to the results obtained before where the high-frequency band element (Figure 48) covers from 1.973 to 2.5 GHz, we have gained 433 MHz in the bandwidth and the levels of the rejection are equitably distributed between -6 dB and -14 dB.

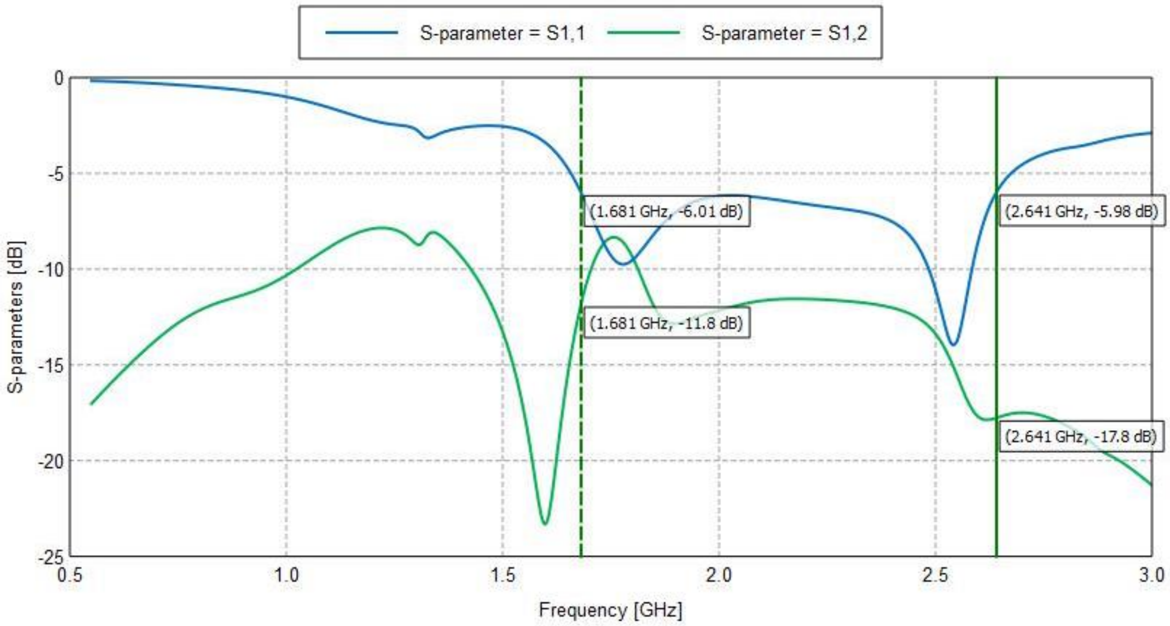
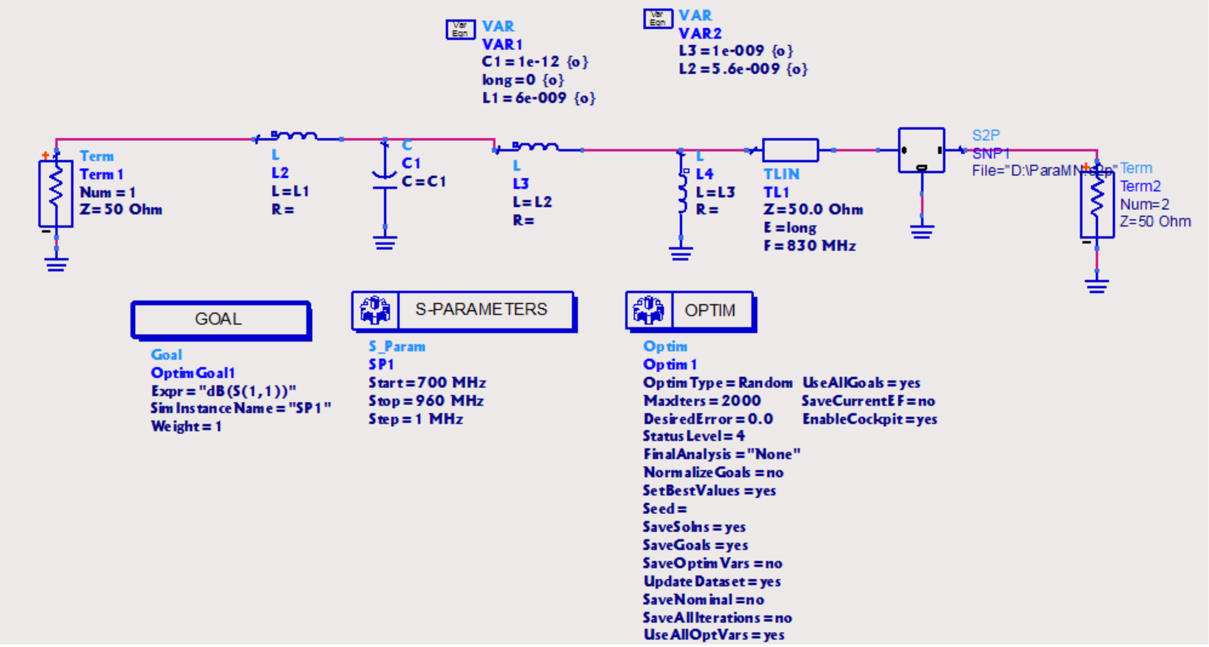


Figure 51 Reflection coefficient of high-band element (blue line)

The results shown in the previous figures depict a good performance of the full planar antenna. In the case of the low-band behaviour it is mandatory –as the non-planar design- the use of a matching network to enhance the bandwidth and to try to cover all the desired frequencies.

4.4.3. Low-frequency band matching network design

Once again, the solution to obtain a wideband matching network to cover the low-frequency band is to use a T model network with a shunt inductance next to the antenna to eliminate the reactance. The model is shown in Figure 52 where the simulation has been done with the help of the optimization routine in ADS. The circuit is composed of a T model L-C-L with different values for the inductor. A third inductor is introduced and shunted to eliminate the reactance of the load. Then a transmission line is added to ensure that the impedance matching will not affect the union between the feeding point ports and the elements of the antenna. The values obtained for the final low-band matching network can be seen in Figure 53. Notice that these values are not commercial and they are used only for simulations purposes.



VAR
VAR1
C1=1e-12 {o}
long=0 {o}
L1=6e-009 {o}

VAR
VAR2
L3=1e-009 {o}
L2=5.6e-009 {o}

Goal
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Expr="dB(S(1,1))"
SimInstanceName="SP1"
Weight=1

S_Param
SP1
Start=700 MHz
Stop=960 MHz
Step=1 MHz

Optim
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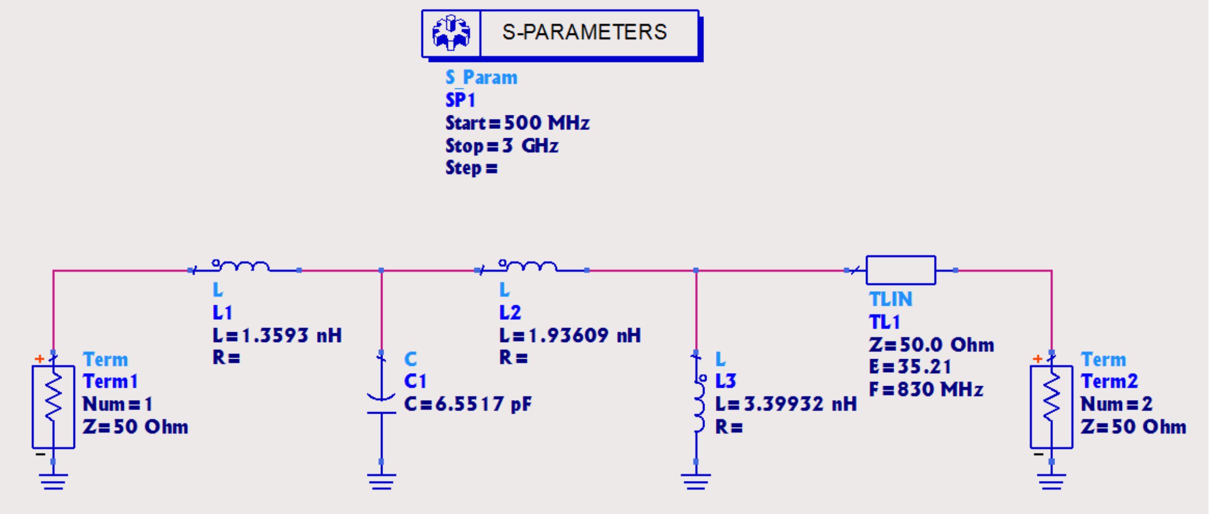
OptimType=Random
MaxIters=2000
DesiredError=0.0
StatusLevel=4
FinalAnalysis="None"
NormalizeGoals=no
SetBestValues=yes
Seed=
SaveSolns=yes
SaveGoals=yes
SaveOptimVars=no
UpdateDataset=yes
SaveNominal=no
SaveAllIterations=no
UseAllOptVars=yes
UseAllGoals=yes
SaveCurrentEF=no
EnableCockpit=yes

Figure 52 Design of a broadband matching network – ADS optimization program

It is important to highlight that in the optimization program, the requirements such as amplitude of reflection coefficient and bandwidth were introduced, that is to say, a coverage from 700 to 960 MHz at -6dB.



S_Param
SP1
Start=500 MHz
Stop=3 GHz
Step=

Figure 53 Final low-band matching network

Consequently, the network obtained in Figure 53 was exported in .snp file to FEKO to simulate the S-parameters of the full antenna, including the two elements and the matching network and, therefore the low-frequency band behaviour is depicted in Figure 54.

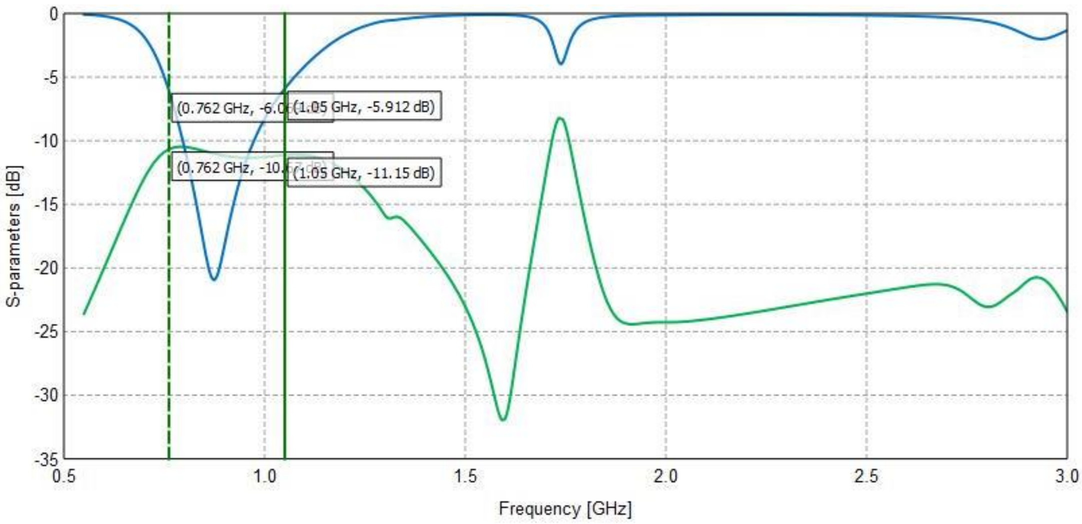


Figure 54 Low-band reflection coefficient due to the final matching network

It is observed from Figure 54 that the bandwidth is covered from 762 to 1000 MHz at -6 dB –almost the full bandwidth required-. The simulation indicates the utility of the use of a matching network for helping to achieve the specs. It is also remarkable that there is no affection in the behaviour of the high-frequency band and the antenna keeps its performance from 1.681 to 2.641 GHz.

4.5. FULL ANTENNA RADIATION PATTERN

Finally, it will present the radiation pattern of the full antenna including the low-frequency band matching network. Figure 55 shows an interesting radiation patterns where in low-frequency band operation the pattern is a dipole-type radiation as it was expected since the main radiator is the ground plane and the functionality of the low-frequency structure is like an asymmetric dipole. In Figure 56 are depicted the radiation patterns for high-frequency operation. Though in high-frequency band the shape is not defined it can be seen that in the operating frequencies the pattern has some wide-angle deep nulls which is important fact for mobile communications. In fact, though the good level of rejection, the radiation pattern presents those nulls that are the disadvantages of the design.

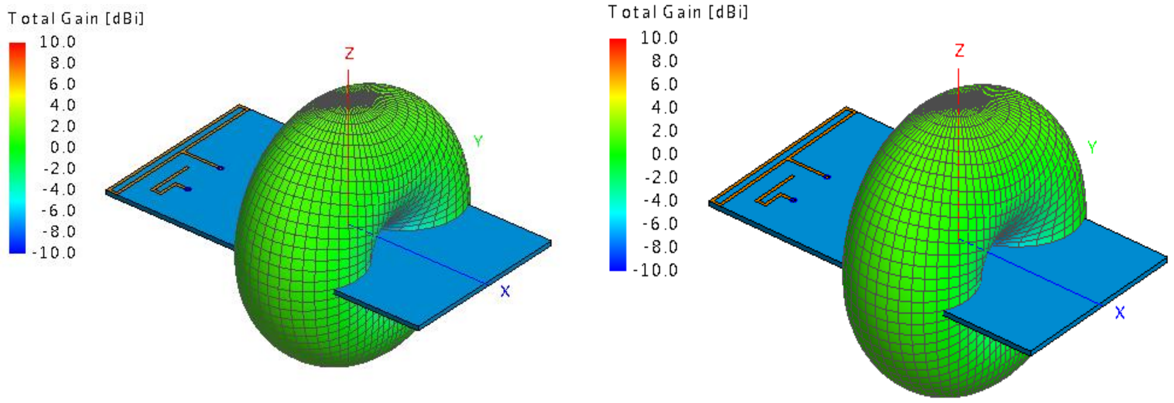


Figure 55 Radiation pattern at a) 795 MHz and b) 876 MHz

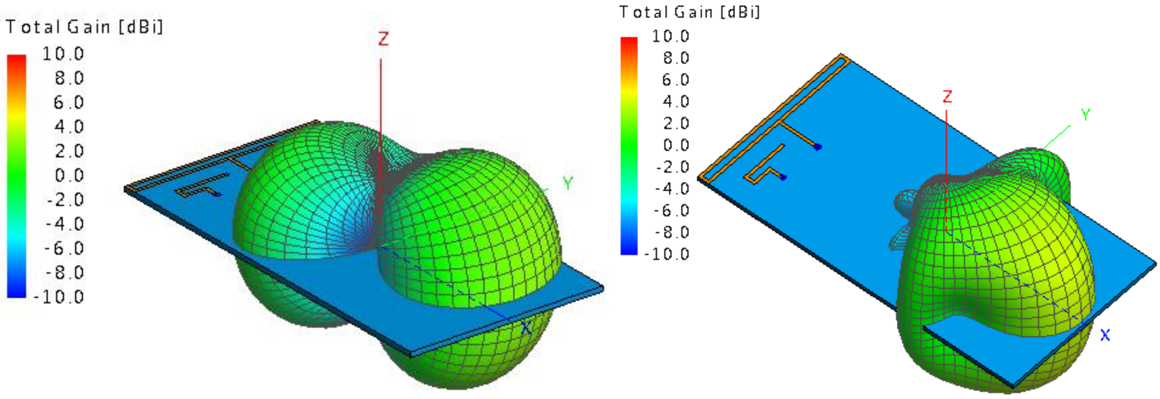


Figure 56 Radiation pattern at a) 1.775 GHz and b) 2.51 GHz

4.6. SUMMARY

A planar antenna for 4G mobile communications coverage was designed based on the main reference mentioned throughout this work. This antenna have been passed for several tests taking into account the proposed design of the reference literature so as to achieve the requirements of 4G technologies and current mobile devices. In this chapter:

- For the coverage of the low-frequency band it has been design a printed hollow coupling element on the substrate, where a reduction of the size is done to gain space for the location of the other element without a performance trade-off. For coverage of the high-frequency band a single monopole resonating at ¼ of lambda is folded to be located below the low-frequency element where the currents are weak and have not effects over that zone. The coverage obtained is from 859 to 1238 MHz and from 1.681 to 2.641 GHz respectively. To try to enhance the poor low-frequency band performance, a T-type matching network was designed, so the full antenna covers from 762 to 1000 MHz and from 1.738 to 2.51 GHz at -6 dB. These facts remark the important impact of a good-designed matching network which adapts perfectly the impedance in the require frequencies.

- All the element’s tracks are made of 0.1 cm of thickness. The results show that the position of the monopole with respect to the printed hollow CE is quite relevant to assure the achievement of the requirements. In fact, a good coupling is achieved when the high-frequency element is working due to the effect generated by the higher modes of the low-frequency element.

- As is shown in section 4.5, the radiation patterns are quite coherent to the reality because their shape is like it was expected. For the low-frequency band we have a dipole-type shape and for the high-frequency band there is no a perfect geometrical form and it is seen that the patterns have nulls in some directions in the bands of interest.

CHAPTER V

PLANAR 4G ANTENNA FABRICATION

In this chapter is presented the fabrication of the planar model obtained in Chapter IV. The model to be constructed was depicted in Figure 49. In the real design was introduced a transmission line in the elements to gain space for the placement of the connectors. The construction was done by the drill machine ProMat S62. After the elaboration of the antenna by removing the unnecessary copper from the FR4 PCB and the placement of the connectors, the measurements were done with the Network Analyser Agilent N5242A. The Figure 57 illustrates the final real planar antenna. It might be noticed that the antenna has no matching network. This is because of the complexity of the construction and due to the difficulty to obtain the components with the values calculated in section 4.4. For practical reasons and for the purposes of this thesis, it will only be tested the antenna without any matching network.

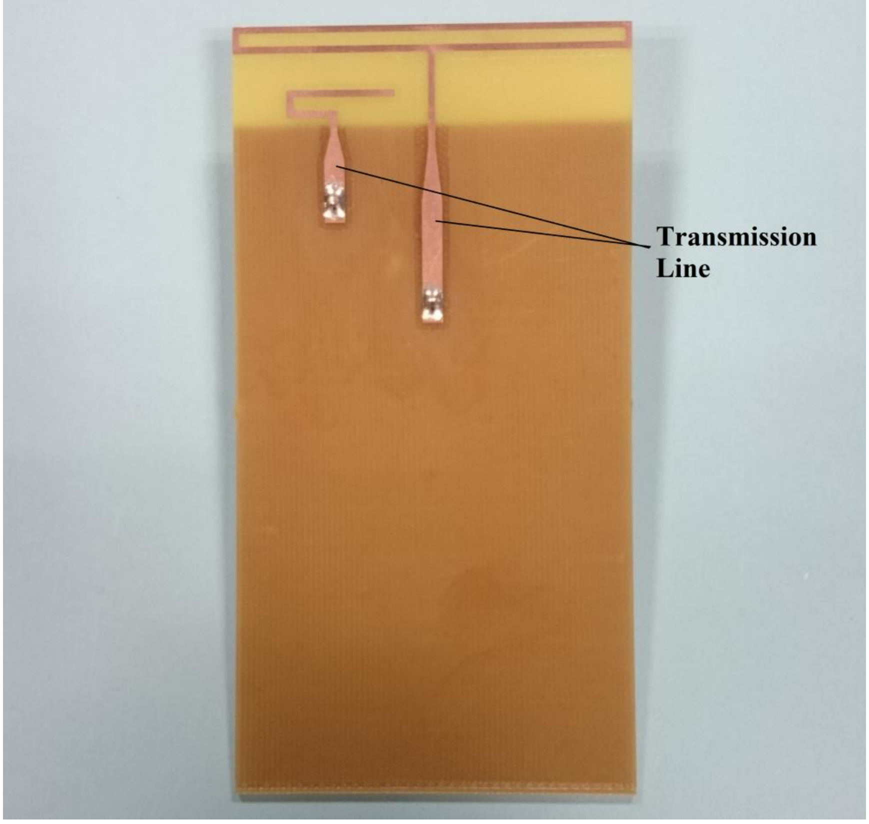


Figure 57 Fabricated planar antenna

5.1. MEASUREMENT PROCEDURE

A critical part in the fabrication is the location of the connectors and the tests. It is important to pay attention to the details at the moment of weld. The connectors might introduce losses in the final response of the antenna as well as the cables of the analyser.

The Network Analyser is the essential laboratory device to make the proofs and measurements of the S-parameters of the real antenna prototype. Once the antenna is connected to the analyser, it is important to make some configurations in the analyser to ensure the correct measure.

- Connect carefully the cables to the antenna. Try to avoid the abrupt manipulation of them and to locate them in free space where could not be metals of materials which produce interferences.
- Setup the frequency ranges to be evaluated and the amplitudes markers. Then, it is important to make a calibration because the cables and connectors enter losses in the machine.
- Export the S-parameters obtained from the measurements to depict them in any other software like FEKO or MATLAB.

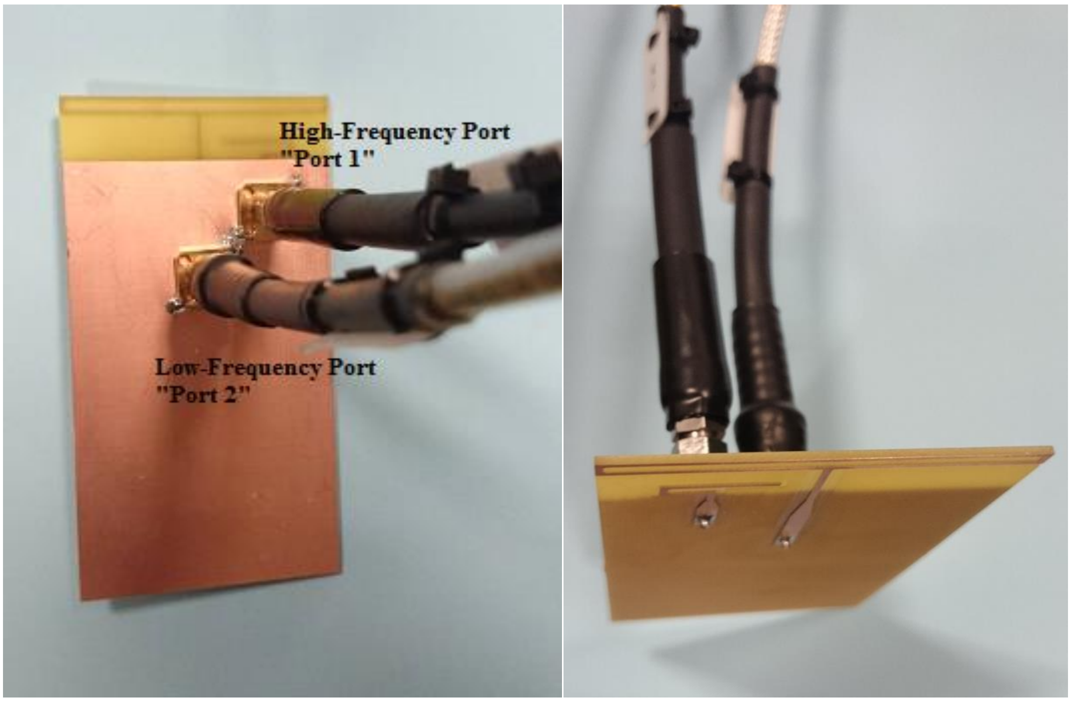


Figure 58 Connecting the antenna to the network analyser

The results of the measurements are displayed in the network analyser screen where the cursors can be set to mark and measure the relevant points, amplitudes and frequencies. Despite the use of the screen, it is convenient to export the result's file to use it in computer software.

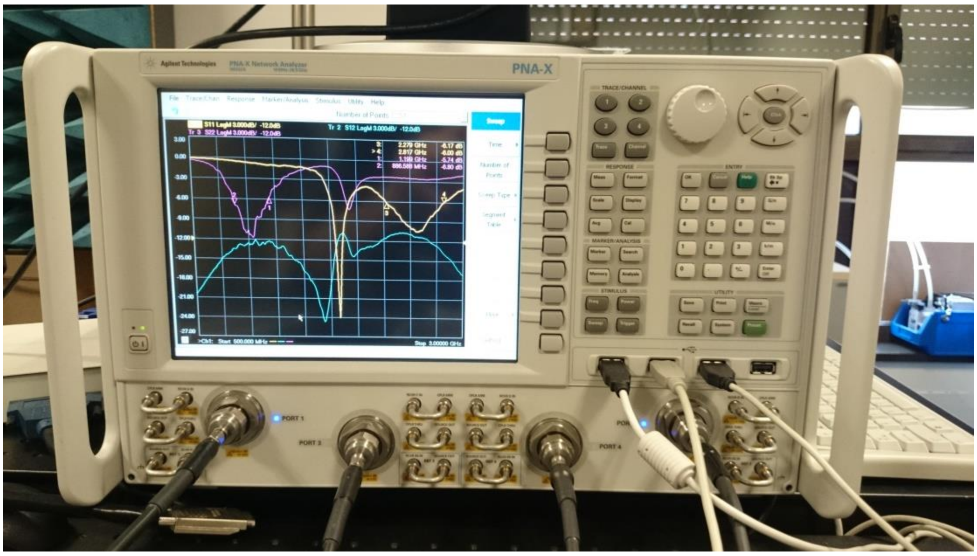


Figure 59 Network analyser screen

5.2. MEASUREMENT RESULTS

The S-parameters of the fabricated antenna were export in order to compare them to the results of the simulations. The measurements are depicted in Figures 60 and 61.

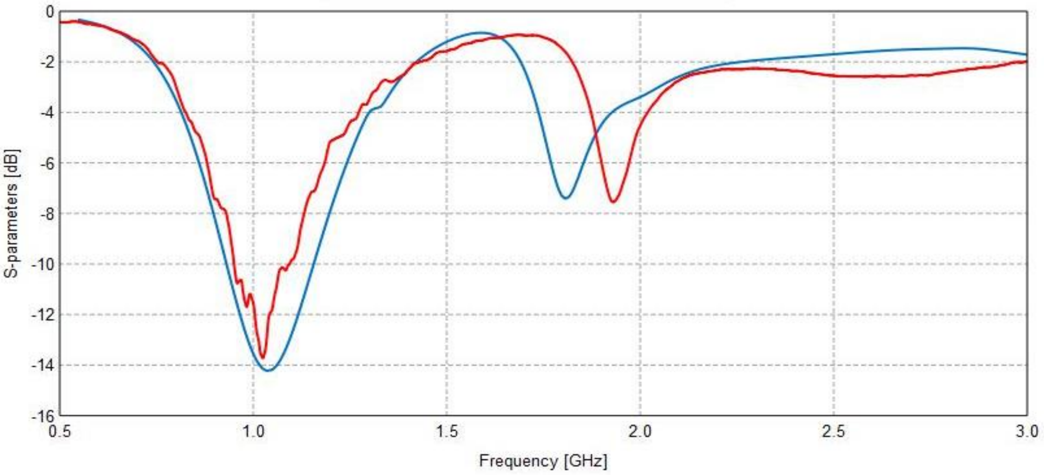


Figure 60 Reflection coefficient regarding to low-band operation S22, simulation (blue line) and fabricated (red line)

It can be seen that in low-frequency band there is a logical similarity in the desired frequencies of operation and, as the frequency increases the curve tends to have a displacement to the left. In fact, the bandwidth at -6 dB suffers a decrease, covering from 883 to 1185 MHz.

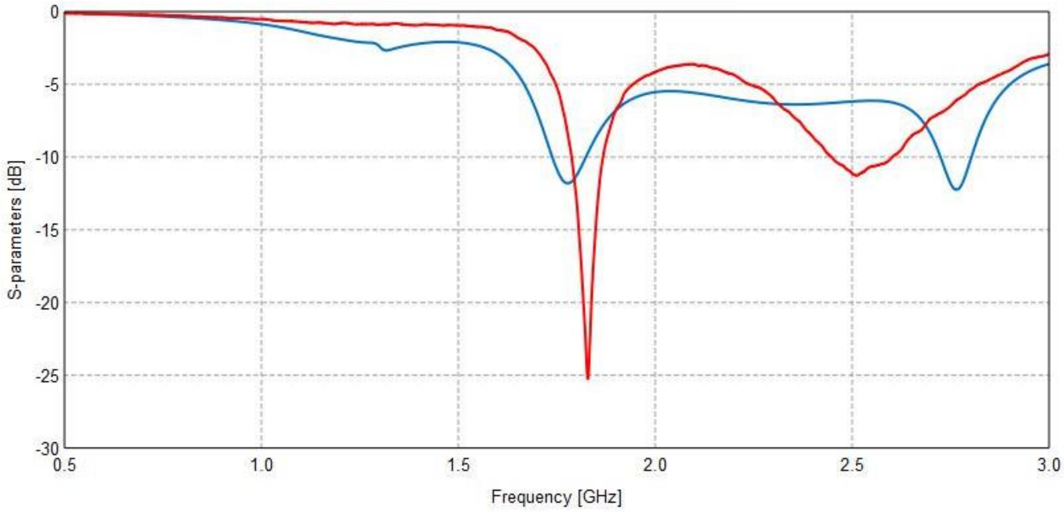


Figure 61 Reflection coefficient regarding to high-band operation S11, simulation (blue line) and fabricated (red line)

The same occurs to the high-frequency operation. As we can see in Figure 61, after 1.8 GHz the curve of the fabricated antenna tends to suffer a displacement to the left. Besides, there is a loss of the rejection level between 1.9 to 2.3 GHz where the amplitude of the reflection coefficient is up to -3.7 dB.

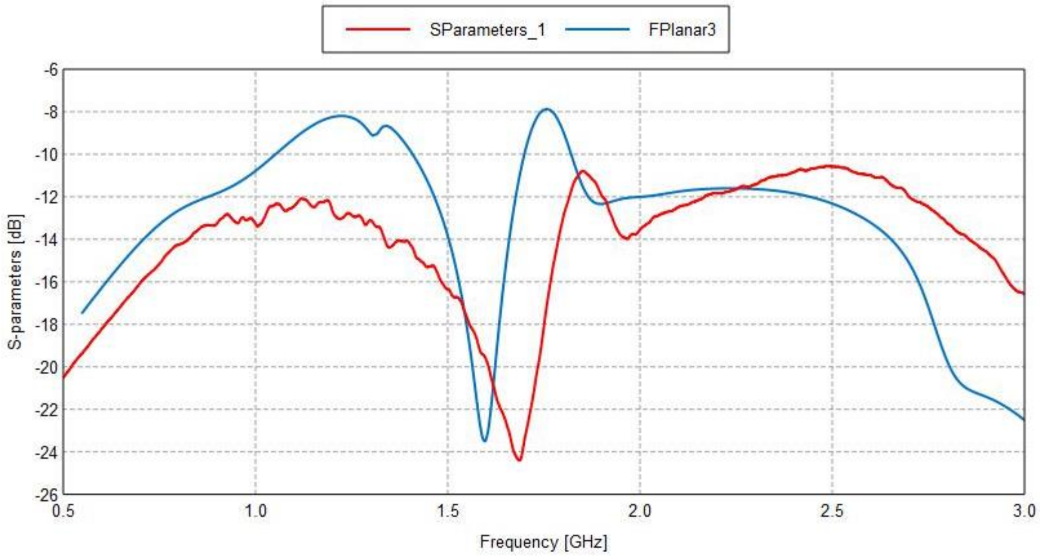


Figure 62 Transmission coefficient S21, simulation (blue line) and fabricated (red line)

5.3. CONSIDERATIONS

The resulted S-parameters of the fabricated antenna have been illustrated in Figures 60, 61 and 62. Comparing to the model designed in the software, it is appreciable that the curves are pretty similar each other. Nevertheless in low-band there is a reduction of the bandwidth while in high-band there is a loss of the rejection level between 1.9 to 2.3 GHz. At this point a question emerges, what is causing the differences between the software model and the manufactured antenna? The answers can be many and different. Now, several reasons that can cause those differences will be listed:

- The imperfections in the simulations. Simulations are always configured to model the designs as a no-loss scheme and there is no consideration in the environment evolving the antenna since it cannot be simulated. The real antenna is exposed to several ambient conditions and many materials can produce effect over it such as metals, tables, chairs, etc.

- The substrate modelling. As FR4 was selected, in real life, there are imprecisions in the material. One reason is the drill of the copper can reduce the thickness of the FR4 making the permittivity to change its value. Those circumstances produce variations in the bandwidth and produce losses and couplings which reduce the level of rejection. In fact, the impedance changes to a capacitive response.

- The copper drilling and the paths of the elements. As the tracks are being drilled the imperfections of the machine can produce microscope variations in the width. Though this idea seems no relevant it must be thought that the software is an idealistic simulator, then the imperfections can produce the malfunction of the antenna – understanding malfunction as a no-desired function-.

- The additional transmission line introduced in the fabricated antenna can also modified the expected response from the simulations. Despite the fact that the transmission line was designed as a 50 Ω TL, the imprecisions of its implementation also induces the losses on the antenna.

CHAPTER VI

CONCLUSIONS

The main goal of this project was to design and construct an antenna for 4G mobile communications coverage, of dimensions according to the actual sizes of mobile devices –like the smartphones- and a planar design which could be easy of manufacturing. To do it, the project has taken two paths:

- First, a non-planar antenna has been designed. The considerations are the use of two elements, one for each band to be covered, with independent feeding points to satisfy the requirement of transmission over several channels. The first element is a coupling element consisting on a plate which after is hollowing to use the gained space to locate the second element inside that region. The free area is thought to be of weak current effects. The hollow coupling element induces properly the currents in the ground plane to work as an asymmetric dipole and to enhance the radiation properties. The second element is a folded monopole which resonates at ¼ of lambda. There is an important high port-to-port isolation while there is a coupling between the elements where the monopole benefits of the presence of the low-band element to improve its bandwidth to achieve the requirements. It can be concluded that the antenna achieves the specifications but is not suitable for its location in the housing of a current mobile phone.

- The second path is the design of a planar 4G antenna. To design it, two elements have been considered, from the previous point, the first element is a printed hollow CE, where the print of the antenna over the substrate has reduced its size giving a free space underneath to locate the high-band element. Several tests have been presented to demonstrate that the selected model is the suitable for the project. The second element –like the non-planar case- is a folded monopole which has been located in a free area where the electric field is as weak as possible. The positions of the two elements have derived into a mutual effect which improves the performance of both. The full antenna achieves the requirements even better than the non-planar design. It can be concluded that this antenna is rather interesting to test it in a real device.

In both cases, it is checked the use of matching networks to improve the behaviours, especially in the low-frequency ranges where due to the reduced dimension of the element, the resonance frequency does not be in the band of interest. Despite the matching network has been designed, it must be considered its use since the components are not commercial and they are difficult to implement in real prototypes.

From the planar antenna design, it has been manufactured a real prototype where its S-parameters have been depicted versus the S-parameters of software design. Several differences are found. It is concluded that the differences are due to the geometry and construction errors. The simulator shows results by considering the structure as perfect and does not consider the environment effects. The drill machine reduces –in many ways- the thickness of the FR4 material and therefore modifies the effective permittivity of that material. Another relevant factor to be taken into account is the addition of the transmission lines to allow the colocation of the connectors in the PCB.

Finally, it is concluded that this project reaches the objectives planned in the beginning. The non-planar antenna covers from 721 to 960 MHz and from 1.738 to 2.51 GHz at -6 dB with the use of a matching network. The planar antenna covers from 762 to 1000 MHz and from 1.738 to 2.51 GHz at -6 dB and it also uses a matching network.

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