Master's Thesis

Master in Telecommunication Engineering

Design of a near-field RFID reader based on metamaterials technology

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UAB

El sotasignant, *Jordi Bonache Albacete*, 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 *Héctor Landa Martínez*.

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

Bellaterra, *8/6/2016*

Signatura: *Jordi Bonache Albacete*

Resum:

En aquest projecte es desenvolupa un lector de camp proper per a dispositius RFID a través d'una ona evanescent creada mitjançant una línia de transmissió artificial, és a dir, que fa ús d'estructures amb metamaterials.

Mitjançant un estudi empíric a través del simulador ADS2009 es van alterant els diversos paràmetres de la línia, extraient les conclusions pertinents per veure quins són els que més s'adeqüen a les exigències d'un model proper a l'ús comercial.

Resumen:

En este proyecto se desarrolla un lector de campo cercano para dispositivos RFID a través de una onda evanescente creada mediante una línea de transmisión artificial, es decir, que hace uso de estructuras con metamateriales.

Mediante un estudio empírico a través del simulador ADS2009 se van alterando los diversos parámetros de la línea, extrayendo las conclusiones pertinentes para ver cuáles son los que más se adecuan a las exigencias de un modelo cercano al uso comercial.

Summary:

In this project a near-field reader for RFID devices is developed which works emitting an evanescent wave created through an artificial transmission line, that means that the device uses structures with metamaterials.

Doing an empirical analysis through the ADS2009 simulator the parameters of the line are being altered to extract relevant conclusions and see which are the most adapted to the requirements for a model near to a commercial use.

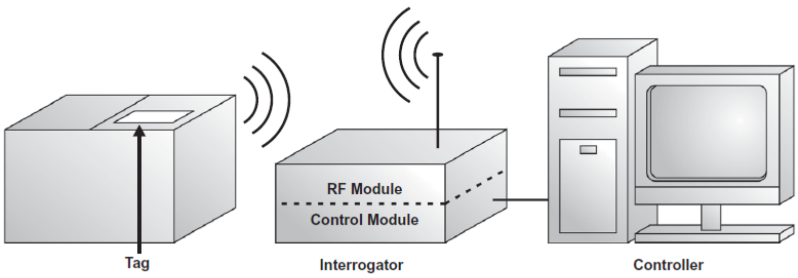
Index:

Introduction:

Radio frequency identification (RFID) is a generic term that is used to describe a system that transmits the identity (in the form of a unique serial number) of a device wirelessly, using radio waves. It's grouped under the broad category of automatic identification technologies. RFID uses electromagnetic fields to identify and track tags attached to an object.

There are three basic components in a RFID system:

- A tag: Composed only by a semiconductor chip and an antenna.
- An interrogator (reader): Composed by an antenna, an RF electronics module
- A controller (host): The workstation which runs the database and the control software.



The tag and the interrogator communicate when a tagged object enters in the reading zone, the reader signals the tag to give its stored data. The interrogator sends tag's data to the controller via network interface.

In this project we'll develop the antenna used by the reader. Technically there's not an antenna, because the device developed doesn't radiate part of the electromagnetic wave which travels along the line. Using the properties of the evanescent waves, described afterwards, we'll capable of excite the tags when these are near the device.

The use of leakage radiation doesn't allow much control of the bounded EM region, with the use of evanescent model we can have more precision with the field confinement.

Thanks of the properties of metamaterials we can alter some parameters of the evanescent wave, like the reach that this one can have to excite the tags. The main idea is to design a reader with a read range of only a few centimeters, to manually put the tag near the reader (or vice versa) and detect them.

To improve the coverage of the reader the purpose is to design not only a simple transmission line (with metamaterials), a structure composed by "branches" in parallel will be implemented to cover more area. Also, the use of metamaterials let us manipulate the frequencies transmitted along the line.

The project is developed in 6 chapters, there's a short description of them:

- **Chapter 1:** In this chapter we try to get familiar with the use of metamaterial structures and the ADS simulator. The design of the substrate and the first simulations realized to establish contact with the Momentum Simulator.
- **Chapter 2:** enters in a more technical description of the model used; The CRLH transmission line, the simulation of this one and the properties of the line to control the evanescent wave.
- **Chapter 3:** Describes the empirical process of manipulation of the basic cell to extract conclusions about the performance that this one provides. Parameters like length or diameter of the rings are studied along the chapter.
- **Chapter 4:** Implements the first design of the Dual Model, and the study about why the model is not working correctly. Schematic workspace is used for that purpose.
- **Chapter 5:** Here we implement the corrected model, called V model with the extraction of the results and the conclusions at the end of the chapter.

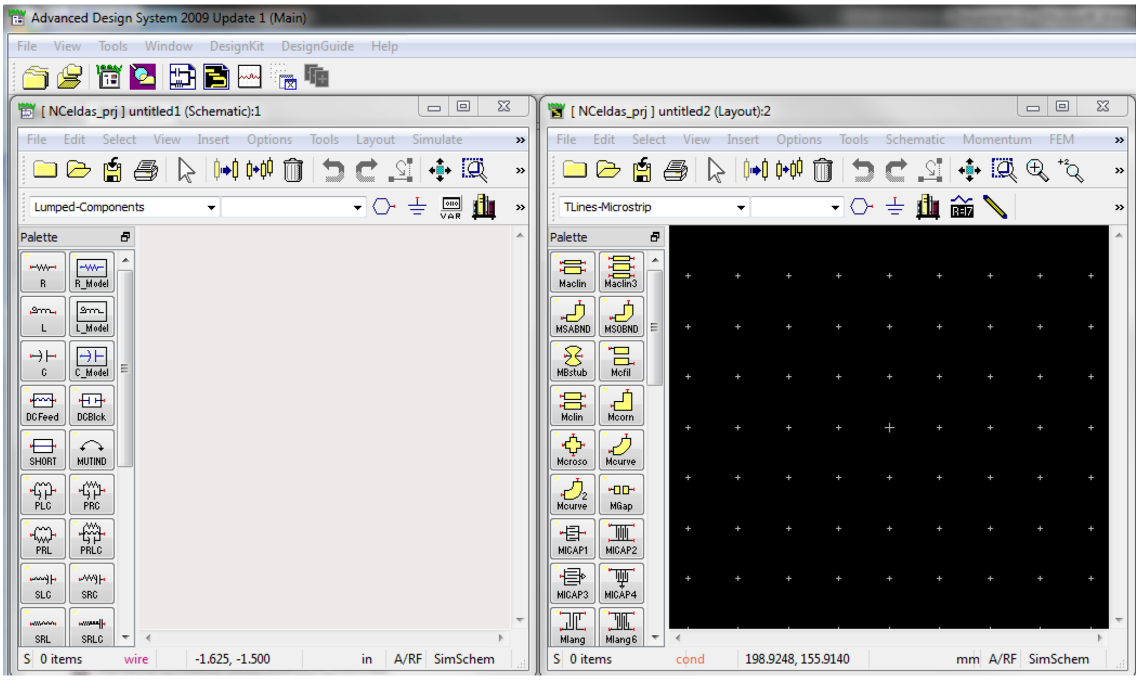
Finally an annex is indexed, to know more data about RFID if this would be pertinent.

CHAPTER 1: ADS Simulator and first steps:

Advanced Design System (ADS) is an electronic design automation software, one of the leading ones for RF. It provides numerous tools for the purpose with an intuitive and easy process.

There are two work-spaces, the most used along the project is the layout workspace, this one, as the name says, let us draw a series of materials (metal, hole, dielectrics) to combine it and design different models of antennas, transmission lines, etc...

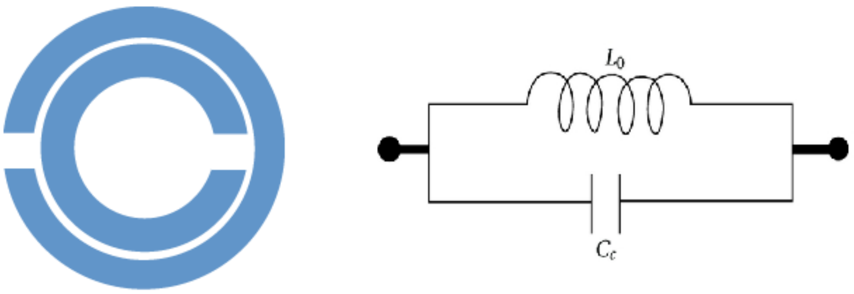
The other workspace is the schematic one, this let us implant theoretical circuit models and import fragments from the layout (or complete models) to test it or evaluate the errors occurred.



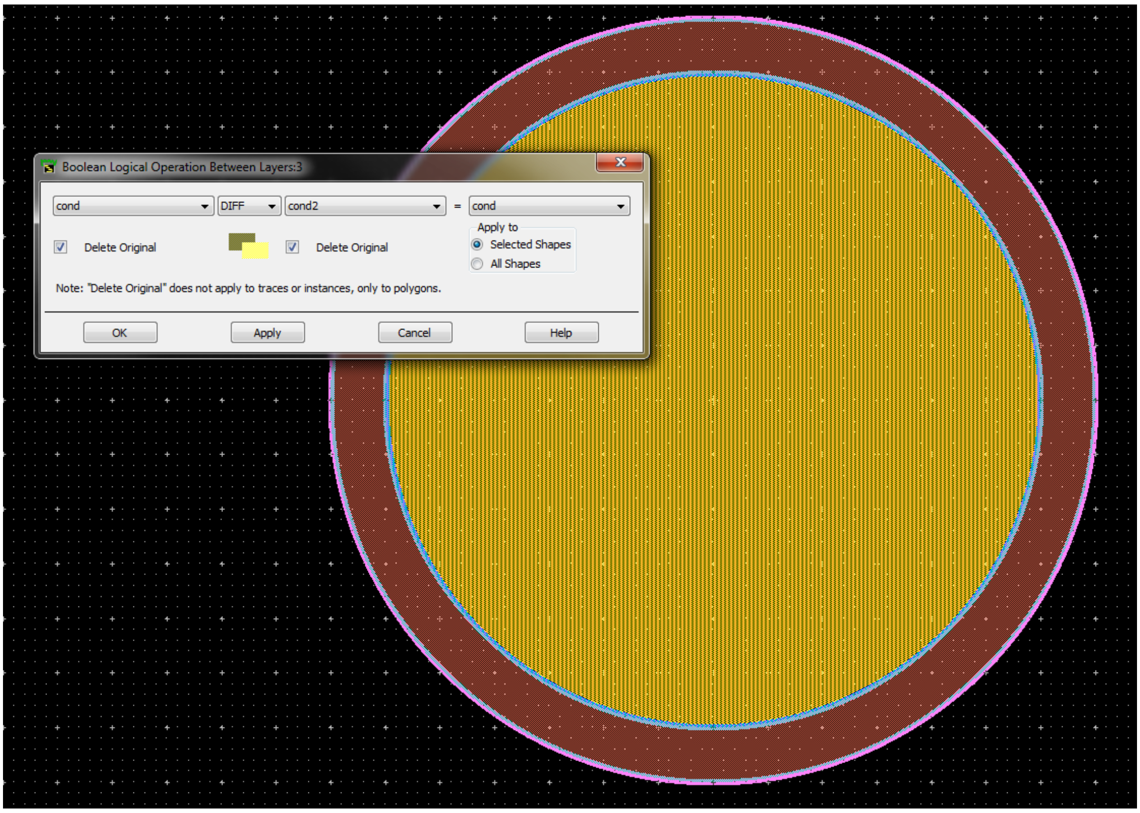
With boolean logical operations inside the layout workspace we can design the circles of the artificial transmission lines implemented, it's important to be familiar with the different tools/menus and design of basic lines.

This first pages describe the first models implemented to acquire knowledge about the program and a proper idea about the design of the RFID reader.

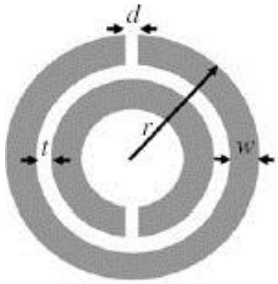
The first step is to design the circles for a SRR-based CRLH lines model, which is the main part in the artificial transmission lines, with the ADS 2009 software, we can take an example of the model in the following image, a classical SRR-based CRLH lines model with his respective circuit model at the left:



Making use of the layout tool we have access to a wide number of design options. We enter inside the Edit > Boolean Logical menu and making the subtraction (DIFF) option we can extract the golden layer (cond2) from the pink one (cond) obtaining the external contour of the SRR in the cond layer:

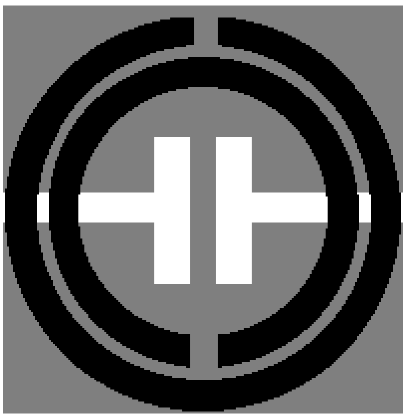


We take the measures from the model developed in *"Controlling the Electromagnetic Field Confinement with Metamaterials"* paper for a first contact with the simulator. The external ring diameter is r = 32 mm and the width of both rings is w = 1 mm with a separation of t = 1 mm between them. The slot in every circumference has a weight of d = 1mm.



We repeat the process for the internal ring with the measures described in the previous paragraph, after doing again the boolean logical operation we obtain the complete SRR structure.

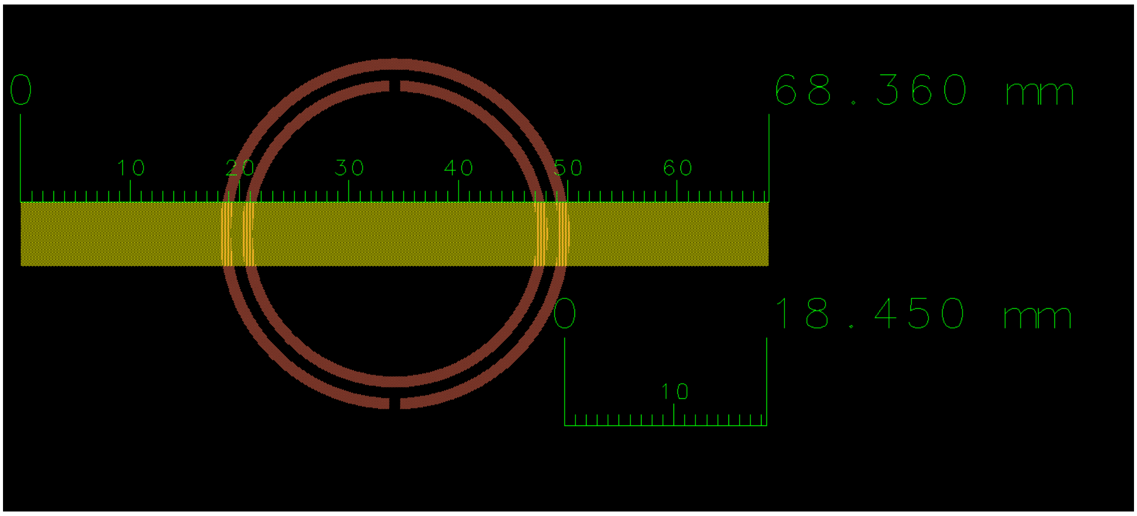
The next step is to do the transmission line which pass through the center of the designed SRR, if we take the model designed in the "*Fundamental-Mode Leaky-Wave Antenna (LWA) Using Slotline and Split-Ring-Resonator (SRR)-Based Metamaterials*" we can see a model very similar with the function to radiate as a leaky-wave antenna, the next image shows the model used in that paper:



Where the transmission line which pass through the SRR is a slot line, with a "slot" in the center of the line to simulate a capacitance required for a correct performance of the model.

This is part of a balanced composite right/left-handed (CRLH) CPW unit cell, to simulate a sufficiently wide central strip to minimize the field coupling between both slots, one half of the structure has been removed. This operation is described later in the chapter 2 : *Design of a Balanced CRLH CPW Transmission Line.*

To emulate this model the first main idea was to preserve the relation between the measures, also to have a general look of the resulting model we can see the following image:



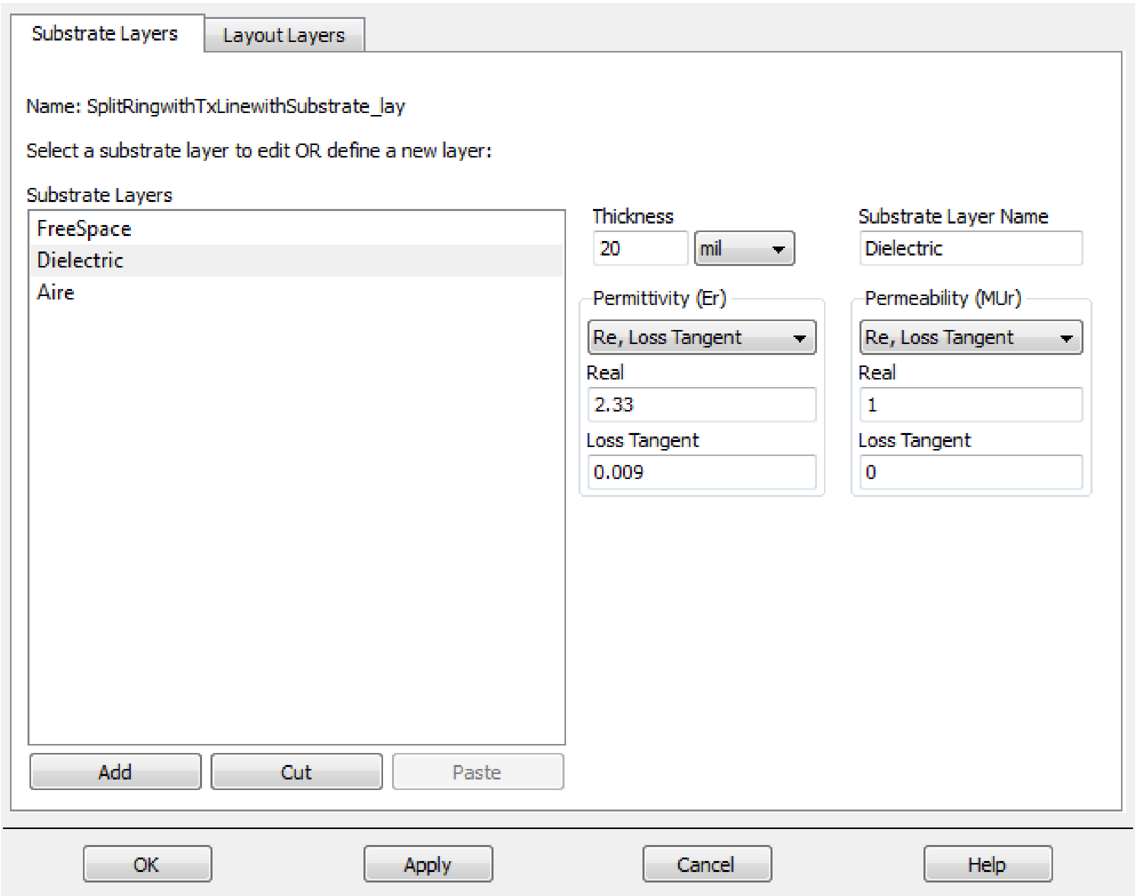
Where the transmission line (slot) has a width of 6.836 cm, the distance from the next unit cell to the external ring is 1.845 cm and the height of the line is 5.82 mm. For the first simulations we don't take consideration of the central slot of the CPW, later it will take place in the design. We're designing an MNG line.

Due to Babinet's principle if you change the slots for metal (and vice versa) the fields magnetic and electric change their positions. That's the aim of the CPW lines.

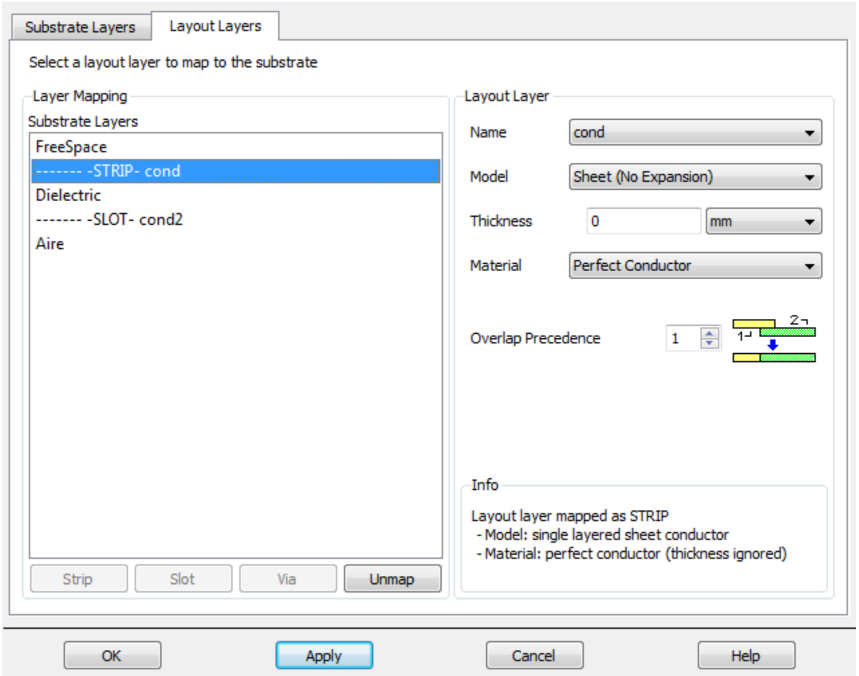
Substrate Design:

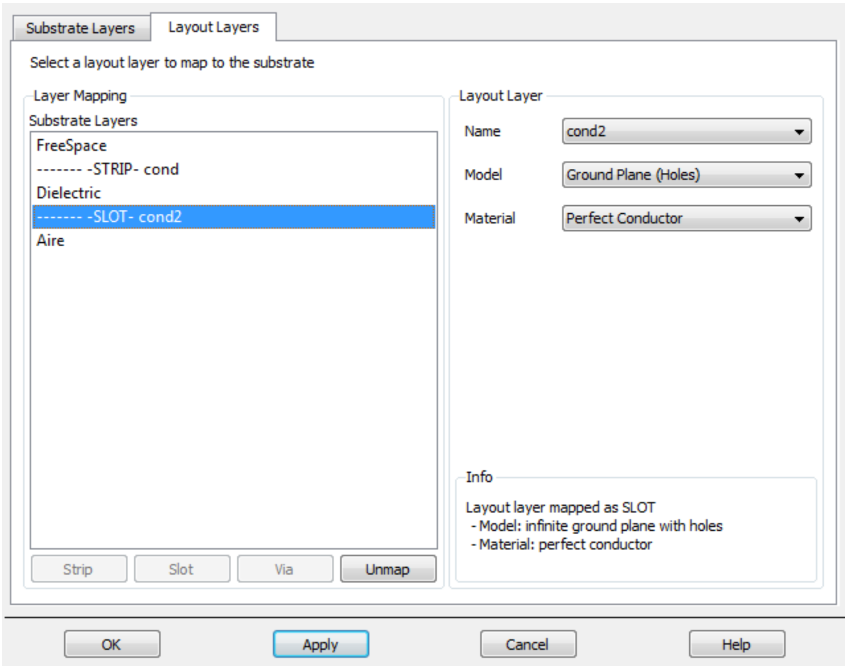
To modify the substrate parameters inside the ADS program we enter inside the layout design and in the Momentum simulator window we can access to Substrate > Create/Modify... where we can see an emergent window with two sections : Substrate Layers and Layout layer.

Inside the Substrate Layers we have two layers which represent the Free Space with a Boundary Open and values of permittivity (ε) and permeability (μ) equal to 1. Between this two layers we have the dielectric, with a thickness of 20 mil and values of permittivity of 2.33 and a loss tangent (to simulate losses in the model) equal to 0.009.



Inside the Layout Layers window we have the layers designed in the previous window, and the metal strips were the model is going to be implemented. This lines are defined as -STRIP- cond for the layer which contains the ring structure, and -SLOT- cond2 for the layer of the transmission line.



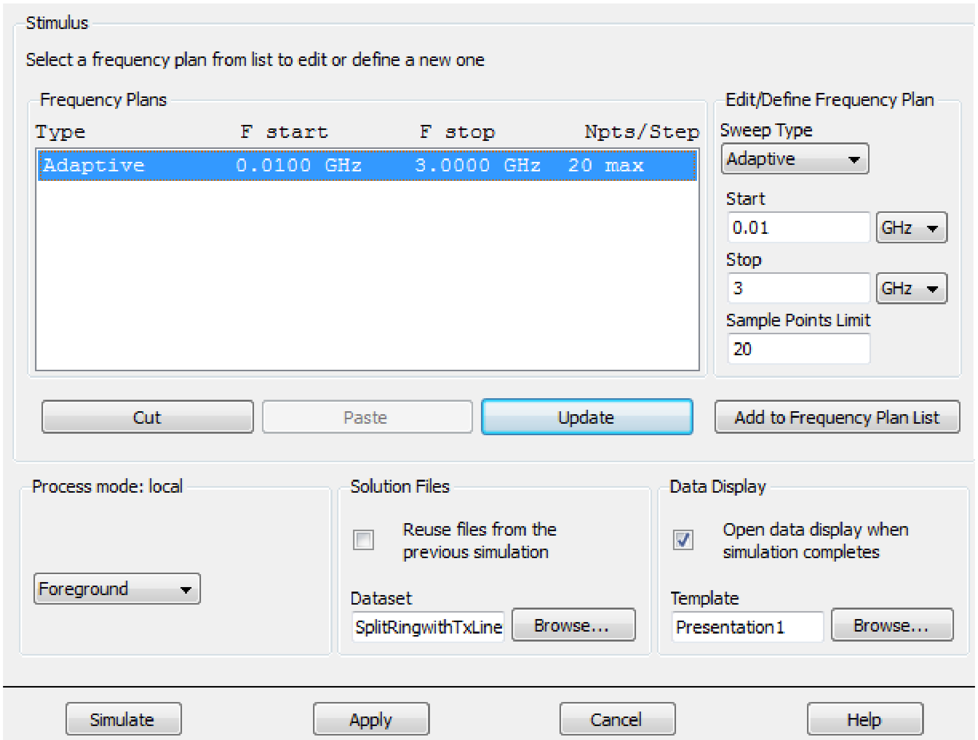


In this second image we can appreciate that cond2 has been mapped as slot, an infinite ground plane with holes. This device is implemented by using two levels of metallization in a planar low-loss dielectric material.

The top layer (cond2) contains a slot transmission line with a metallic connection within the slot, whereas the bottom layer (cond) contains a CRLH SRR magnetically coupled to the slot line.

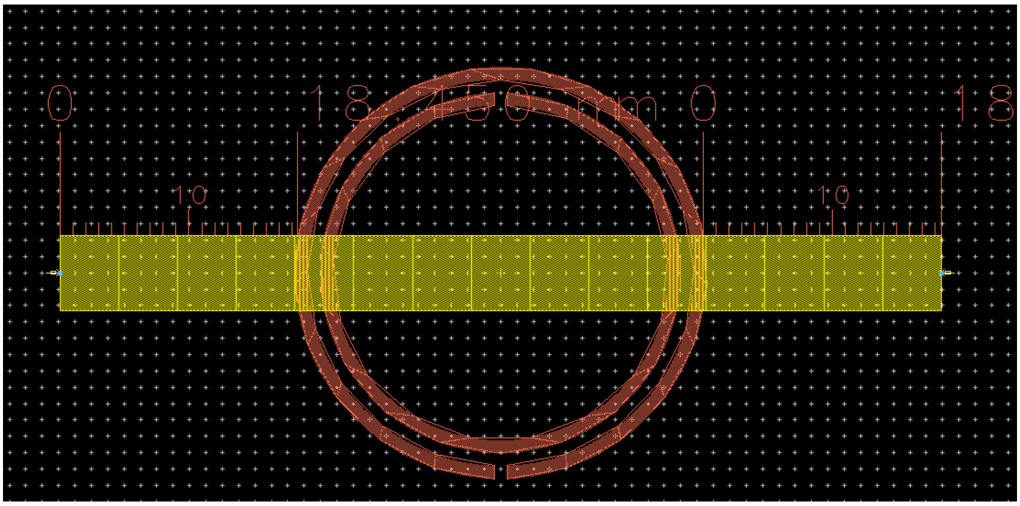
First Simulations

The model was simulated by Momentum, one of the two simulators that ADS have. All simulations follow a similar process, a simulation of the S-parameters with a sweep of the work frequencies, from a low value (10 Mhz) not equal to zero to avoid simulation errors of the program to 3 GHz to look if the antenna presents a good response in the UHF band of the RFID devices (2.5 Ghz).

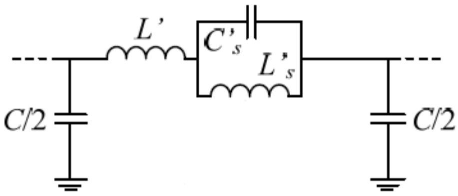


With a Sample Points Limit of 20 points we have a main idea of the response of the model that we're simulating. If we find a model that fits our expectations we can make this value higher with the penalizations of time when we do the simulation due to the high number of calculus.

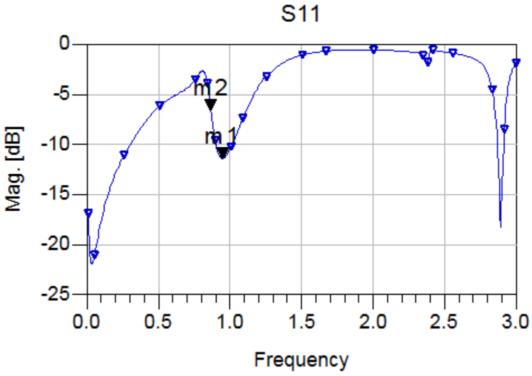
The first simulation is the unit cell without the aperture in the transmission line, we will do this step to test a fictional model and later appreciate the use of the partition in the slot line:



We can see here the circuit model of the designed structure:



This is the response of the simulation:



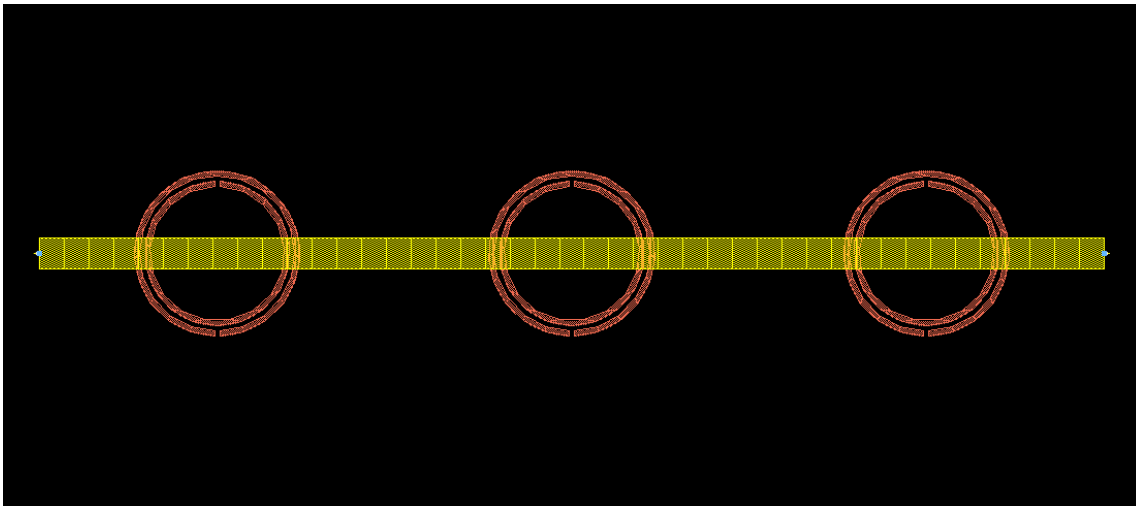
m1
freq=947.8MHz
dB(SplitRingwithTxLinewithSubstrate_mom_a..S(1,1))=-11.371
Valley

m2
freq=866.5MHz
dB(SplitRingwithTxLinewithSubstrate_mom_a..S(1,1))=-6.600

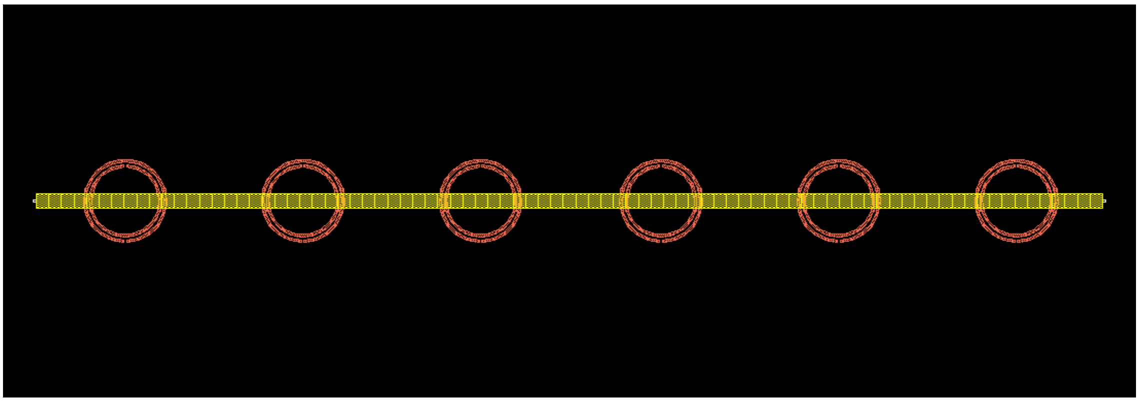
We can see that the values of the reflection function S11 have a good response between the 860 Mhz to 1.2 Ghz approximately, a value of -6.6 dB in our frequency work is a good value but the BW is not centered in this value. The maximum transmission corresponds to 947.8 Mhz, near the frequencies used in EEUU for RFID work.

We made the proves with a higher number of cells, 3 rings and 6 rings. To test if the use of more cells improves the response of the reflection matrix.

- 3 Rings model:

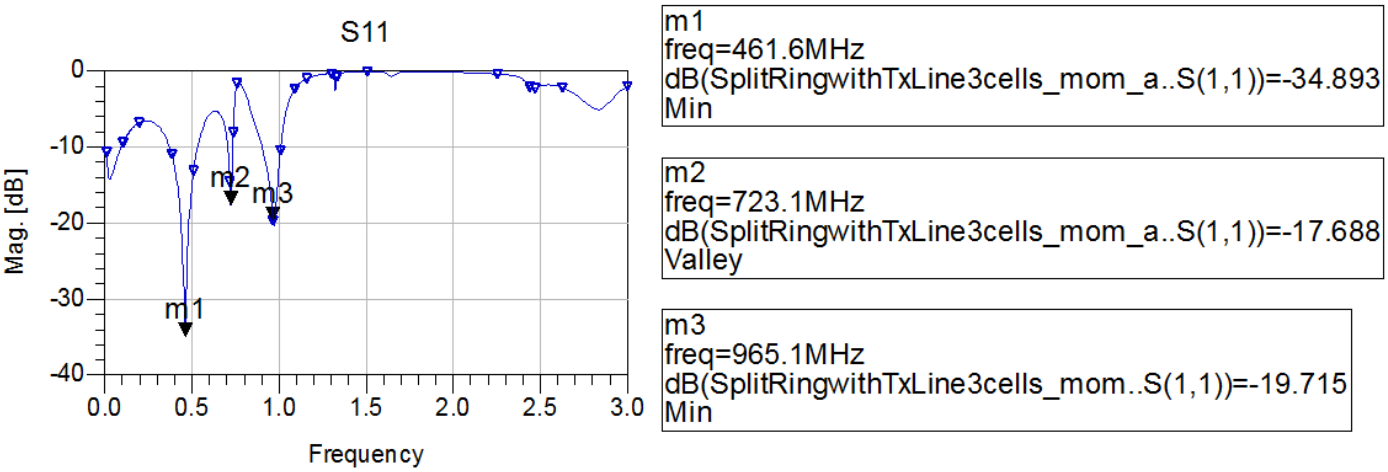


- 9 rings model:



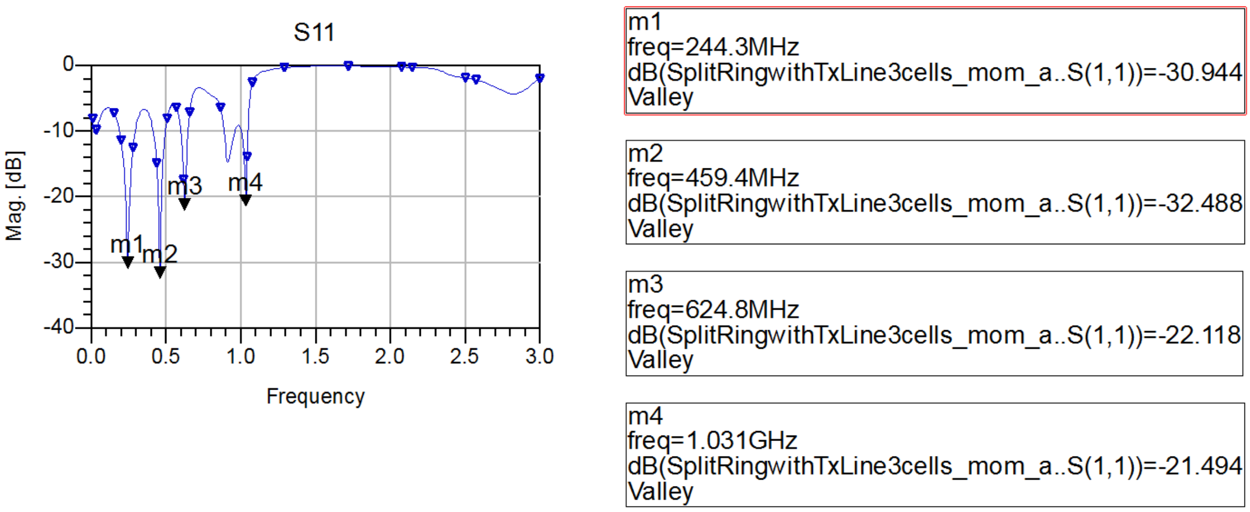
Before the results of the Momentum simulation we can appreciate that the total length of the antenna is too much bigger than the usual RFID models, in the model of 3 cells we have a total value of 20.5 cm and, for the model of 9 rings , a total length of 41 cm.

- 3 Rings model S11 function:



We can see that the response doesn't improve with the number of cells, unlike the results expected we have a group of values which are not relevant for our design.

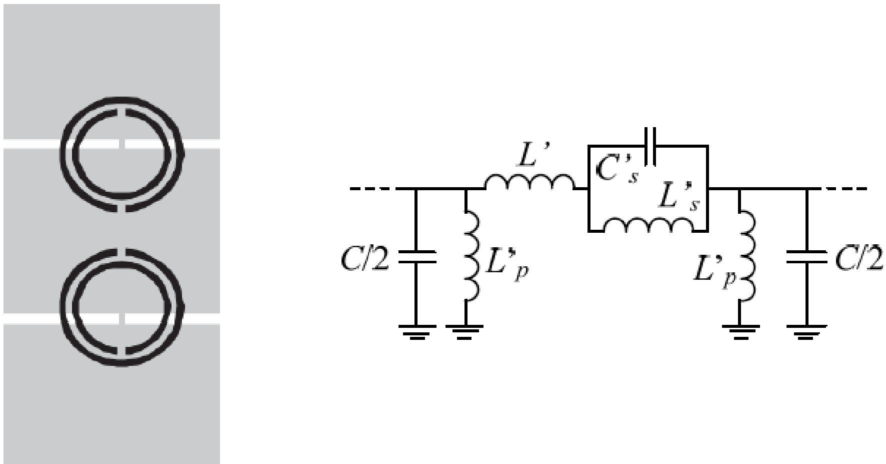
- 9 Rings model S11 function:



We left behind this structure model for undesired results, the peaks of the response don't work; the Q values of the bandwidth are too high and the firsts peaks are in too low frequencies.

Chapter 2: Design of a Balanced CRLH CPW Transmission Line

The propagation characteristics of a CRLH CPW transmission line based on Split Ring Resonators and wires can be obtained through the analysis of the dispersion relation. This can be inferred from the lumped element equivalent-circuit model of the elemental cell of the next image:



The lumped elements of this equivalent-circuit model are given by the next equations:

$$L' = \left(2 + \frac{L}{L_p}\right)\frac{L}{2} - L_s'$$

$$L_P' = 2L_p + \frac{L}{2}$$

$$L_s' = 2\omega_0^2 M^2 C_s \frac{\left(1 + \frac{L}{4L_p}\right)^2}{1 + \frac{M^2}{2L_p L_s}}$$

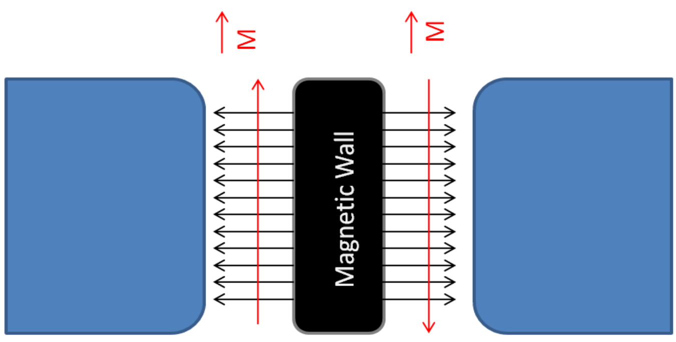
$$C_s' = \frac{L_s}{2\omega_0^2 M^2}\left(\frac{1+\frac{M^2}{4L_pL_s}}{1+\frac{L}{4L_p}}\right)^2$$

In this equations L and C are the per-section inductance and capacitance of the host CPW, Lp is the equivalent inductance of the connecting wires. If we take a look in the "First simulations" section, the model developed is a MNG line without this inductance in the design and in the circuit-equivalent model.

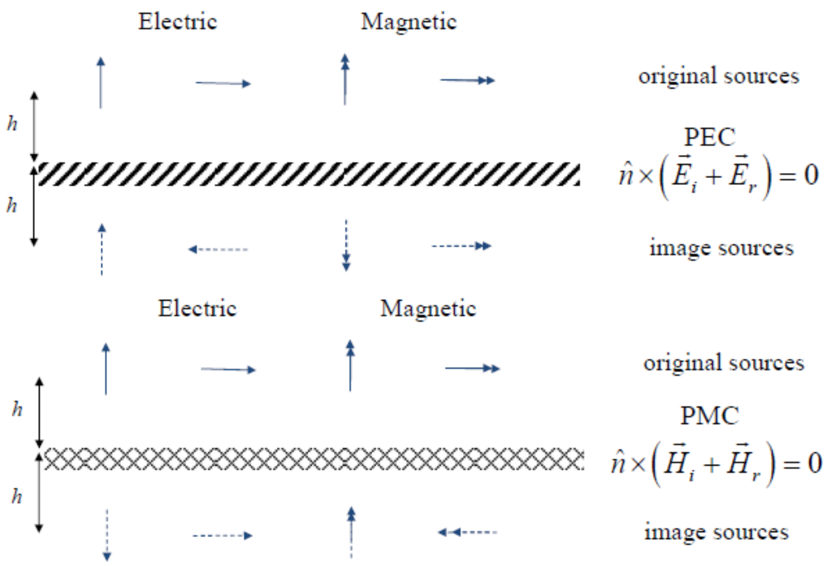
The mutual inductance M induces the parallel resonant tanks which are modeled by the SRRs with inductance Ls and capacitance Cs. The resonance frequency of the circuit is done by:

$$\omega_0^2 = \frac{1}{LsCs} = \frac{1}{L_s'C_s'}$$

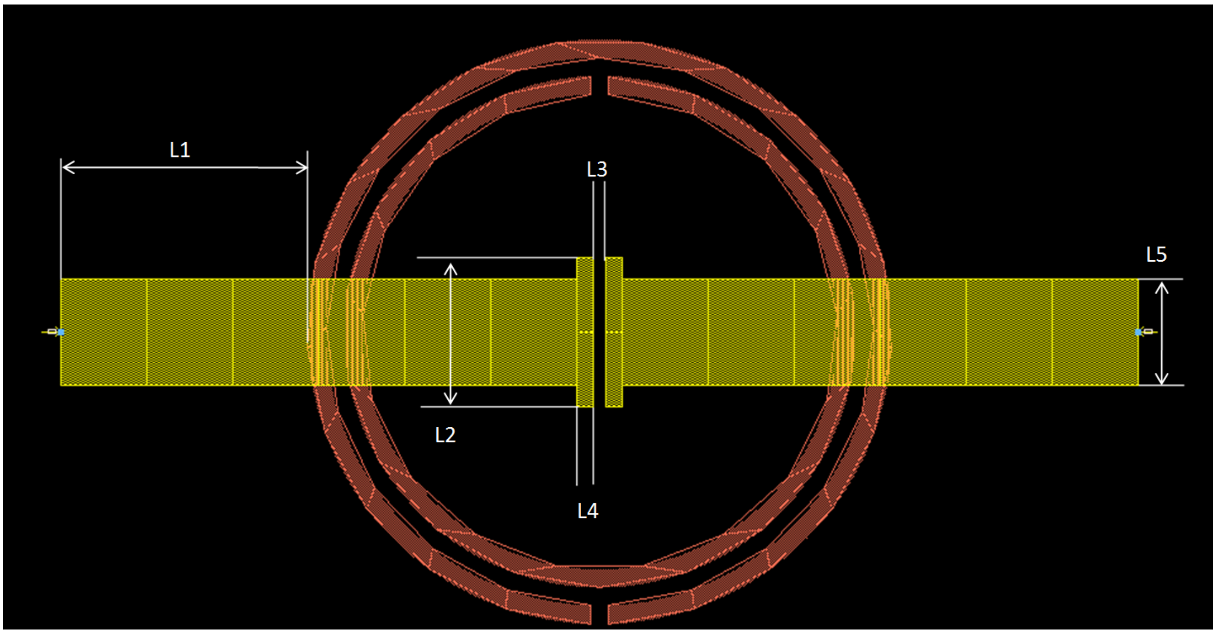
The model designed pretends to have a magnetic wall in the symmetry plane, to suppose a significant cancellation of the far field, as occurs in a dipole antenna parallel to a tiny close electric conductor, an asymmetry was forced by removing the set of the SRRs present at one of the sides of the symmetry plane of the CPW.



By Image theory if the electric original source is parallel to the ground plane the reflected field is generated by a image source positioned a similar distance that the original source from the ground plane.



Here we have the design of the final model cell, as we have done with the MNG design we will preserve the relation of measures done by the Leaky-Wave Antenna using Slotline and SRRs.



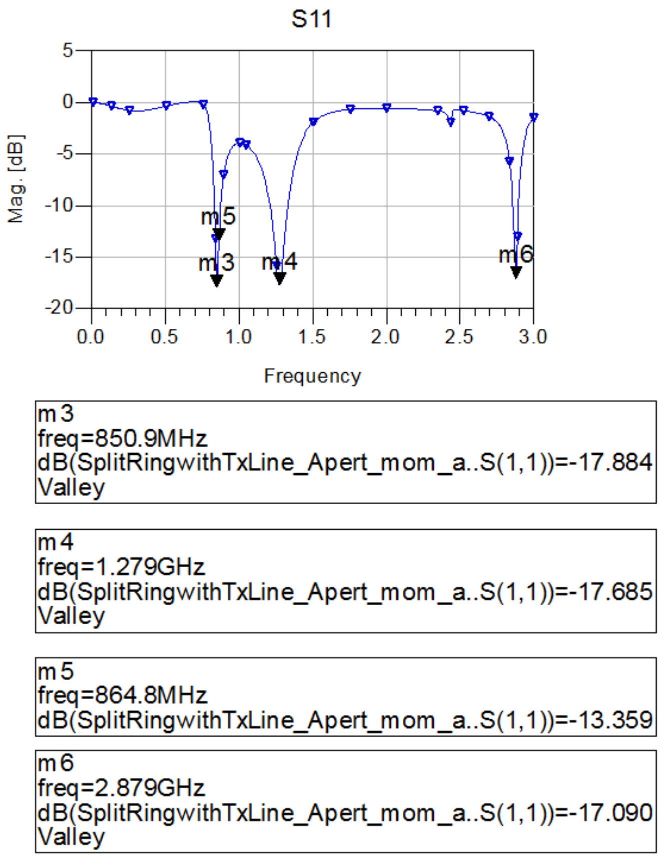
The summary of the total measures of the design have been included in the next table:

Design part	Length/cm
Ring Diameter	1.6
Ring Width	0.1
Distance between Rings	0.1
Ring slot	0.1
Total length transmission line	6.836
L1	1.8178
L2	0.8147
L3	0.0727
L4	0.0872
L5	0.582

Simulation of the SRR-based CRLH line

We proceed with the simulation of the SRR-based CRLH line using Momentum and the simulation of the S-parameters, with a frequency range identical to the one used in the MNG line, from 10 Mhz to 3 Ghz.

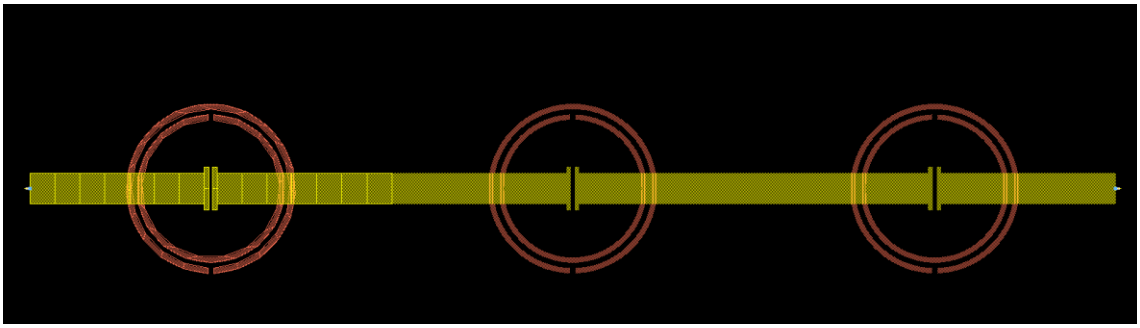
Results of the simulation are the following ones:

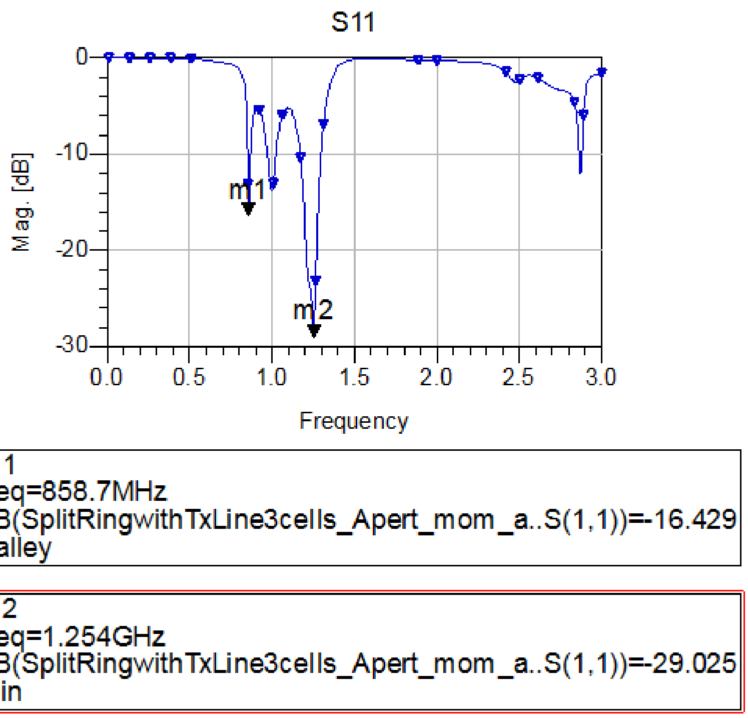


We can see a good response in interesting bands, with a Bandwidth which begins at 820 MHz and finish at 1.3GHz and peaks in 850 MHz and 1.28 GHz and a good value for the European RFID response (865 MHz).

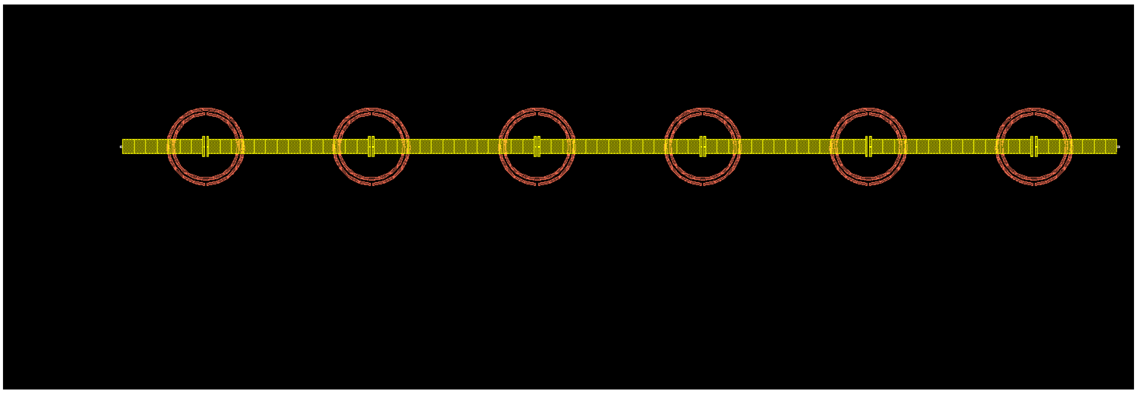
The simulations of the models with 3 cells and 6 cells are the following ones:

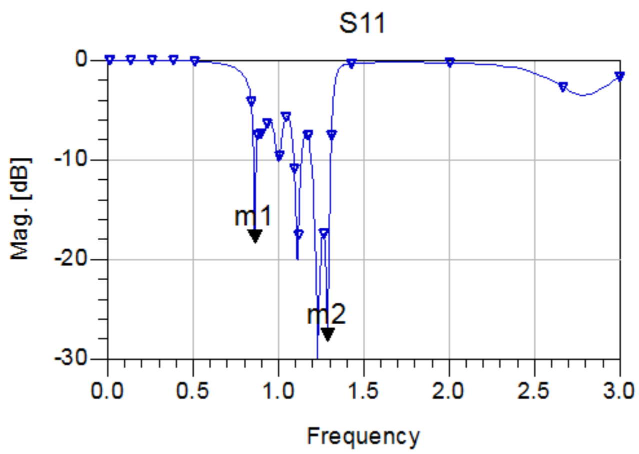
- 3 rings model:





- 6 rings model:





m1
freq=861.3MHz
dB(SplitRingwithTxLine6cells_Apert_mom_a..S(1,1))=-18.363
Valley

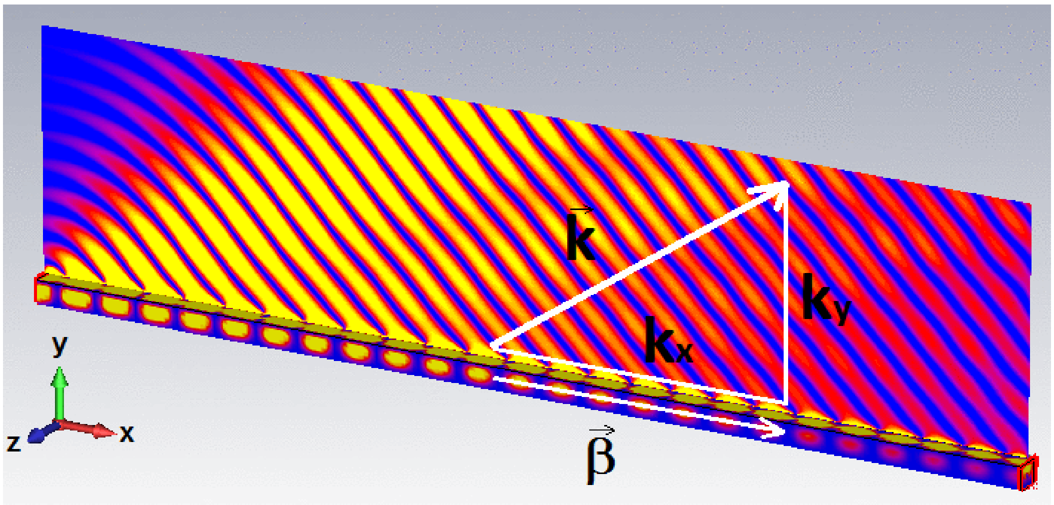
m2
freq=1.288GHz
dB(SplitRingwithTxLine6cells_Apert_mom_a..S(1,1))=-28.266
Valley

We can see here better results than in the MNG line, with the capability to operate in a range of frequencies which are not going down if the number of cells grow. All configurations present a good balance near the 865 MHz.

Evanescent wave

The control of the electromagnetic field distribution over the space is of fundamental importance where we need an interaction between the field and the reader. Evanescent wave coupling has been considered to define a region instead the use of energy leakage in form of radiation to acquire more precision. The field intensity of the evanescent wave decreases exponentially with distance and is not able to radiate. with this method the objects inside the small reading distance are detected, whereas those outside this region are ignored.

Returning to the basic cell model if we try to illustrate the propagation of the wave in the metamaterial structure travelling through the x-y plane we have a model similar to this one :



Where β corresponds to the wave vector of the wave which is traveling along the split rings and *k* vector is the wave which is propagating in the surrounding medium .

We can modify the vector β choosing the effective dielectric permittivity (ε) and the effective magnetic permeability (μ) of the structure. To ensure compliance with the relations of continuity at the interface between the metamaterial structure and the surronding environment the magnitude of β must be equal to k_x. So if:

$$k^2 = k_x^2 + k_y^2 = \beta^2 + k_y^2$$

$$k_y = \pm\sqrt{k^2 - \beta^2}$$

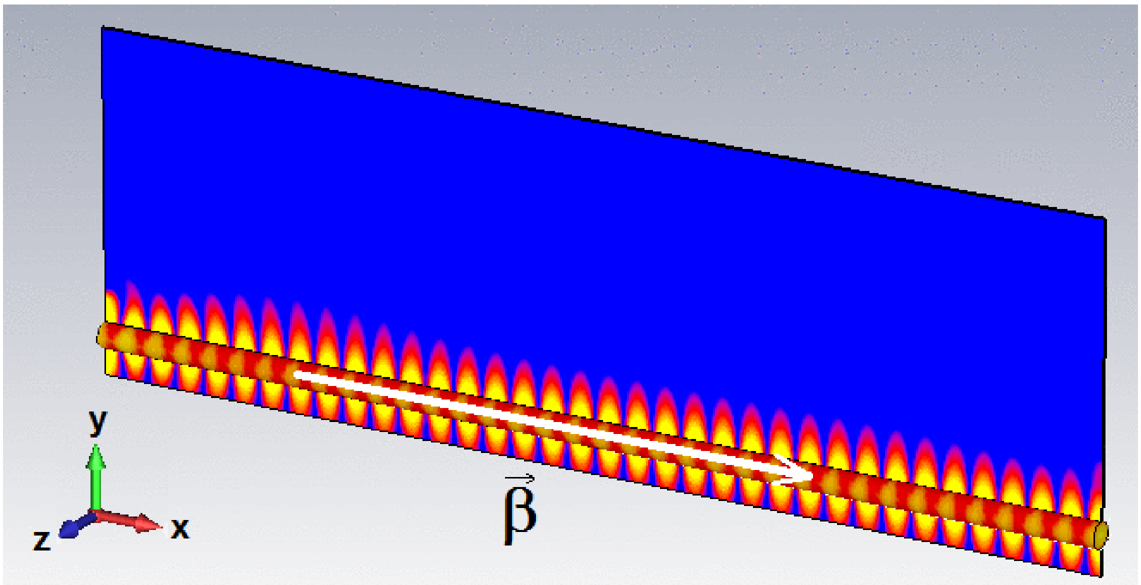
Real values of k_y lead to radiative solutions (here β determined the direction of the radiated beam), imaginary values of k_y give rise to evanescent solution inside the general solution of plane wave propagation in free space:

$$A_i(x, y, t) = A_i e^{-jkr} e^{jwt} = A_i e^{-jKxx} e^{-\alpha y} e^{jwt}$$

Where:

$$\alpha = |\beta^2 - k^2|$$

Is a positive real number that supposes an exponential decrease of the electric and magnetic fields with distance in the broadside direction (y direction).



The value of β can be adjusted in the design stage of the metamaterial structure, it's possible to impose the level of confinement of the electromagnetic field around the structure.

The parameter 1/α can be defined as the distance that determines the maximum length where the field will be present. The attenuation of 99% with respect to the field at the surface of the device corresponds to a distance of 5*(1/α).

Chapter 3: Analysis of the model as a function of the length of the line.

In this case, to analyze and optimize the range of the evanescent wave and other parameters like the phase coefficient or the matrix of scattering parameters, we're going to do an empirical study with the ADS Momentum simulator with different lengths of the line and extract the pertinent conclusions.

The lengths have been elected by cutting (or adding) different sections of the mesh created by the simulator in the first model simulations. This distance corresponds to 94.13 mm between one model and the upper (or downer) one. The accuracy on the length values only corresponds to a work protocol elected and comfort with the ADS Mesh-tools. The values work as a guide for future improvement of the model.

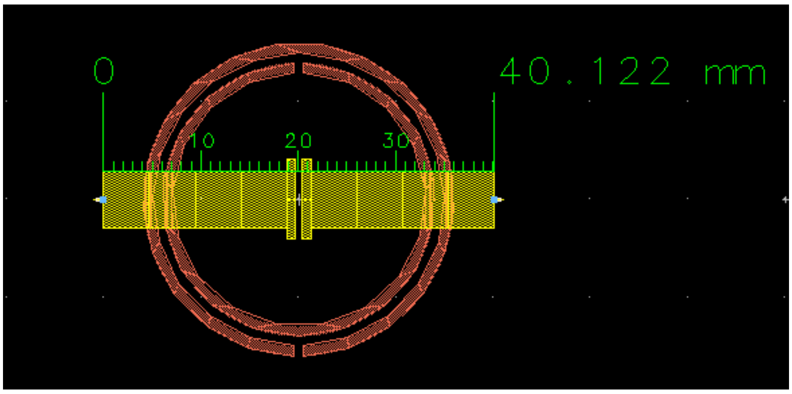
So the models studied have the lengths showed in the next table:

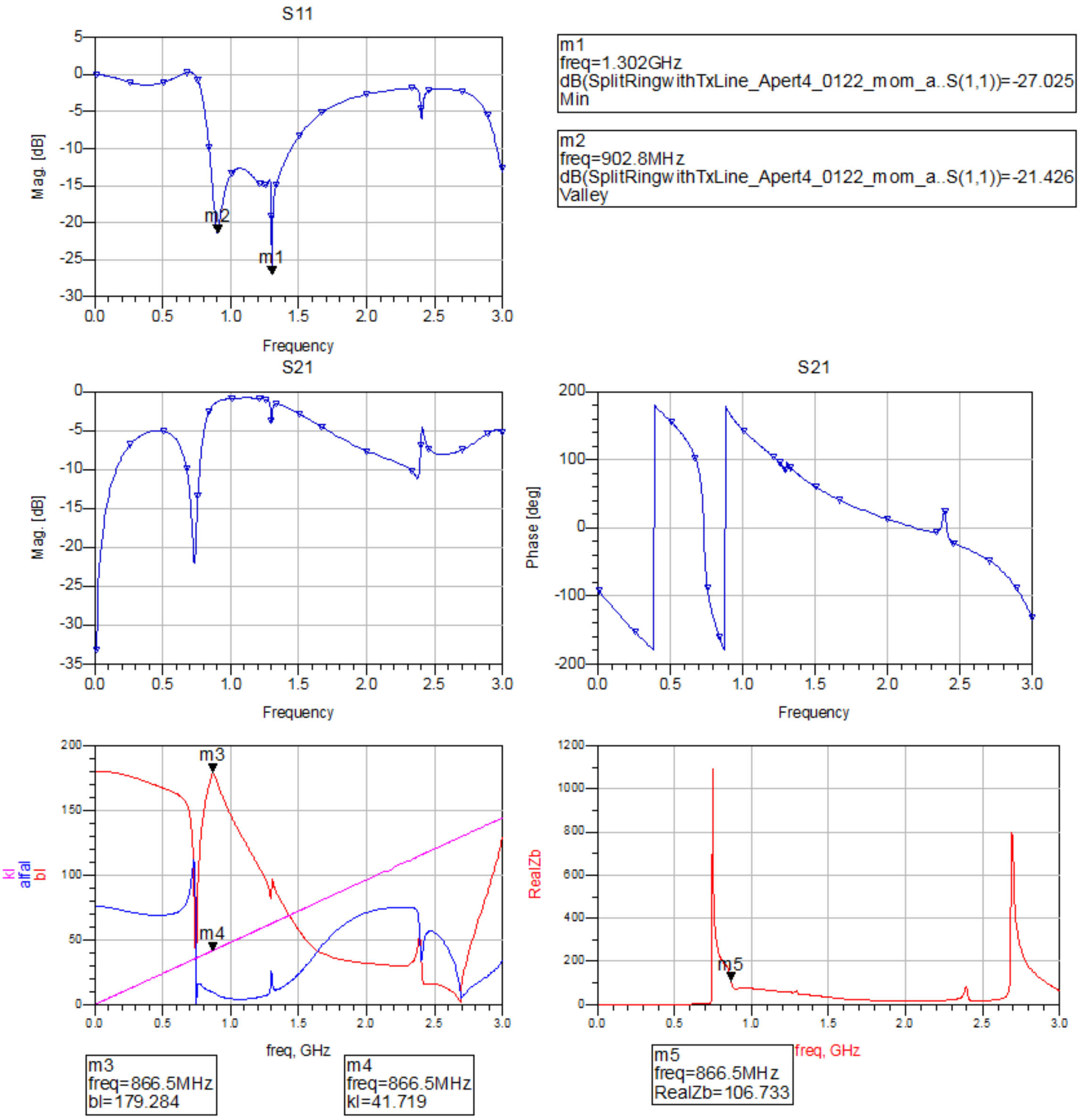
Model number	**Length**
Model nº 1	40.122 mm
Model nº 2	49.535 mm
Model nº 3	58.947 mm
Model nº 4	68.360 mm
Model nº 5	77.773 mm
Model nº 6	87.185 mm

Model nº4 is the basic one, the transformations of the line have been made through this one. Only the lenght in the z axis has been alterated, the other dimensions remain equal in every model. The diameter of the ring remains equal too.

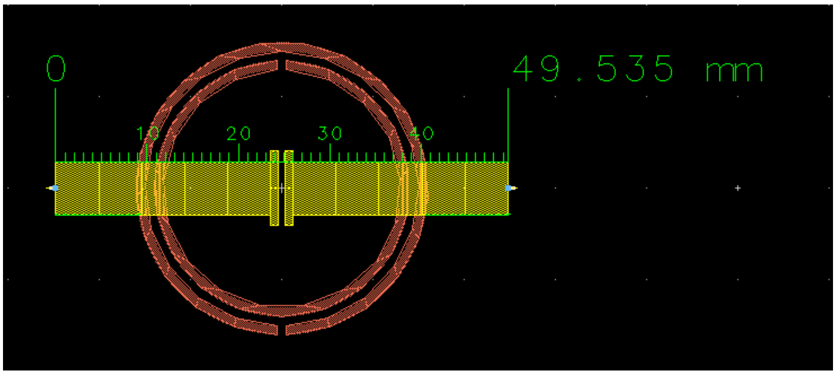
The simulation of the S parameters sweeps the frecuencies until 3 Ghz, with a number of points in simulation from 20 to 100, when the circunstances require more points to improve the definition. These are the same values that the ones simulated in the chapter *First Simulations.*

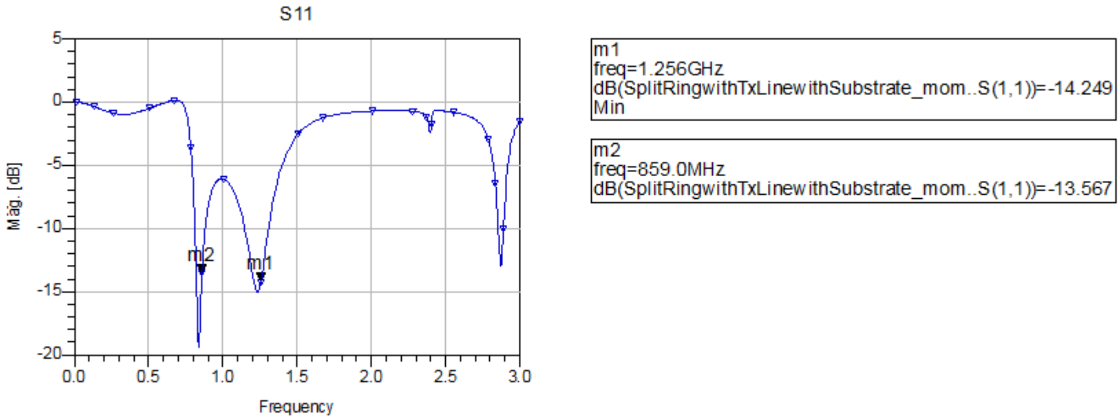
- Model nº1 (40.122 mm)

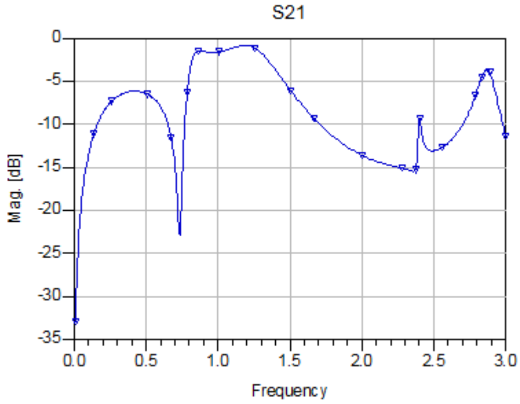


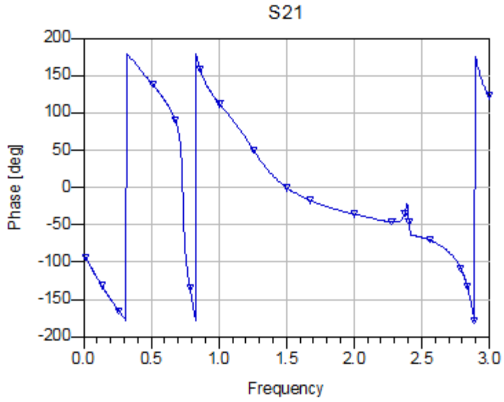


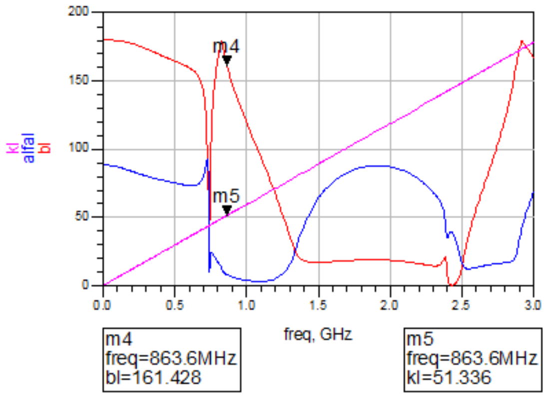
- Model nº2 (49.535 mm)

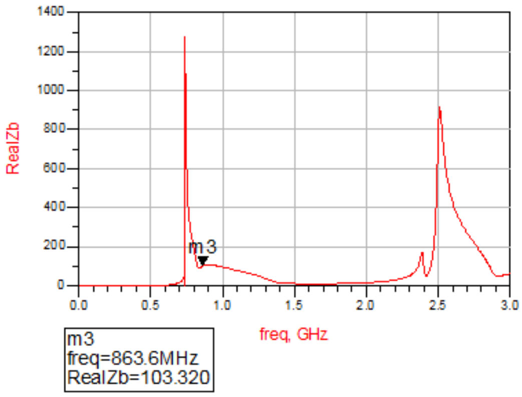




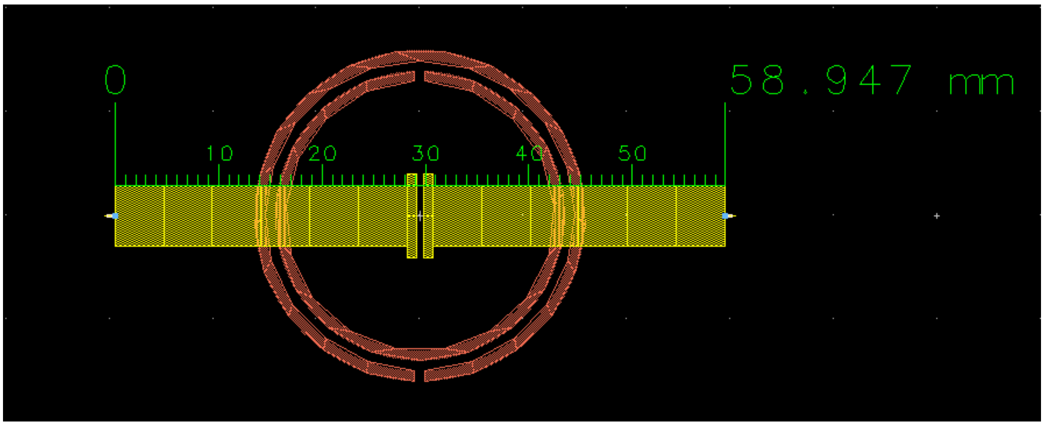


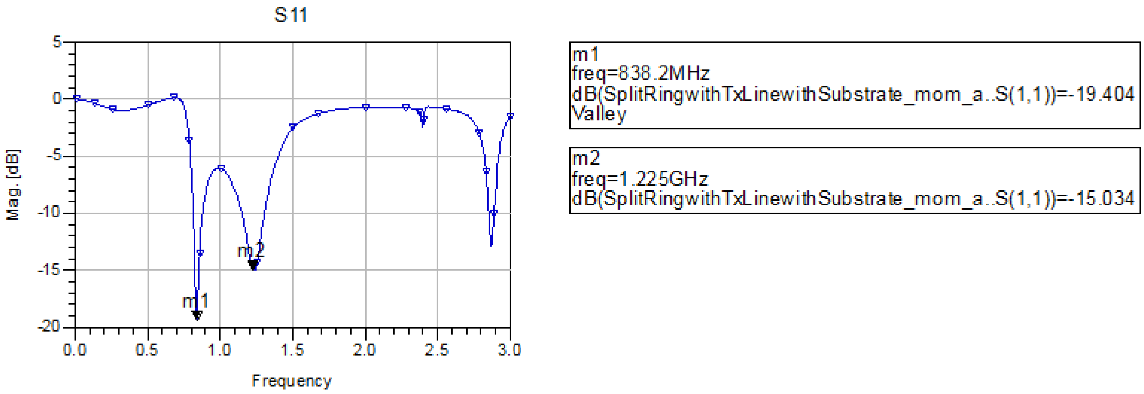


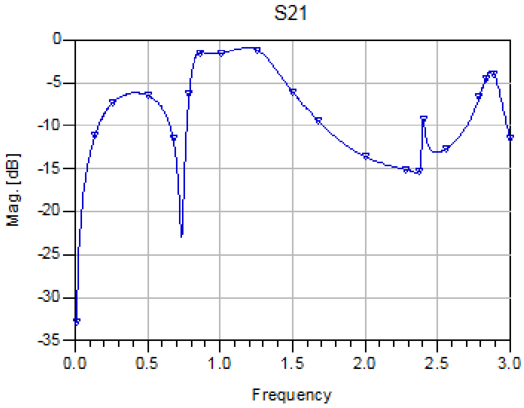


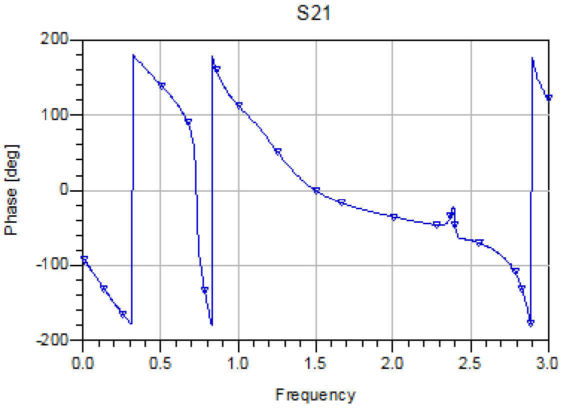


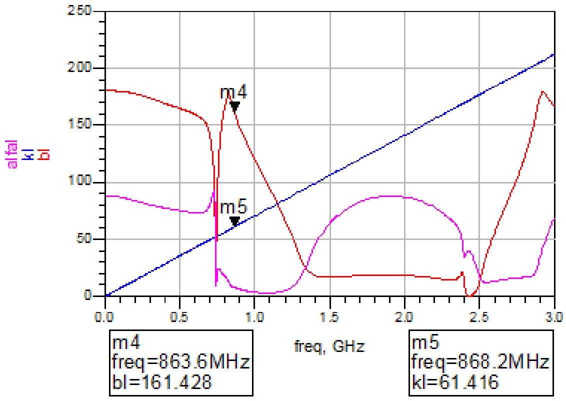
- Model nº3 (58.947 mm)

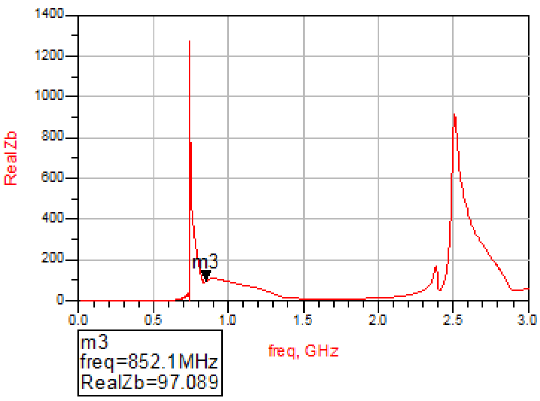




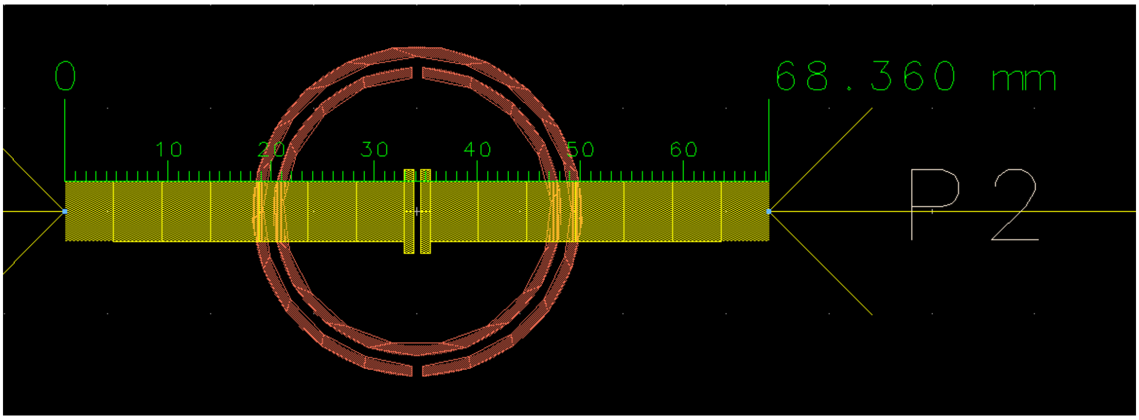


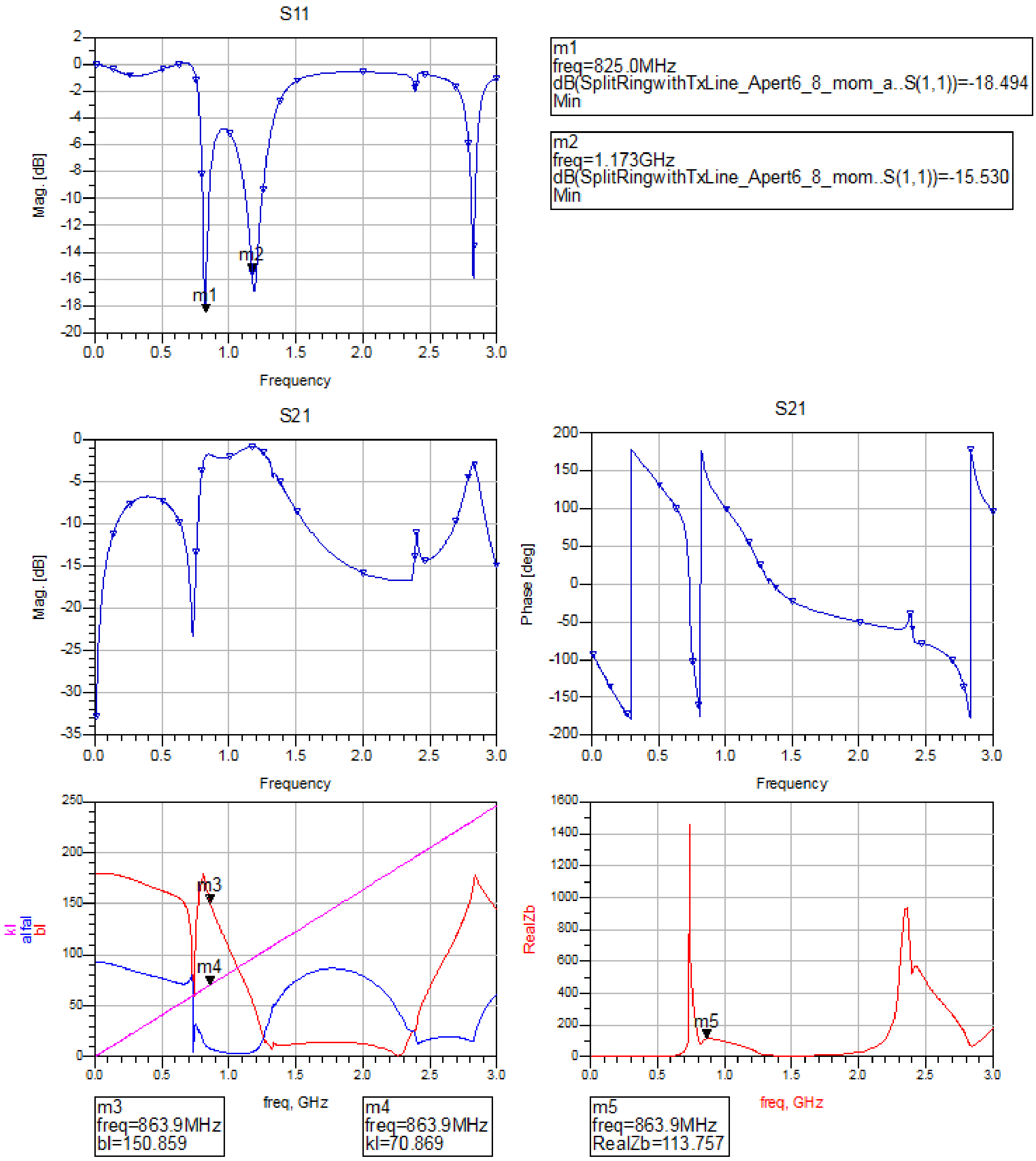




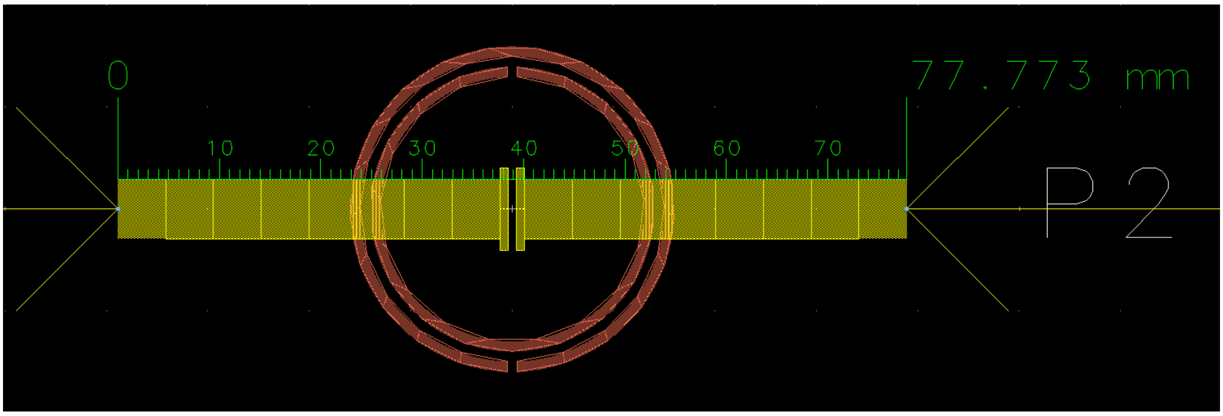


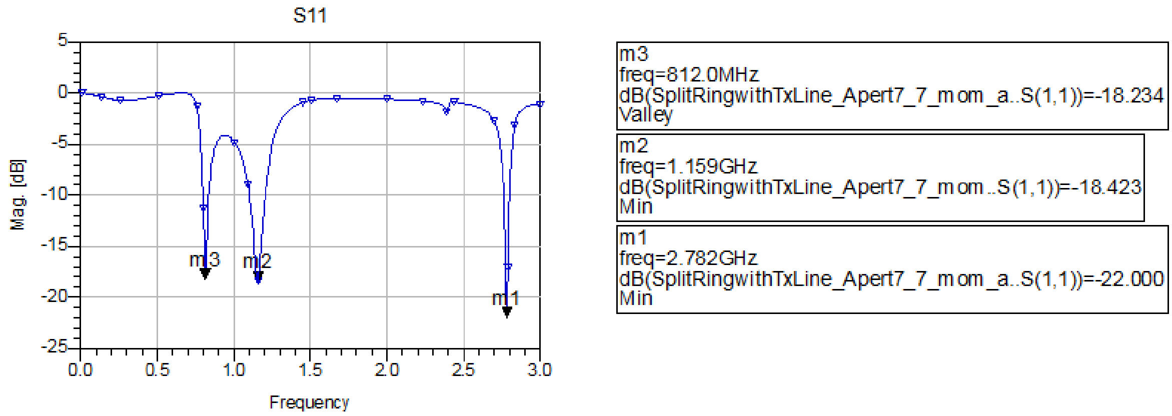
- Model nº4 (68.360 mm)

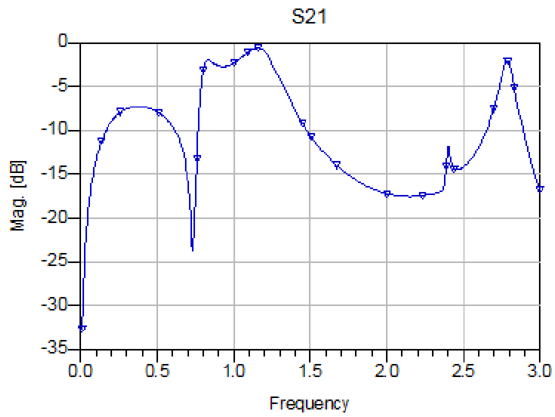


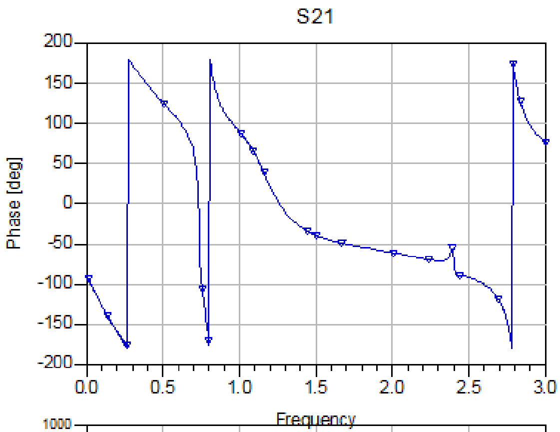


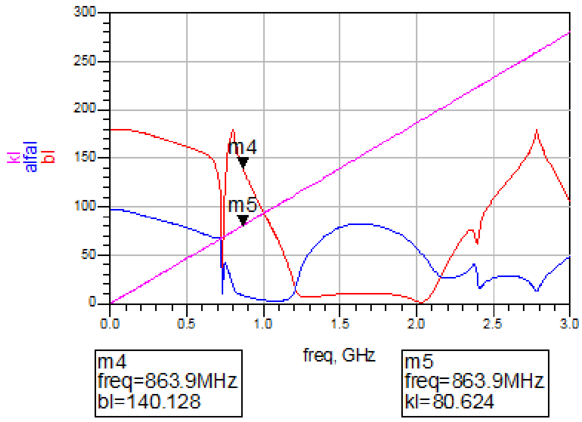
- Model nº5 (77.773 mm)

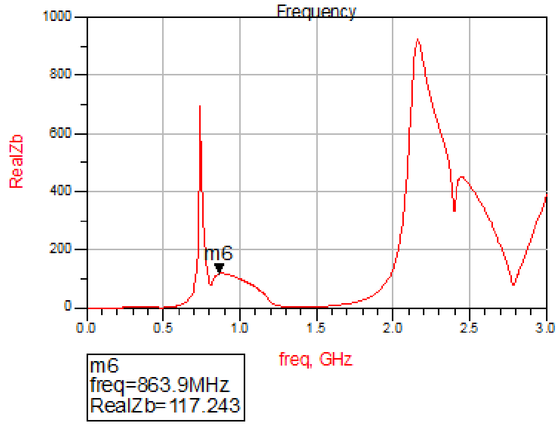




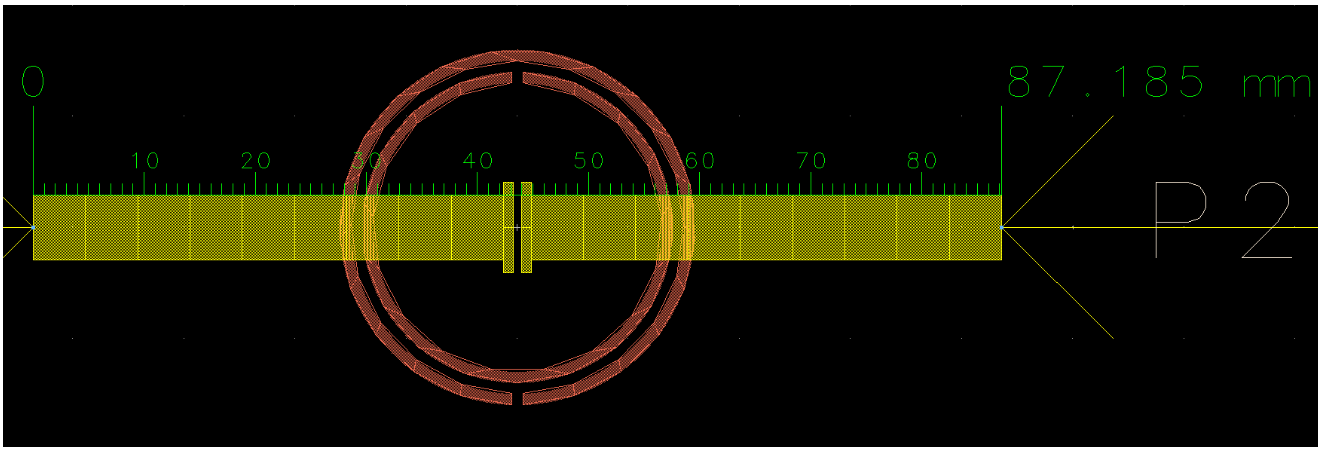


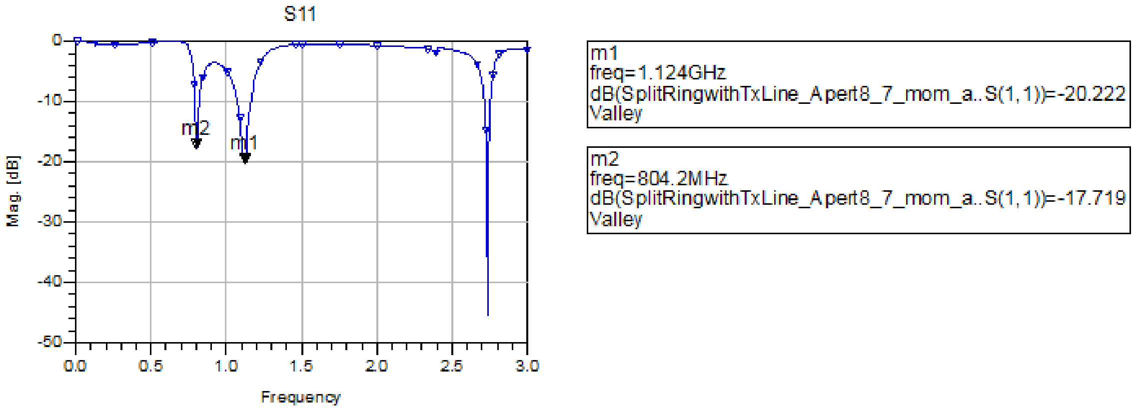


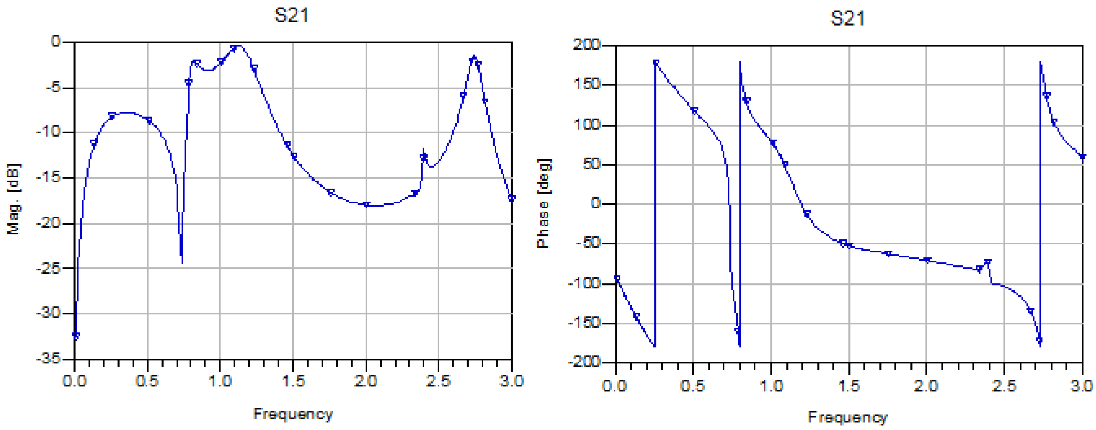


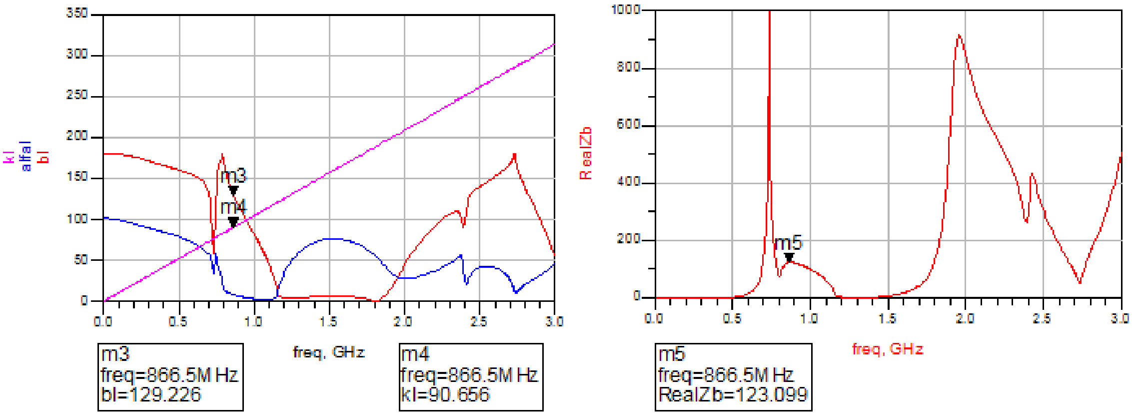


- Model nº6 (87.185 mm)









The next table synthesizes the most relevant parameters:

Length of the line (mm)	βl	kl	Zb (Ω)	α (wave)	Range (wave)	1st gap	2nd gap
40.122 mm	179	41	106	5771	0.17 mm	902 Mhz	1.3 Ghz
49.535 mm	161	51	103	2888	0.35 mm	859 Mhz	1.25 Ghz
58.947 mm	161	61	97	1949	0.51 mm	838 Mhz	1.22 Ghz
68.360 mm	150	70	113	1150	0.86 mm	825 Mhz	1.17 Ghz
77.773 mm	140	80	117	665	1.5 mm	812 Mhz	1.16 Ghz
87.185 mm	129	90	123	341	2.9 mm	804 Mhz	1.12 Ghz

Through the table we can extract the following conclusions:

- Model nº1 doesn't work in the LF band, there's a point between model nº1 and model nº2 where the length of the line become's useful to our purpose.
- The bandwidth of useful frequencies tends to take lower values if the line grows (902 Mhz at 40 mm and 804 Mhz at 87 mm). Values in the second gap are not valid to work in the UHF band of the RFID devices.
- The Bloch impedance tends to grow with the length of the line in the frequencies of interest (867 Mhz).
- The distance between phase constant and the vector k decreases significantly. But not enough to achieve evanescent waves with a read range upper to 3 mm.

Analysis of the model as a function of the diameter of the ring.

We have seen in the previous section an analysis of the model in function of the length of the line to optimize the parameters of the model. In this case we're going to do a similar analysis but playing with the diameter of the ring.

We expect to reduce the distance between the value of the β and the *k* vector to decrease the absorption coefficient (α) of the evanescent wave and get a better range for this one.

All the models have been tested with a length of 59.947 mm which corresponds to the nº3 model of the previous section. The radius increments are steps of 2mm, from a 14 mm model to 24 mm model. The 16 mm model is the basic one, so it is not exposed here. We can see the performance of this one in the previous section.

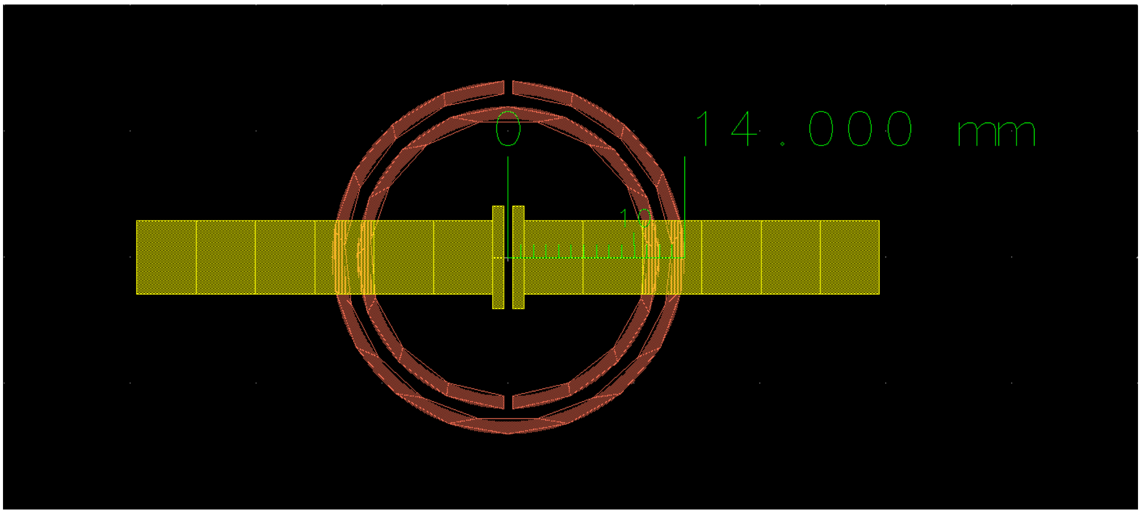
So the models studied have the radius showed in the next table:

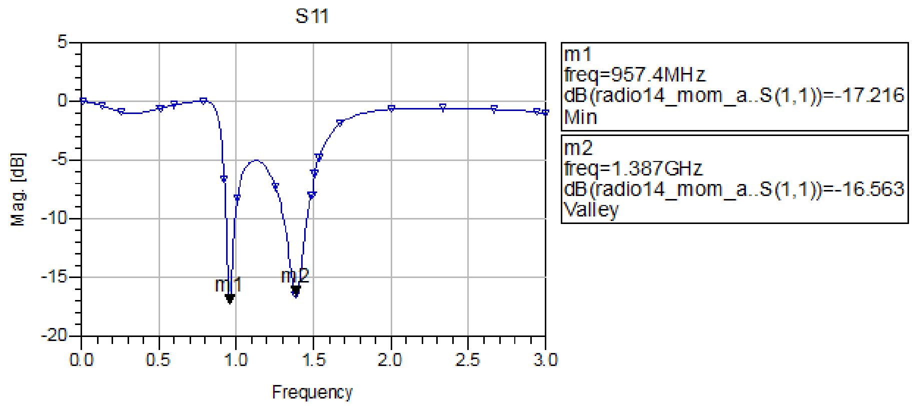
Model number	**Radius**
Model nº 1	14 mm
Model nº 2	18 mm
Model nº 3	20 mm
Model nº 4	22 mm
Model nº 5	24 mm

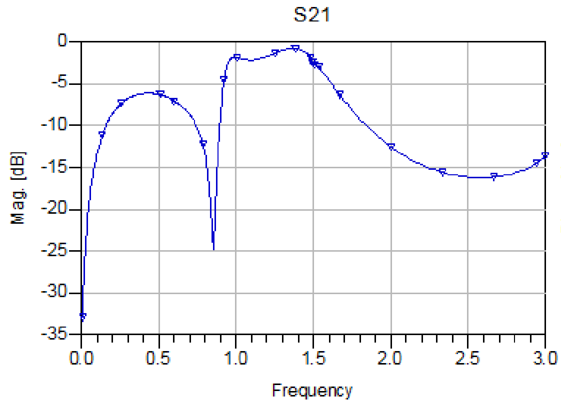
The purpose of this chapter is the same that the previous one, extract conclusions for a future improved design inside of an advanced disposition of the reader. With more information of the basic cell structure we can achieve the desired parameters in the structures that will be developed after.

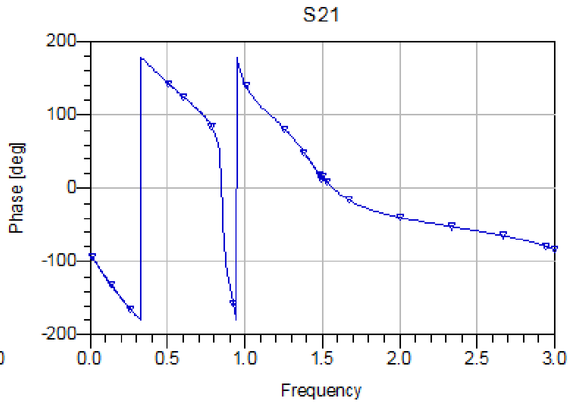
The simulations of the S parameters are the same ones of the previous section.

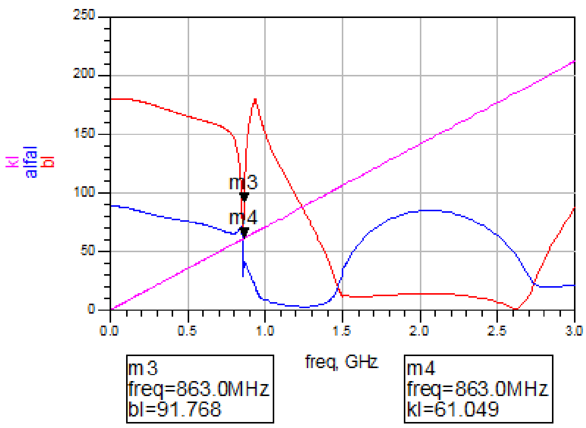
- Model nº1 (14 mm)

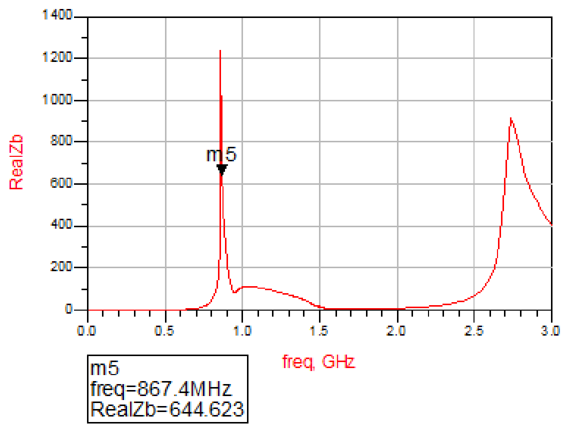




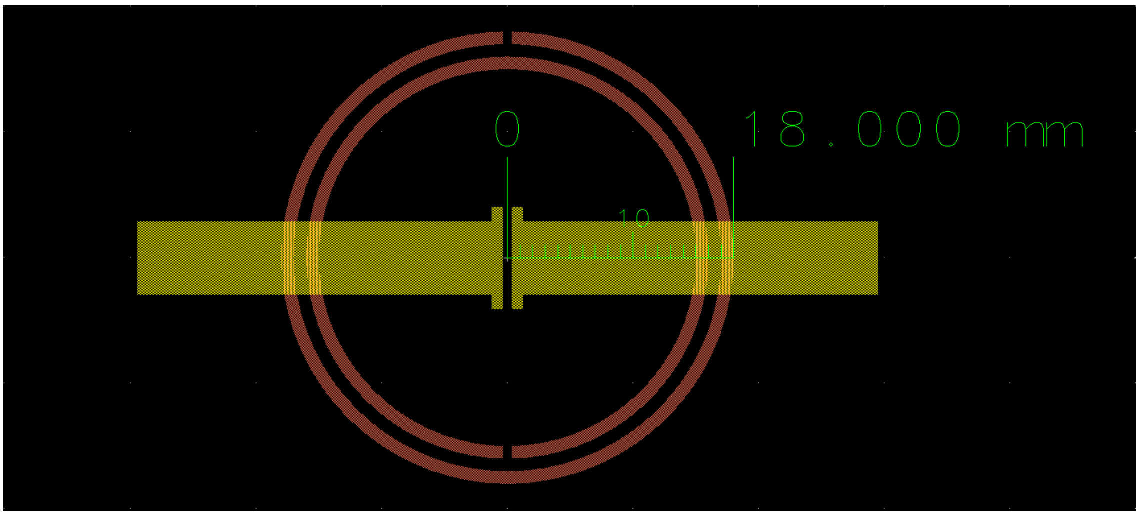


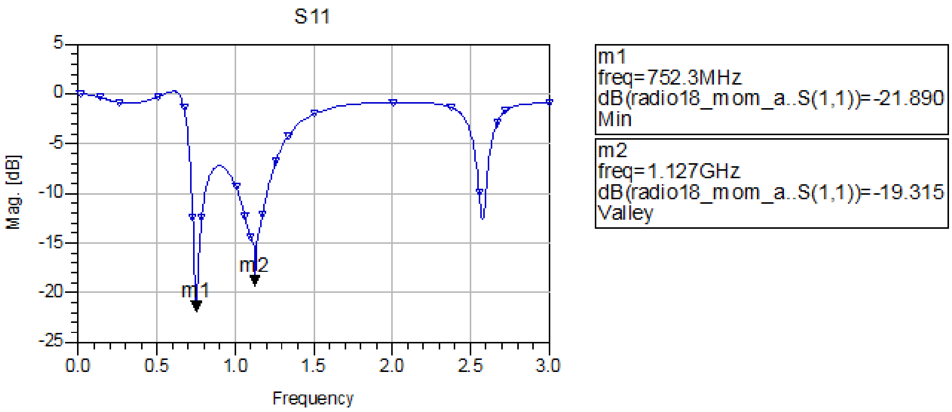


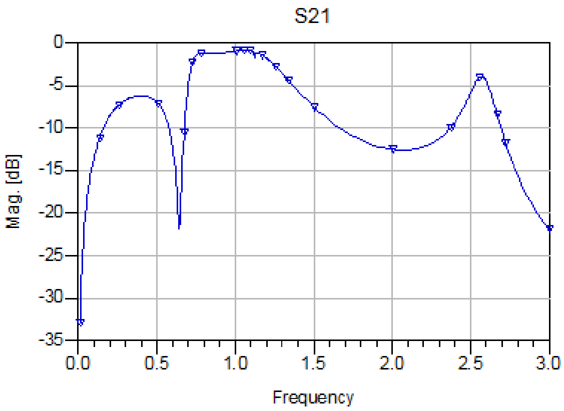


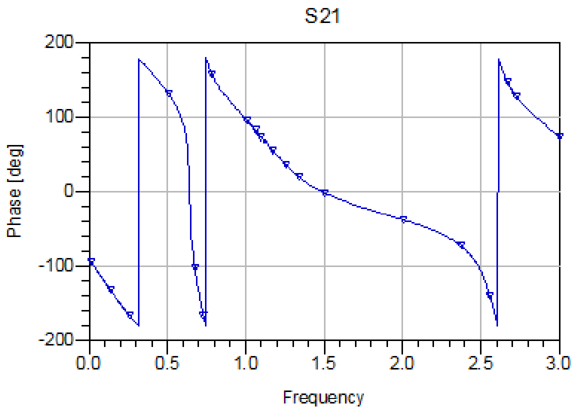


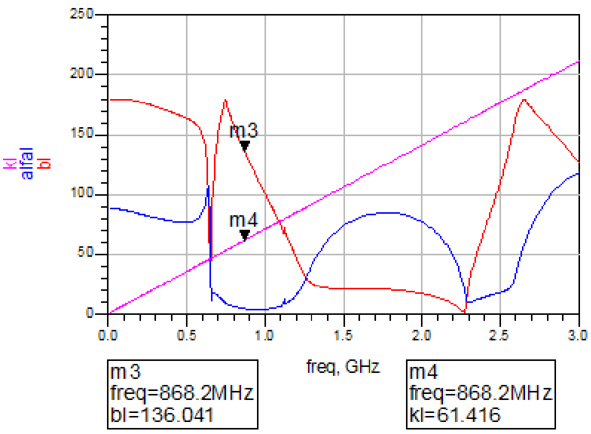
- Model nº2 (18 mm)

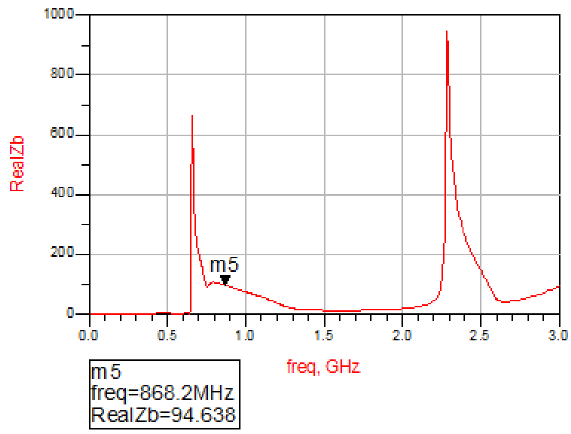




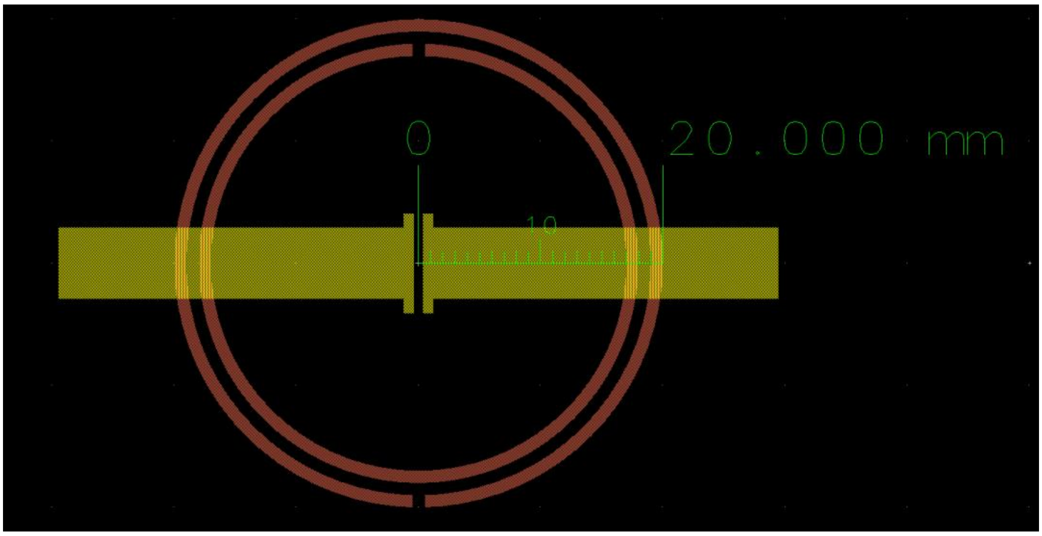


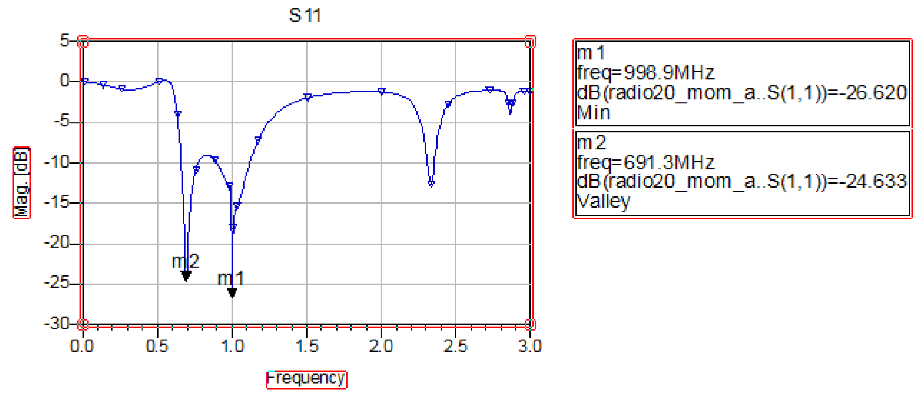


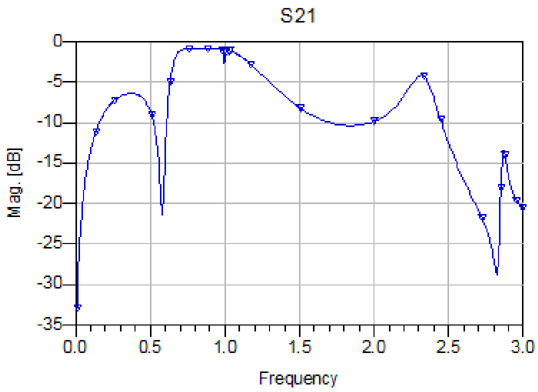


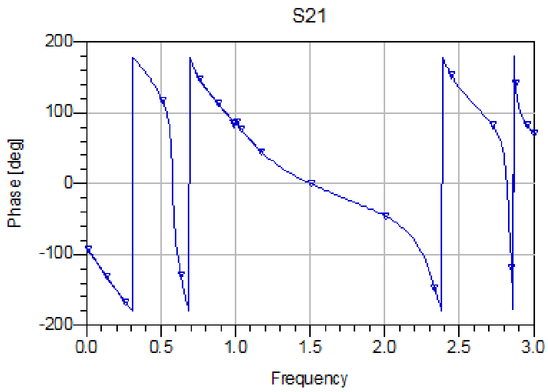


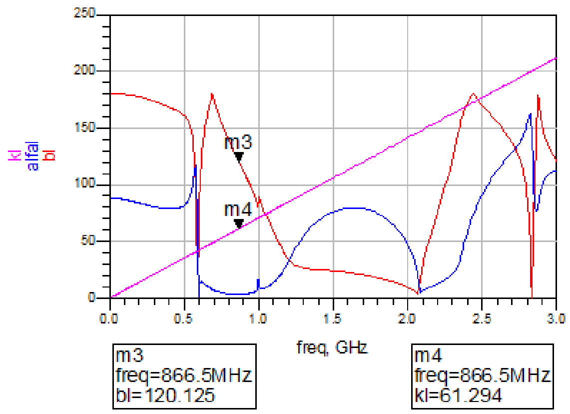
- Model nº3 (20 mm)

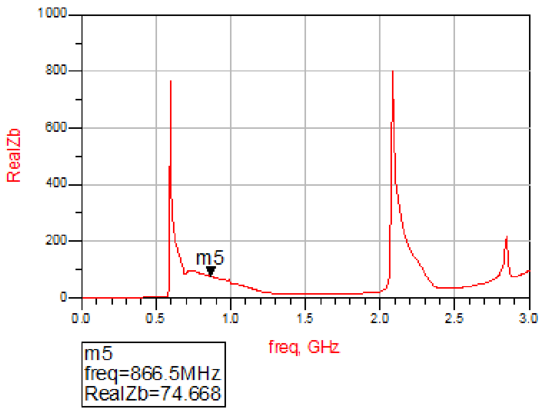




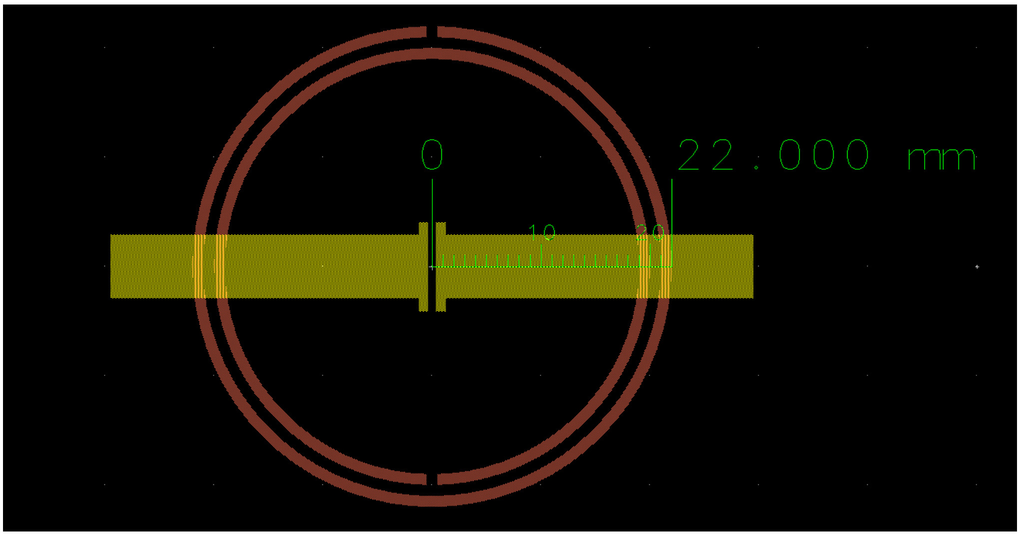


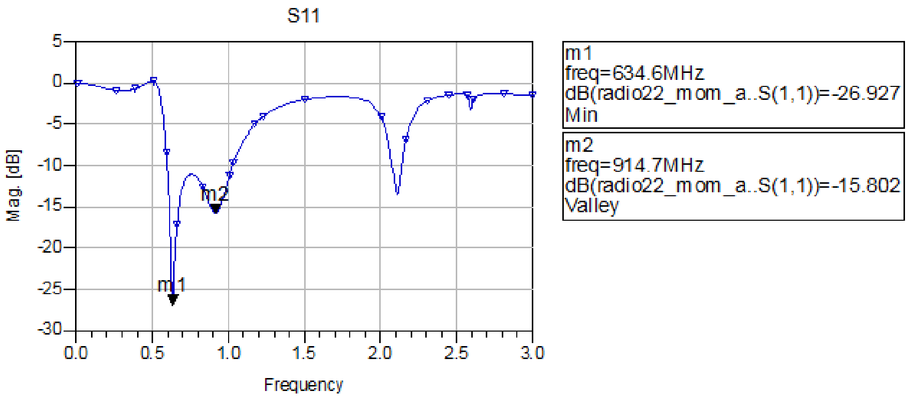


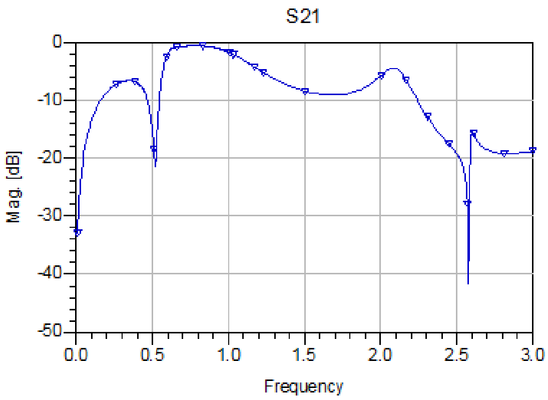


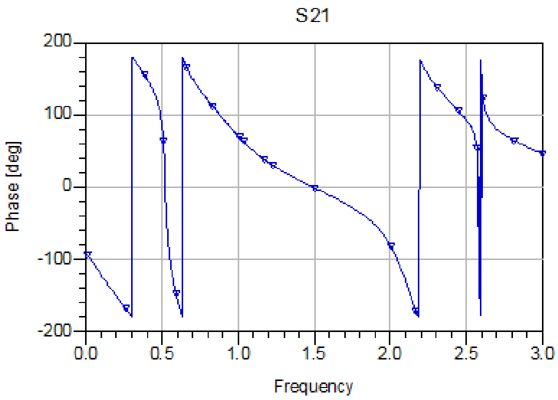


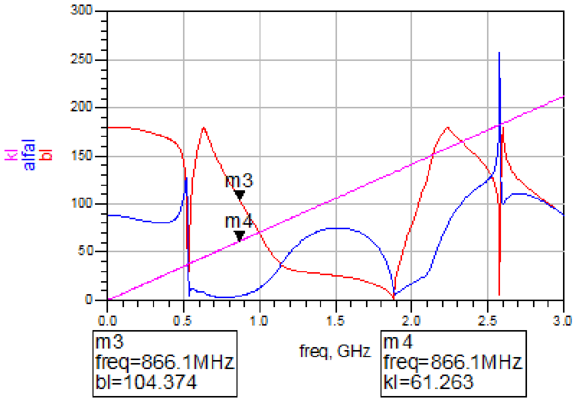
- Model nº4 (22 mm)

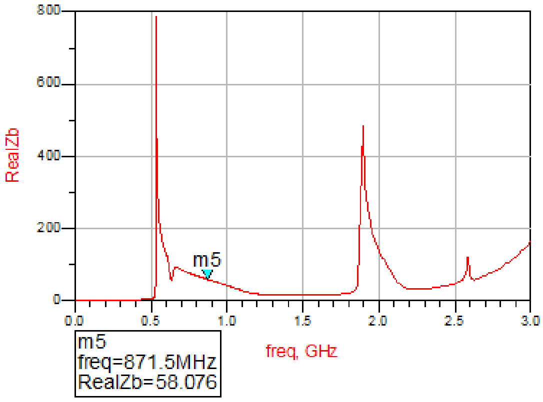




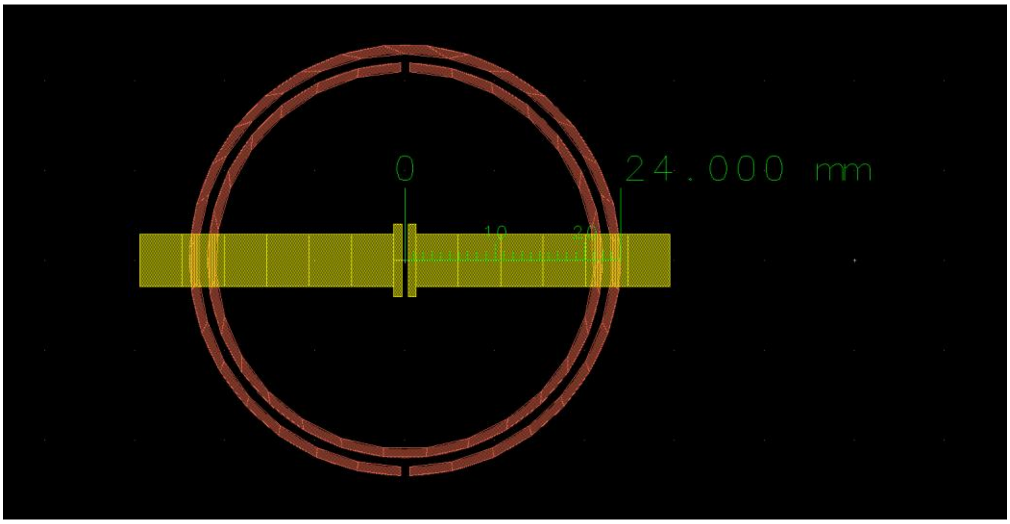


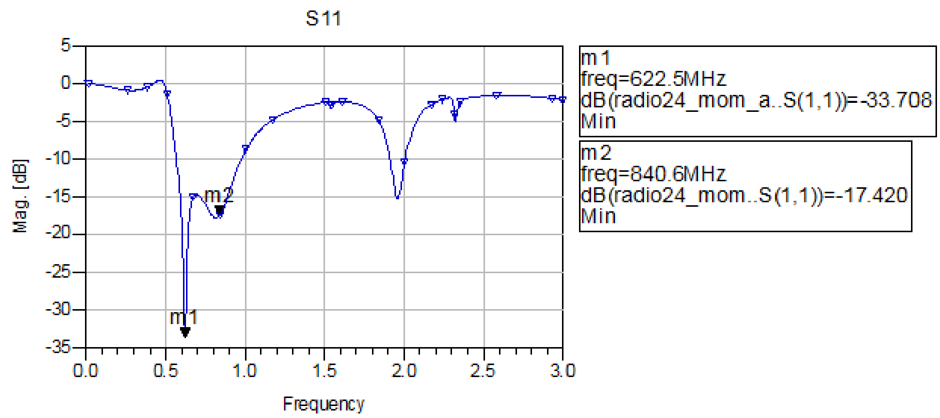


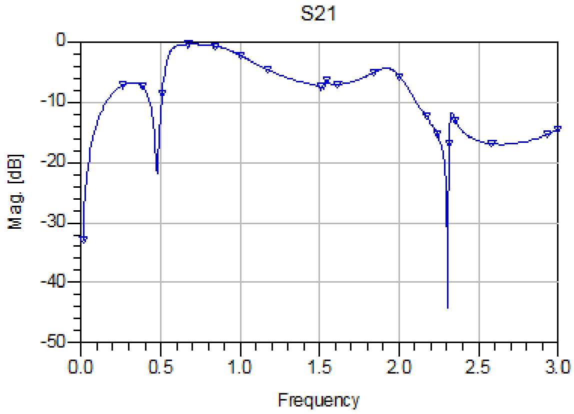


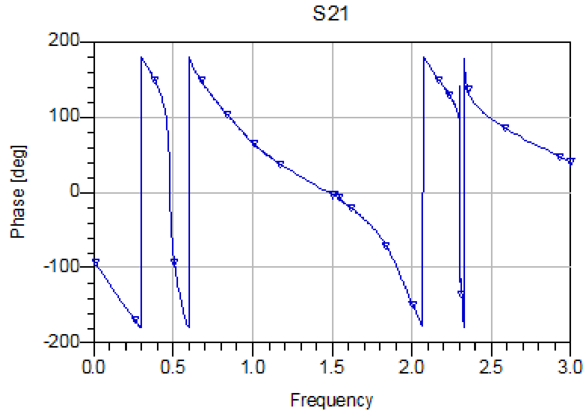


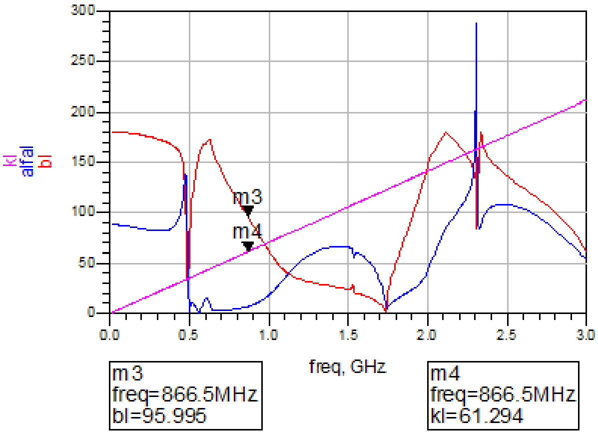
- Model nº5 (24 mm)

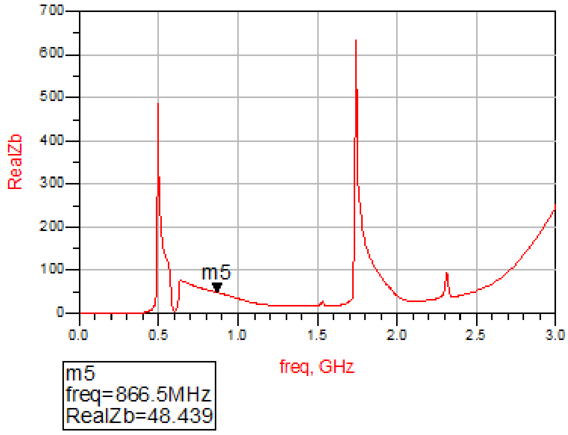












The next table synthesizes the most relevant parameters:

Radius of the line (mm)	βl	kl	Zb (Ω)	α (wave)	Range (wave)	1st gap	2nd gap
14 mm	92	61	644	423	2.3 mm	947 Mhz	1.38 Ghz
16 mm	161	61	97	1949	0.51 mm	838 Mhz	1.22 Ghz
18 mm	136	61	95	1294	1.1 mm	752 Mhz	1.12 Ghz
20 mm	120	61	75	934	1.07 mm	691 Mhz	1 Ghz
22 mm	104	61	58	630	1.59 mm	634 Mhz	914 Mhz
24 mm	96	61	48	489	2.04 mm	622 Mhz	840 Mhz

Through the table we can extract the following conclusions:

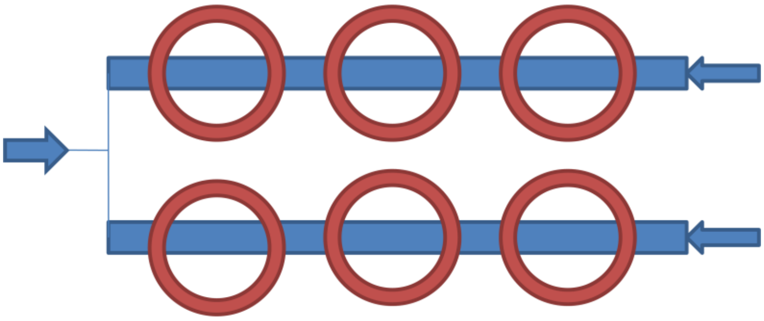
- Model nº1 clearly doesn't work in the LF band instead the values of βl and kl are nearer than in other models.
- The bandwidth of useful frequencies tends to take lower values if the radius of the ring grows (838 Mhz at 16 mm and 622 Mhz at 24 mm).
- The Bloch impedance descends drastically when the radius of the ring grows. The models upside the 18 mm of radius, presents values of Bloch impedances with which are hard to work.
- Vector k is a constant.
- The distance between phase constant and the vector k decreases significantly. But not enough to give relevant values.

Other similar studies, done with the basic cell, that are not described in this chapters are; the analysis of the width of the line and the length of the central gap that the structure presents in the line. Other similar studies, not developed in the project, are the width of the ring structures, the separation between the two rings and the gap that the rings present in their forms.

Chapter 4: Dual model

The next pages shows the beginning of the implementation of the dual model whit their graphic results and the analysis of the different lines and problems and conclusions that appears during the procedure.

To offer a better area-coverage to excite more RFID devices, the purpose of the chapter is the design of a model with two branches inside a structure that has a first port in one of its sides and two ports in parallel in the other one. Every branch is designed as we have seen previously and its design is duplicated and united to the other one with a simple wire-string trying to emulate a simple wire union.



At first we test all the models with a single cell to, below, add more cells to the maximum capacity of the length-model (limited by the maximum capacity of the work-dimensions of the milling machine in the lab). So, the models with a lower line-length (see *Analysis of the model in function of the length of the line*) allow to implement more cells.

With more cells, at first, we have to expect a better response, but we have seen that the models with low line-length tend to have high separation between βl and kl with the consequent low range for the evanescent wave.

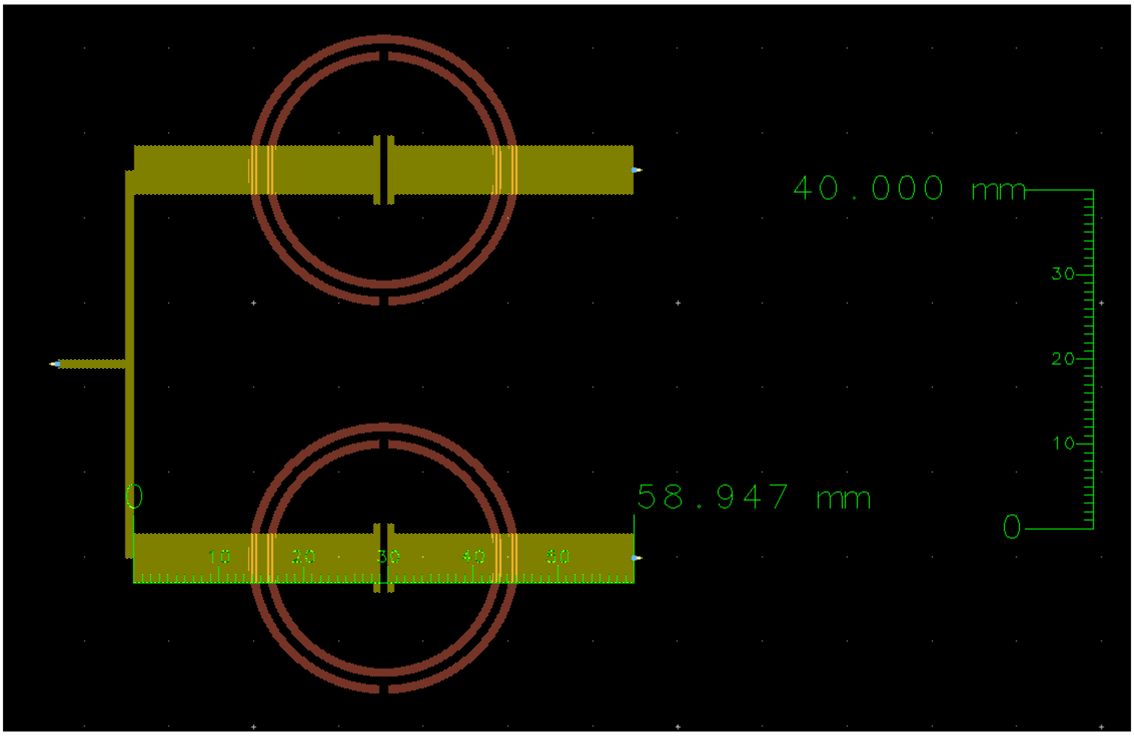
The aim is to establish a comparison between the models with less line-length and more cells and the others with the features interchanged. We study this kind of model with structures with different radius, as we have seen in *Analysis of the model in function of the diameter of the ring*, too, to extract more conclusions.

All models have been tested with an input impedance of 50 Ω (standard value) in the first port and 100 Ω in the ports of the right due to the parallel structure of the model.

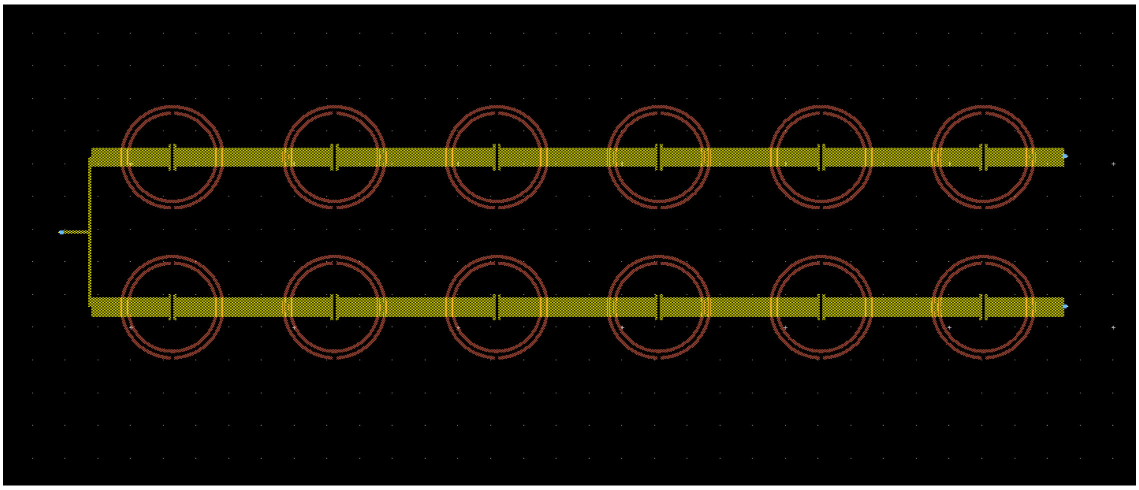
All the models tested with different lengths are described in the next table:

Model nº	**Length (cm)**	**Nº Cells tested**
1	4.012	1, 3, 5, 6, 9 (max)
2	4.9535	1, 3, 5, 8 (max)
3	5.8947	1, 3, 5, 6 (max)
4	6.836	1, 3, 5 (max)
5	7.7773	1, 3, 5 (max)
6	8.7185	1, 3, 4 (max)

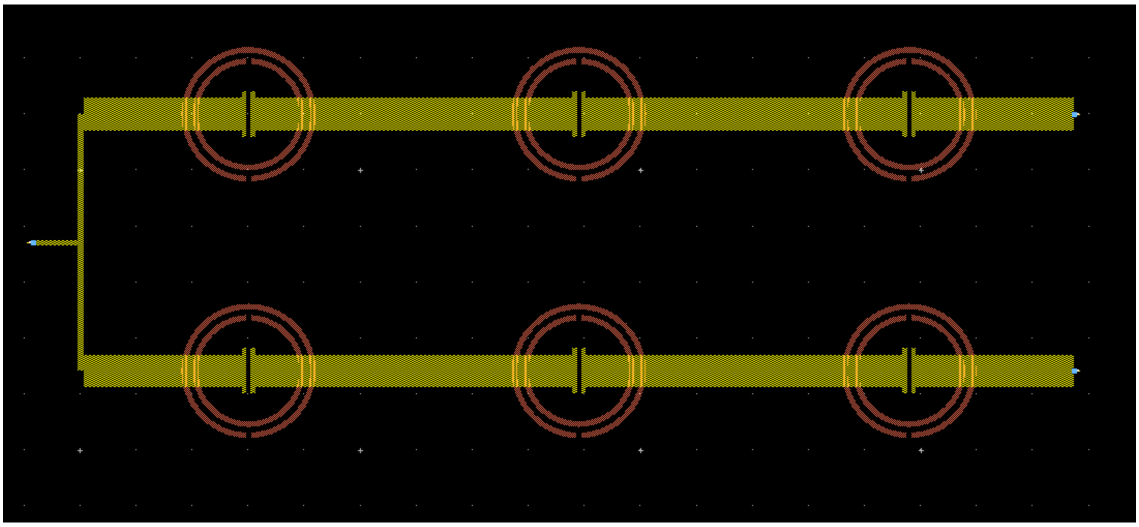
The analysis of the line with different diameters of the ring has been done taken the length of the model nº2 as an standard model to take conclusions. Only the models with 12 and 20 mm have been analyzed, because, the models used previously have already 16 mm and the model with 24 mm requires more distance between the branches that we're using in the analysis.



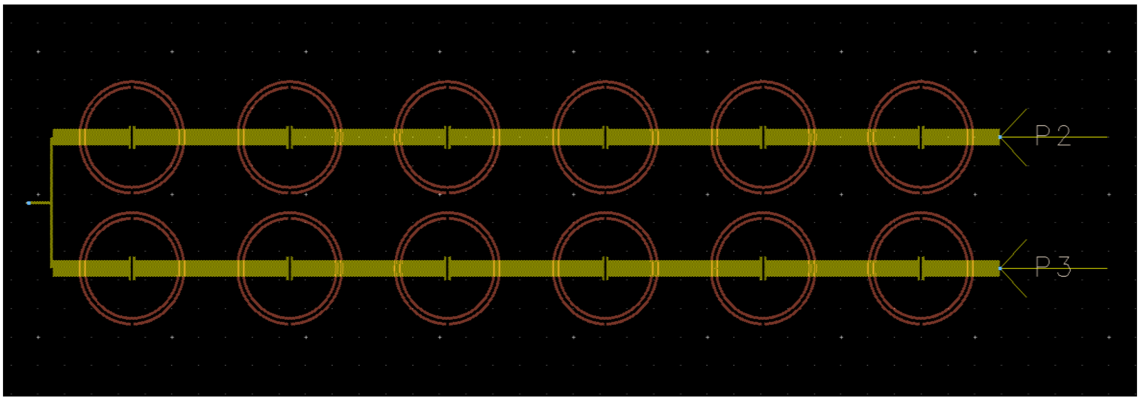
Model of one cell in each branch with a length of 5.89 cm.



Model of 8 cells in each branch with a length of 4.9 cm.

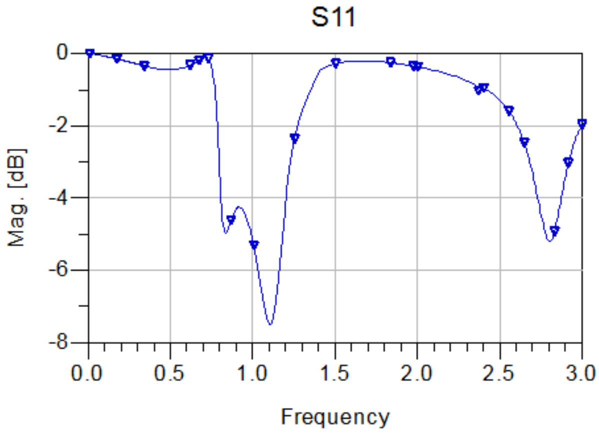


Model of 3 cells in each branch with a ring with 12 mm of diameter.

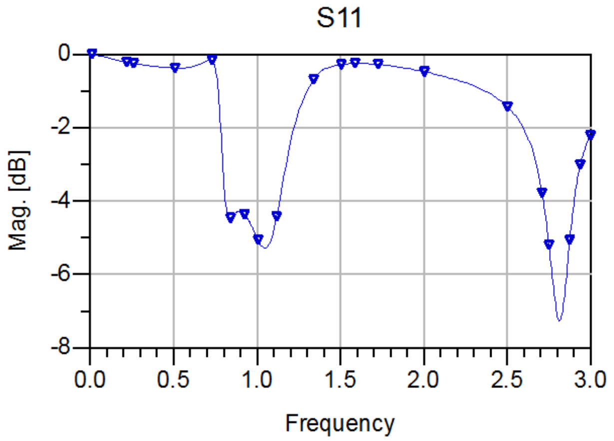


Model of 6 cells in each branch with a ring with 20 mm of diameter.

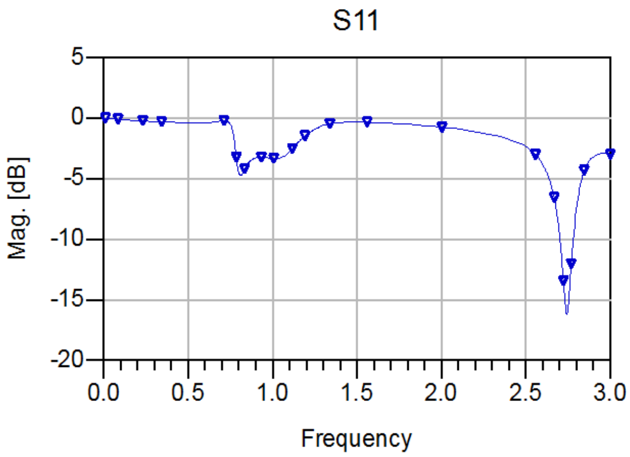
This are the results for the S11 matrix for the 1 cell models:



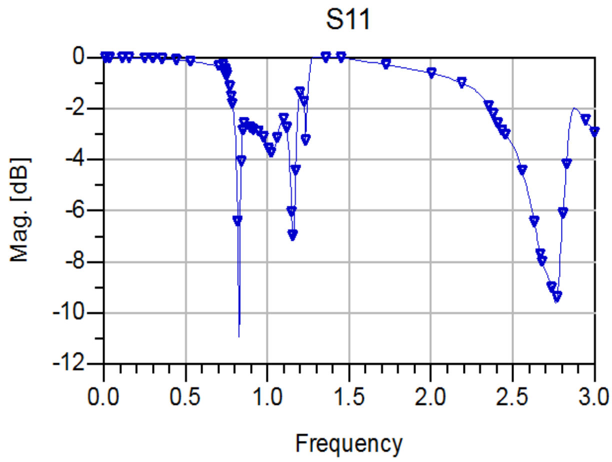
Length: 4.012 cm



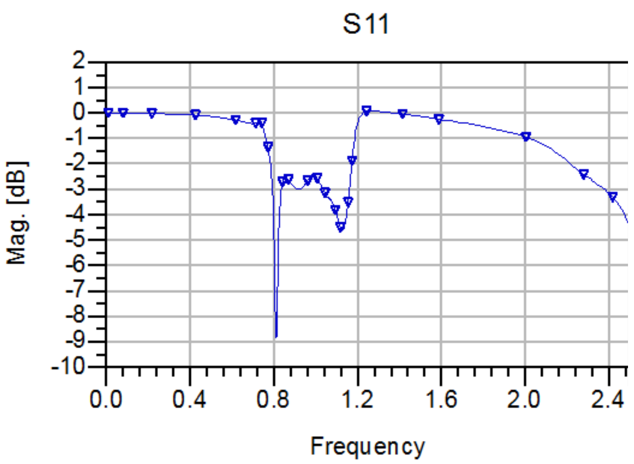
Length: 4.953 cm



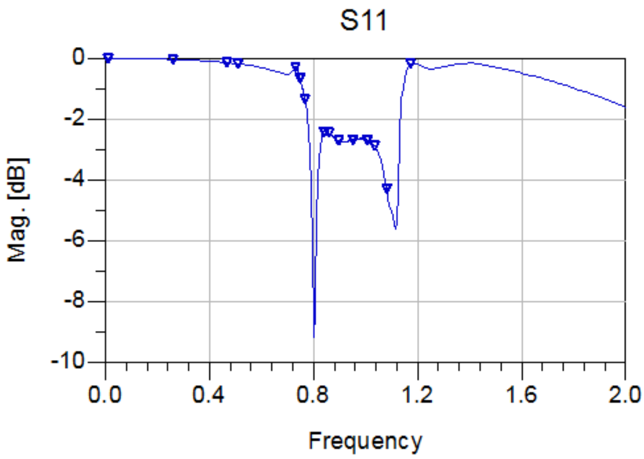
Length: 5.894 cm



Length: 6.836 cm

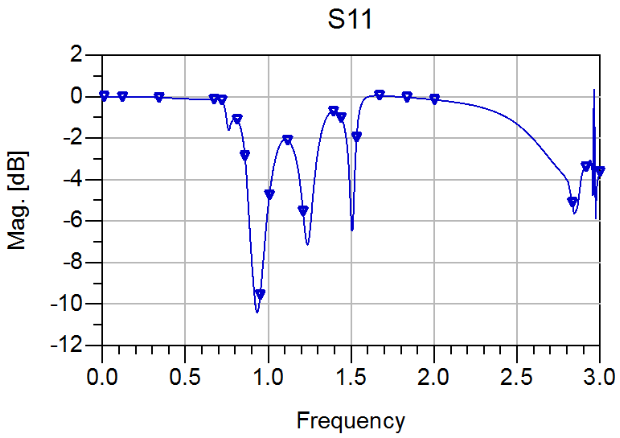


Length: 7.777 cm

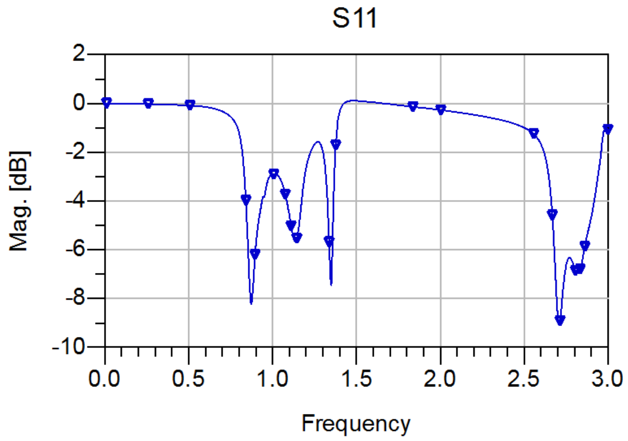


Length: 8.718 cm

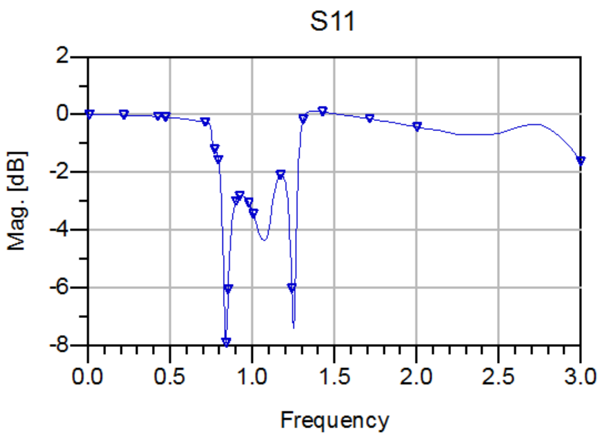
This are the results for the S11 matrix for the 3 cells models:



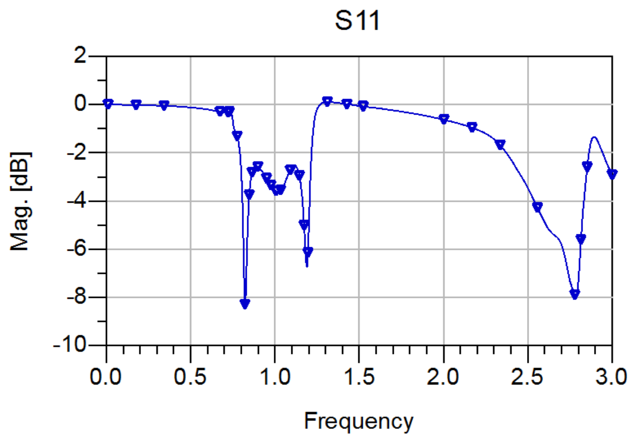
Length: 4.012 cm



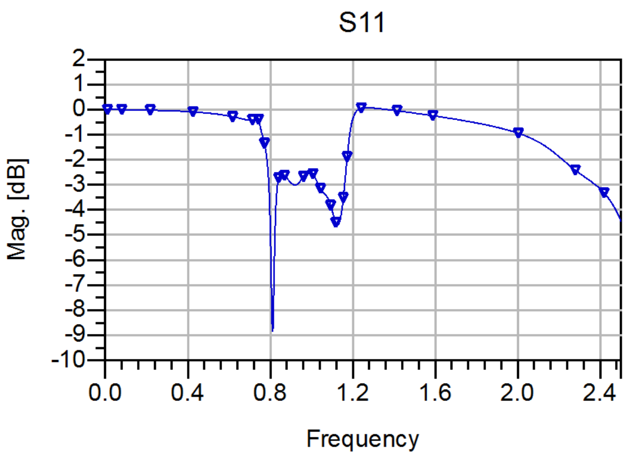
Length: 4.953 cm



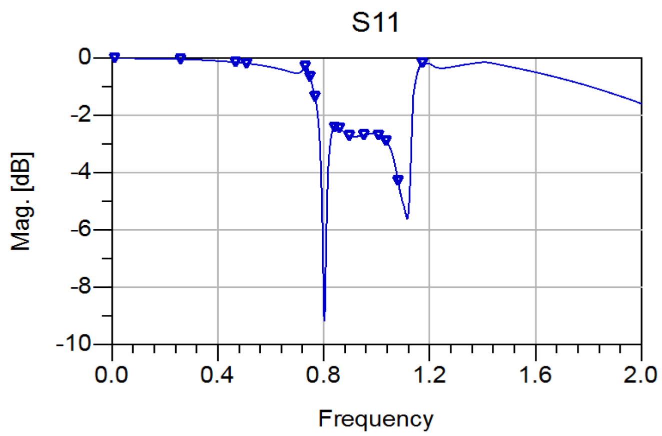
Length: 5.894 cm



Length: 6.836 cm

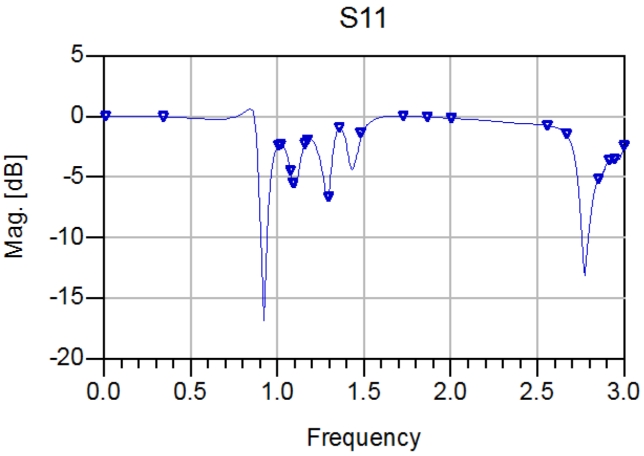


Length: 7,777 cm

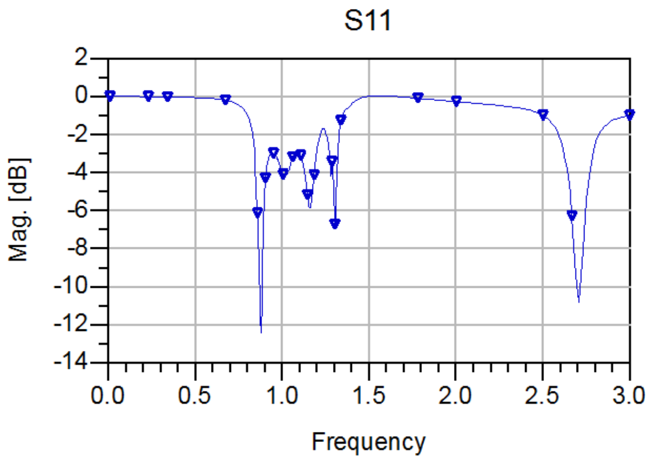


Length: 8.718 cm

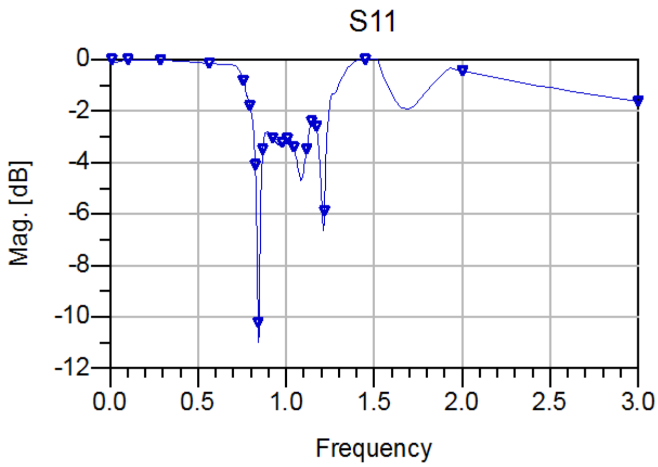
This are the results for the S11 matrix for the 5 cells models:



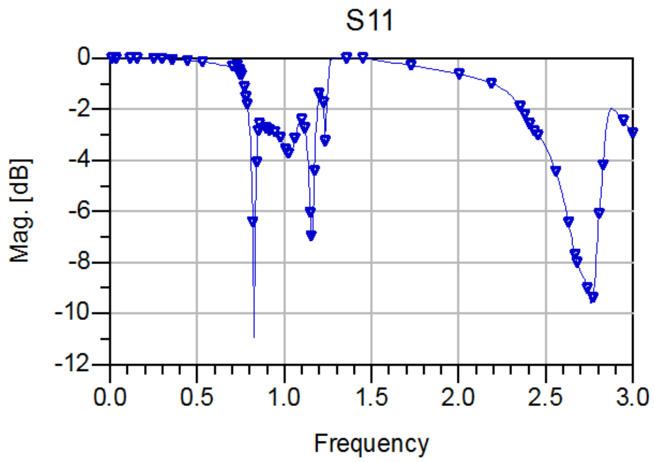
Length: 4.012 cm



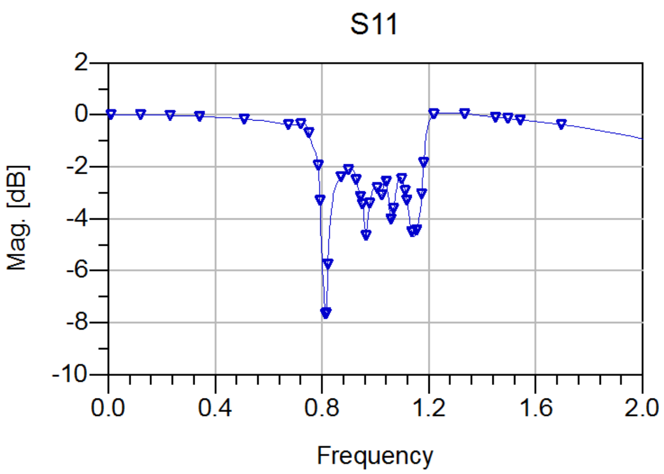
Length: 4.953 cm



Length: 5.894 cm

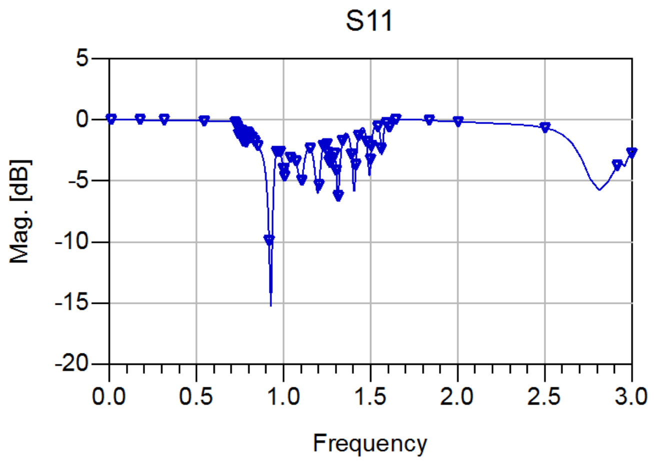


Length: 6.836 cm

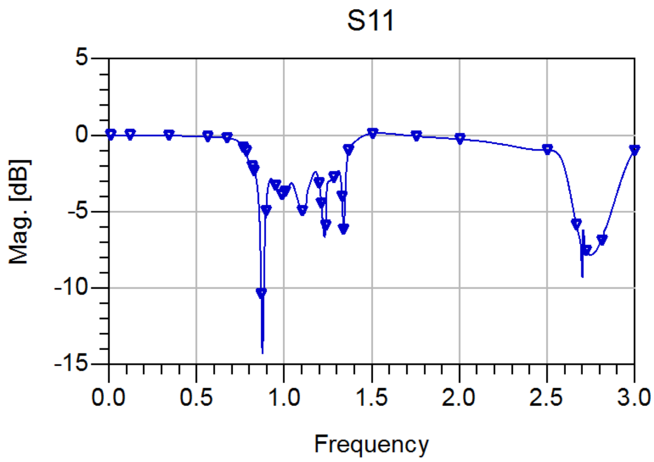


Length: 7.773 cm

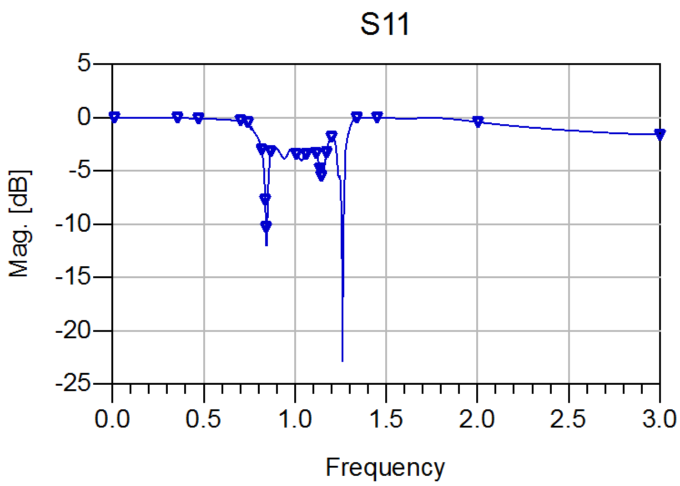
This are the results for the S11 matrix for the maximum length capable:



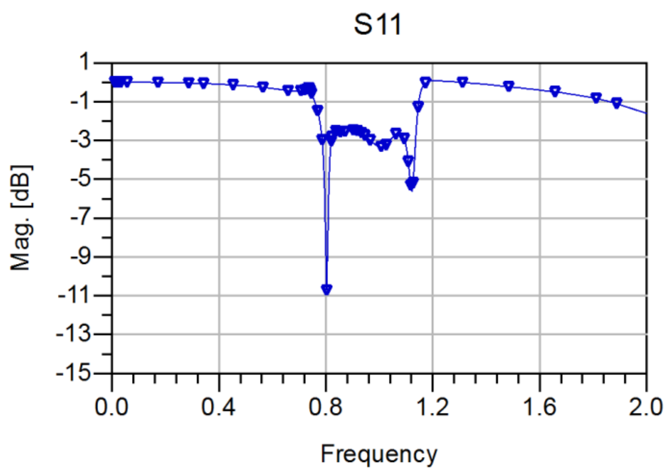
9 cells 4.012 cm



8 cells 4.953 cm



6 cells 5.894 cm



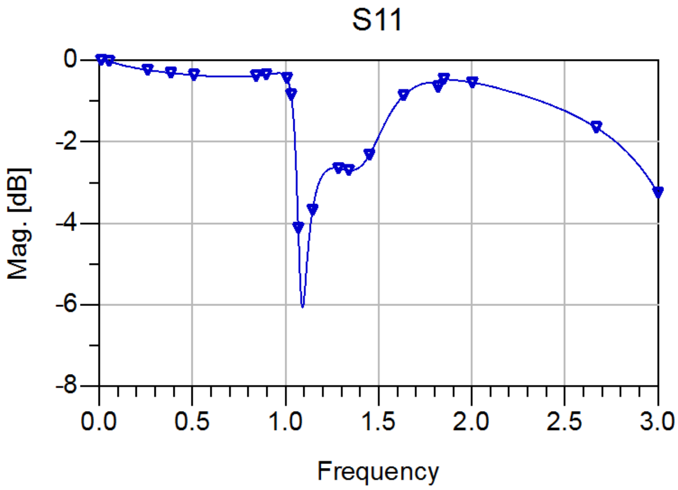
4 cells 8.718cm

As we can see, the results are not good for the purpose required. The frequency band is correct for RFID devices, tends to be lower for long-length line models but in all cases it works near the desired values.

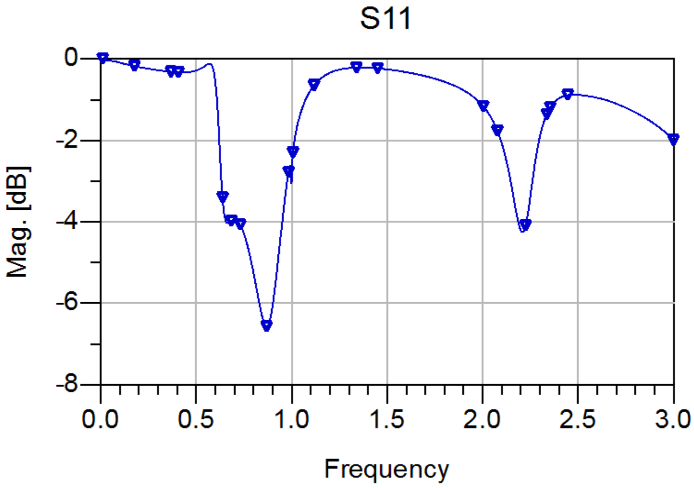
The problem comes with the matrix of reflection, the medium values of transmission don't reach the desired ones (-10 dB) and, when they do, the signal doesn't have enough BW to work correctly.

We can see now the values for different diameters with a length of 5.894 cm, they suffer the same problem that the previous ones.

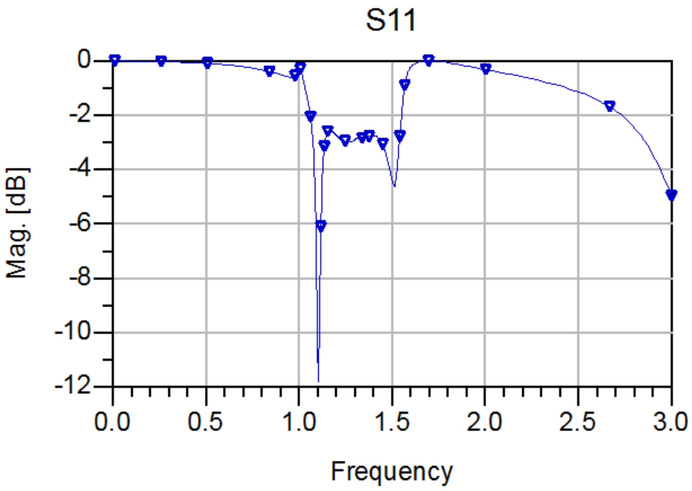
This are the results for the S11 matrix with different diameters and number of cells:



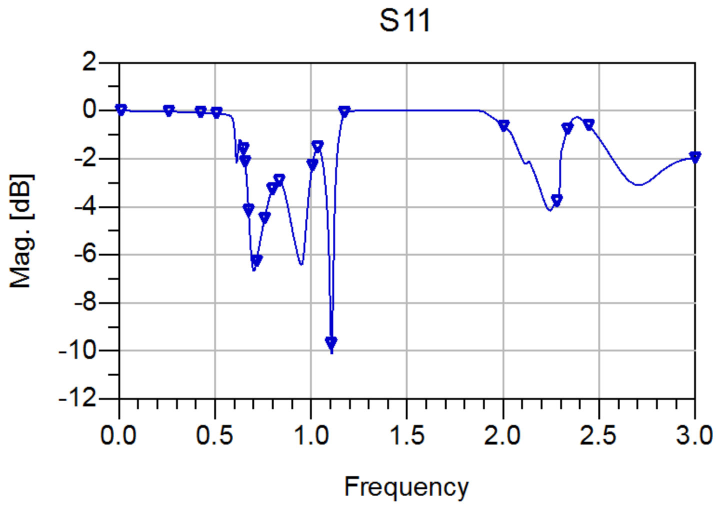
1 cell 12 mm of radius



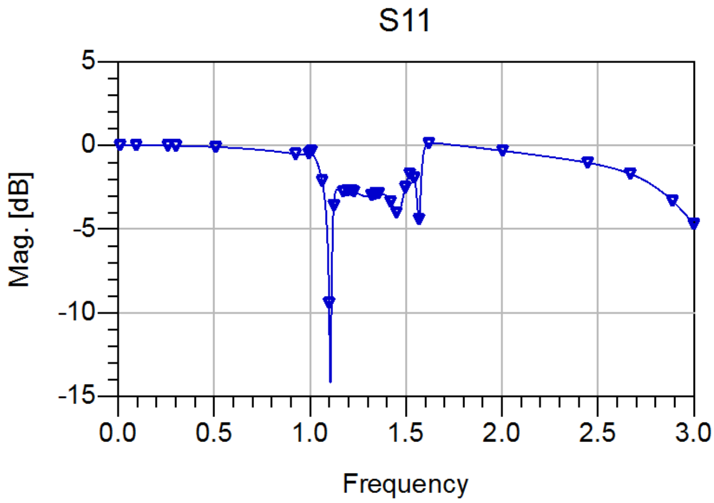
1 cell 20 mm of radius



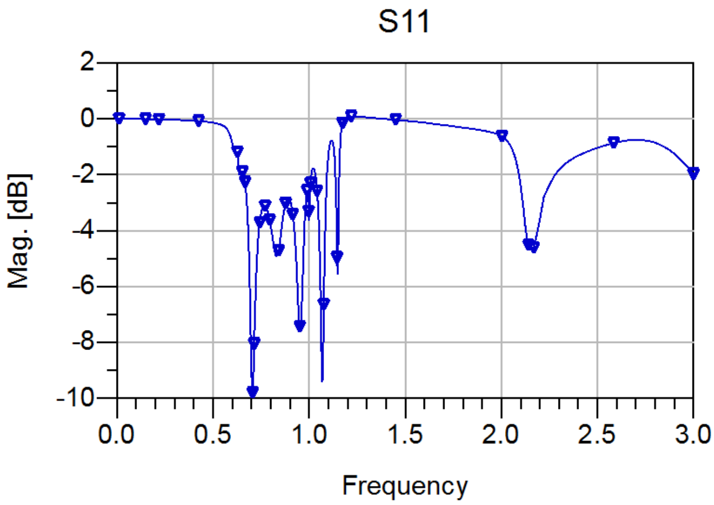
3 cells 12 mm of radius



3 cells 20 mm of radius



5 cells 12 mm of radius



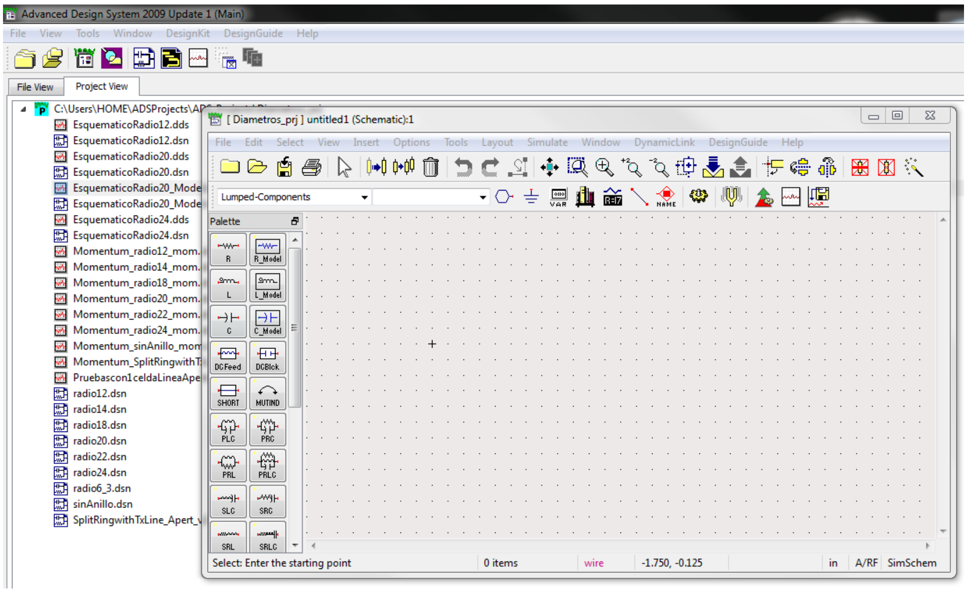
5 cells 20 mm of radius

Why the results are not the desired ones, with a low transmission values in the frequencies of interest? At this step the idea was to test if the proposed model works in an schematic design, one which applies the theoretical equations instead a meshing of simulations.

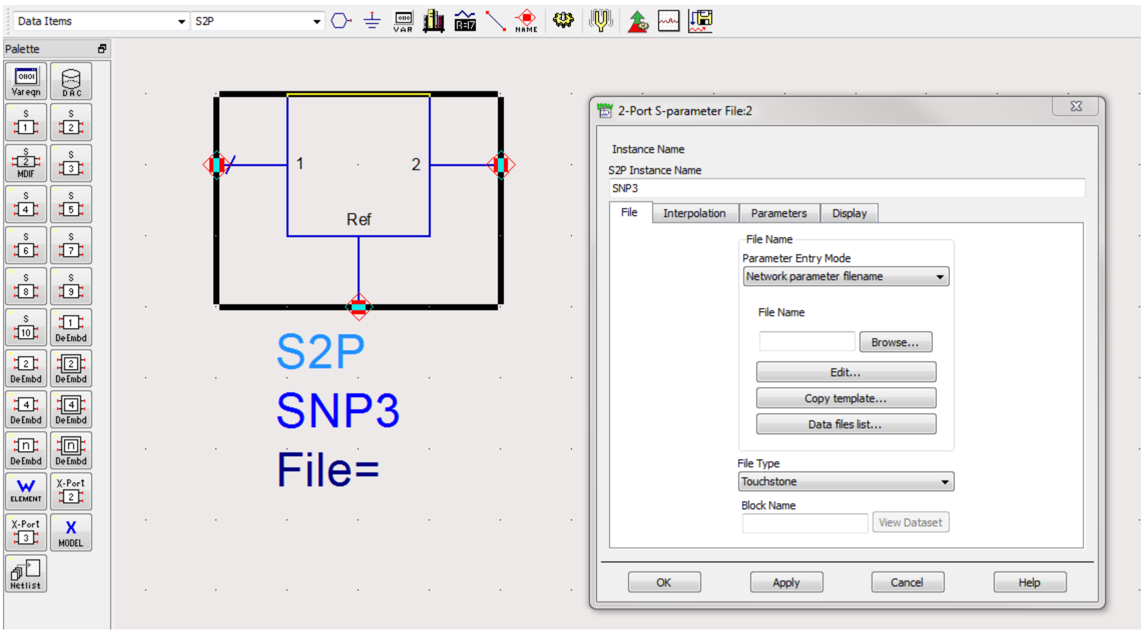
In the Schematic Part of the ADS 2009 we have the tools needed to apply this testing as we can see in the next chapter. The first conclusions are that the actual disposition of the model doesn't allow to detect the tags due to an incorrect flow of the electromagnetic wave along the line.

Schematic model testing

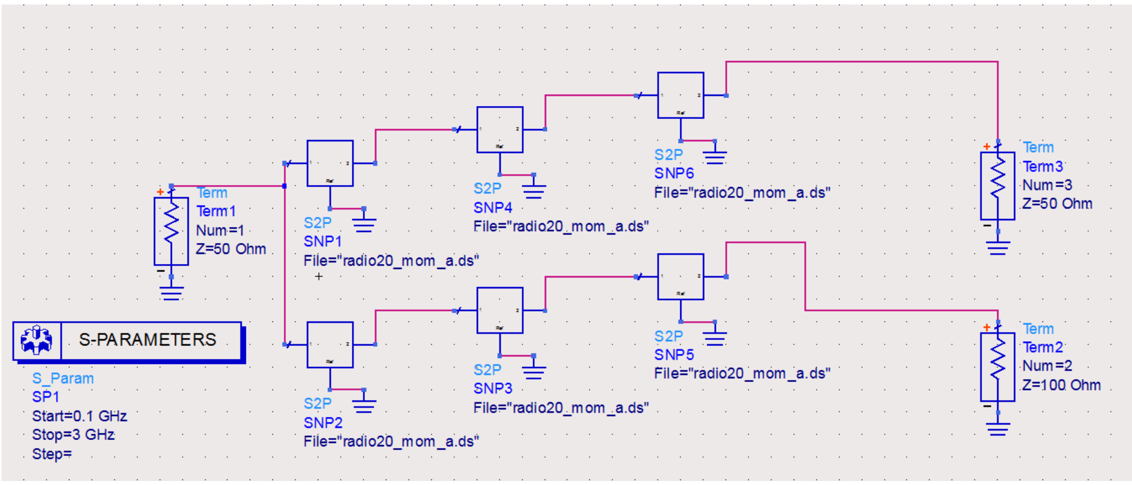
As we have seen in the previous chapter, we're experimenting problems with the first disposition of the dual model. To test the viability of this path of the project, the purpose is to check if the theoretical model works using the schematic simulator.



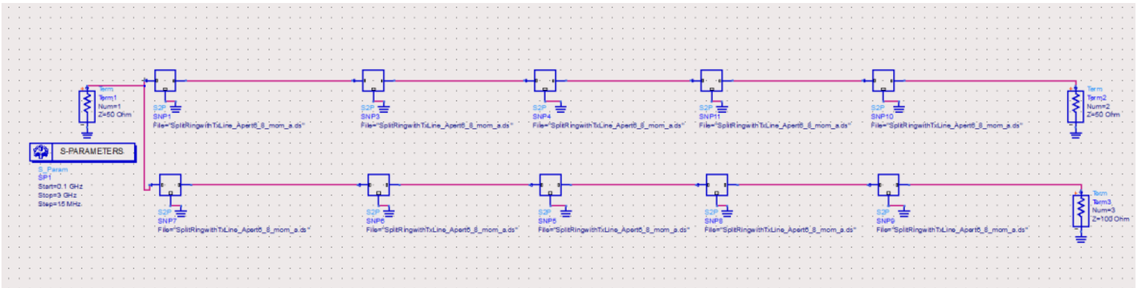
This is a circuit model design system with the capability to import models from the Layout. The idea is to take the cells designed (with different lengths and diameters) in the layout, export it to the schematic, and make the dual model using simple wires and input/output ports.



Inside the data items menu, we select a 2-port "box" to import the model. With the browse button we select the file to charge. The next images show two models of the schematic construction:

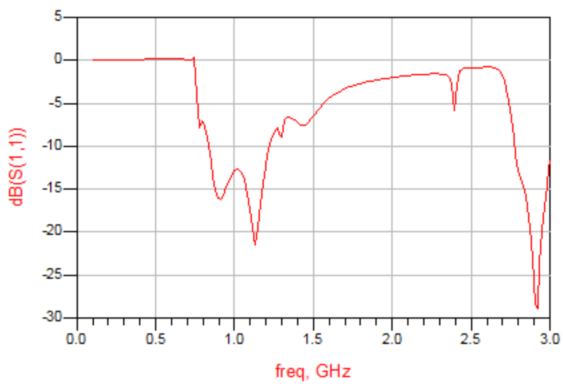


Schematic of the model of 3 cells with 20 mm of radius.

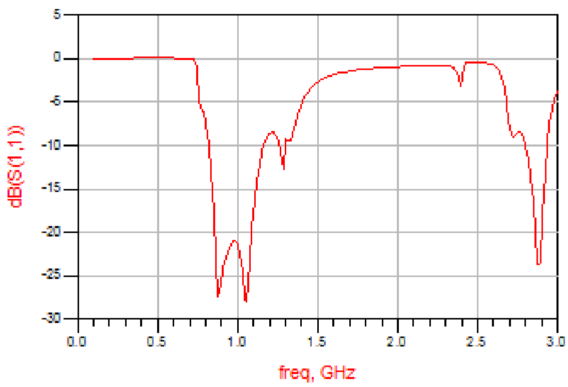


Schematic of the model of 5 cells with 6.836 mm of line-length.

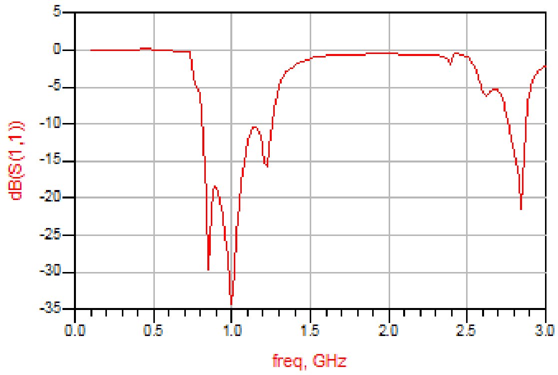
Making the simulation of the S-Parameters with all the different lengths of the line previously tested with different number of cells, and the test of the models with different diameters, we obtain the following results to extract conclusions.



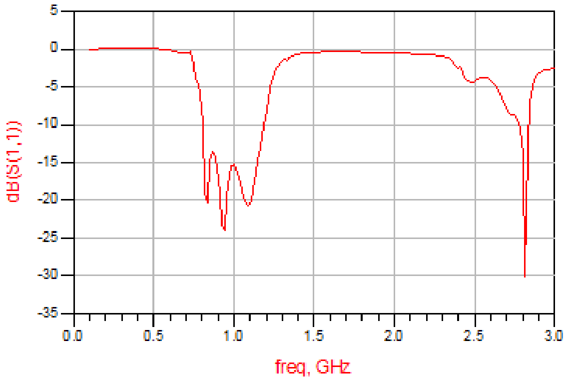
3 Cells Length 4.012 cm



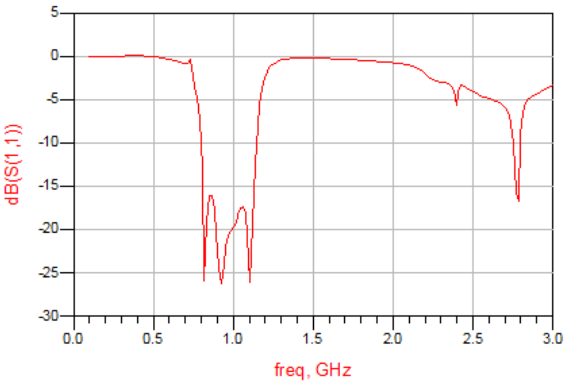
3 Cells Length 4.953



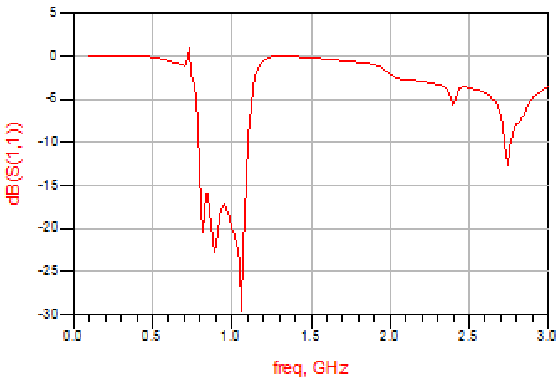
3 Cells Length 5.894 cm



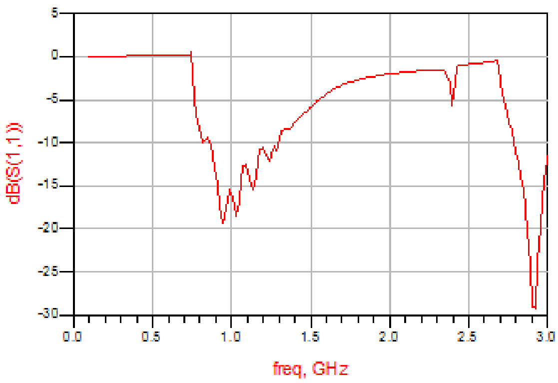
3 Cells Length 6.836 cm



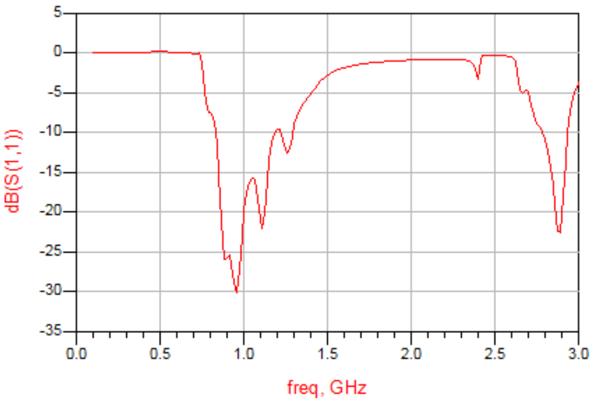
3 Cells Length 7.777 cm



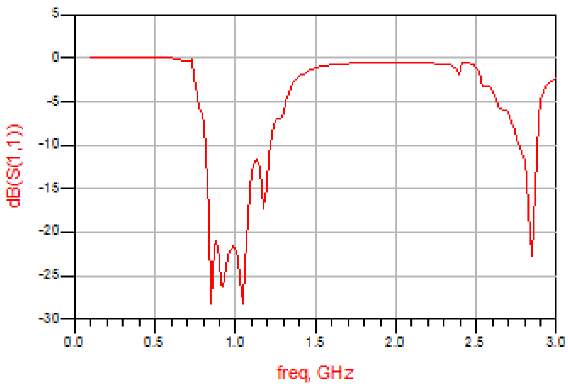
3 Cells Length 8.718 cm



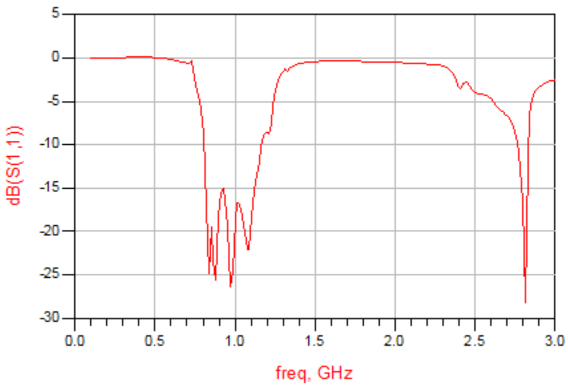
5 Cells Length 4.012 cm



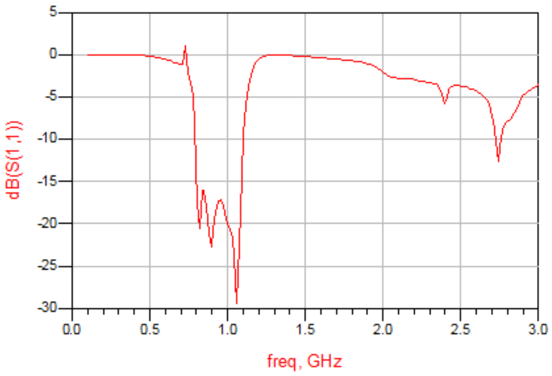
5 Cells Length 4.953 cm



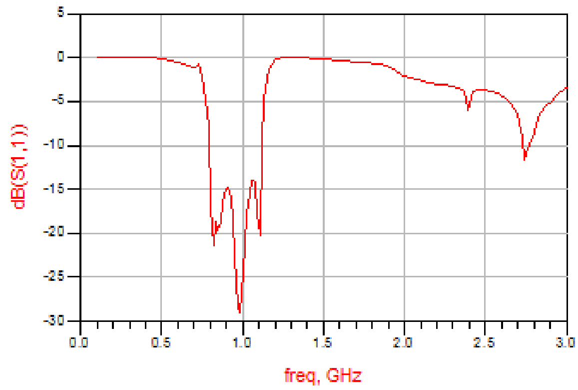
5 Cells Length 5.849 cm



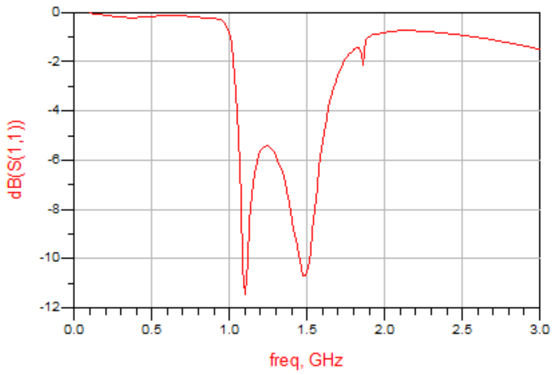
5 Cells Length 6.836 cm



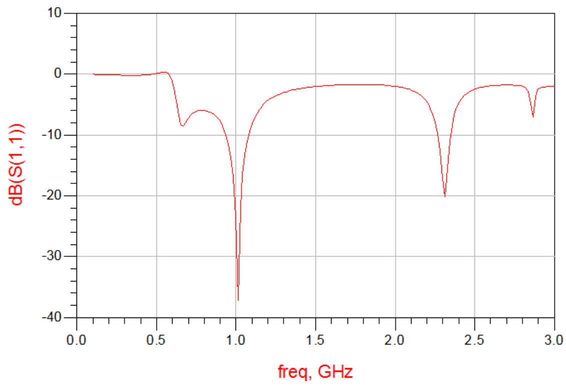
5 Cells Length 7.777 cm



4 Cells Length 8.718 cm



1 Cell 12 cm radius

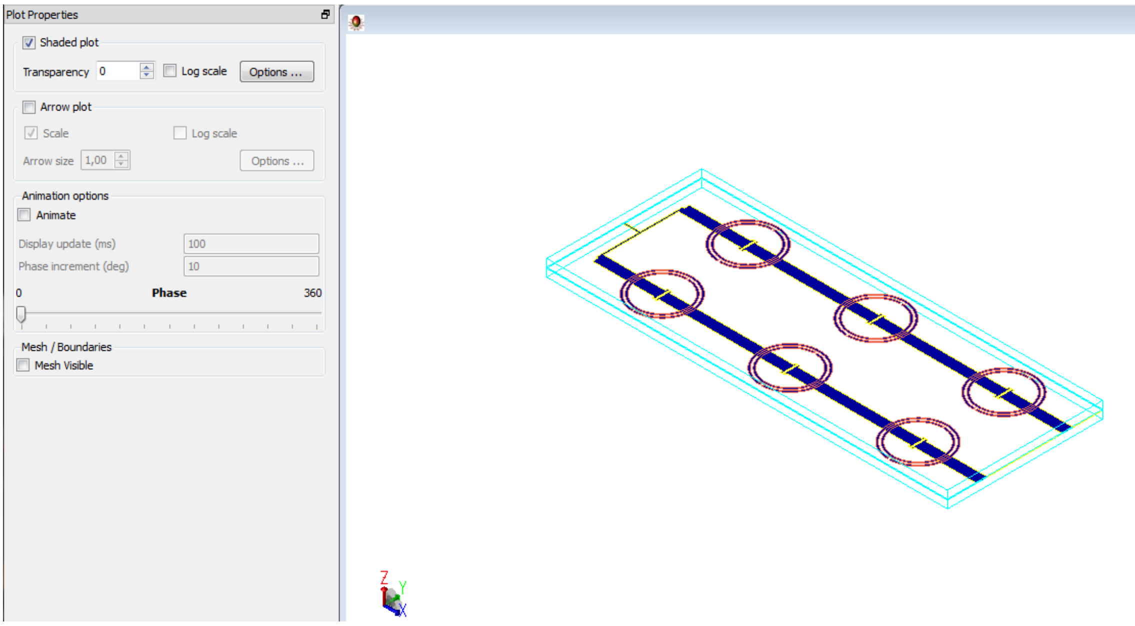


1 Cell 20 cm radius

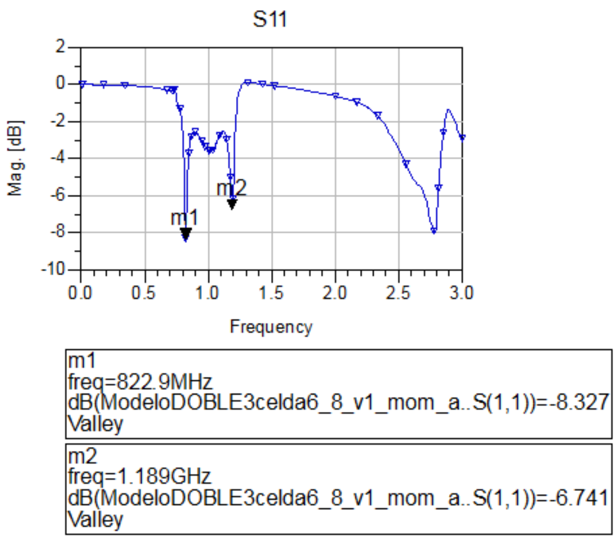
Therefore, as we can see, the values of signal transmission between ports for all this cases, are really good, most cases under 10 dB in the working frequencies. Theoretically the dual model supports those experiments, so why in the layout design the transmission values go dawn drastically.

Inside the momentum simulation tools inside the section of Post-Processing/ Visualization we can watch how the electromagnetic signal travels through the design in a 3D view which allows an animation of the travelling wave.

We can see if the travelling wave goes along the line with an homogeneous dispersion or it has some sites (presumably the corners of the model) with the wave becoming stationary.

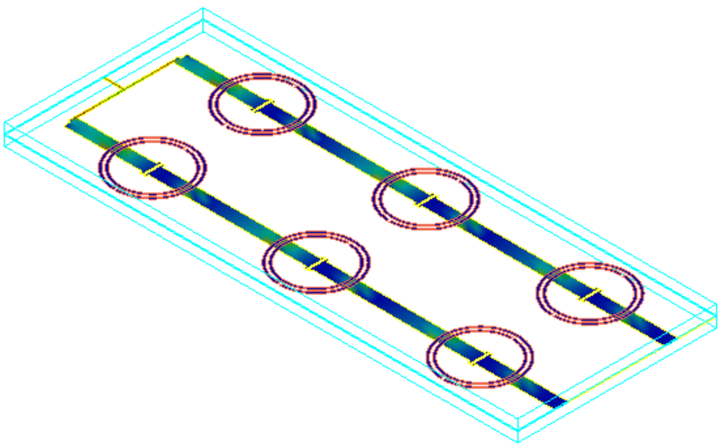


Taking as example the model with 3 cells and 6.8 cm of length we take the analysis of the S11 matrix and see that the peaks are at 823 MHz and 1.19 GHz.

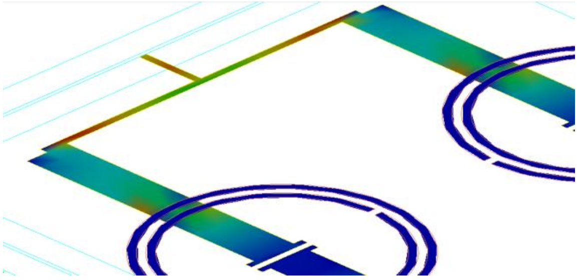


Let's proceed with the simulation at these frequencies and the ones between these values to see if/how the electromagnetic wave travels.

This is the simulation of the post-processing near the 823 MHz. We can see that the flow of the wave is good (that is the best frequency of this model) from the generation at port 1 to the end in port 2 and 3.

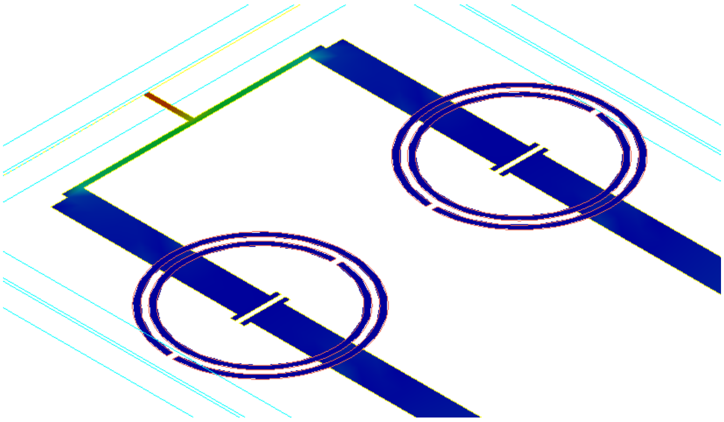


But if we take a close look at the beginning of the model, we can see that most of the energy is dispersed in the hard change experimented with the different orientation of the line (angle of 90 degrees) from the Y axis to the X axis.



Taking a look of the colour patron we can see that already half of the power is dispersed by reflection , as occurs in optical fiber with the hard transitions in the line.

Taking a look of the other frequencies (1Ghz) where we have , at the best case, a -3.7 dB value of reflection, we can see the same case; practically all of the wave is reflected at the beginning of the model.



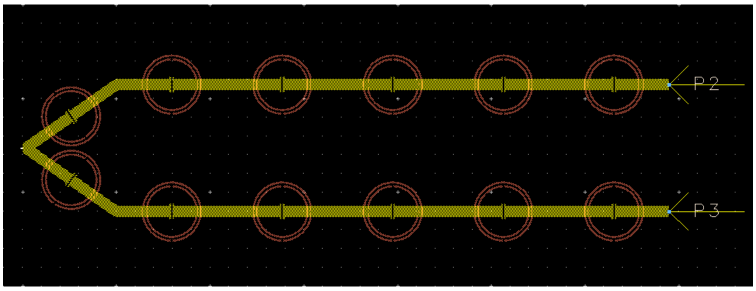
All the dual models have the same problem that we've seen. We have the need to improve the entry of the project, with soft angles and a similar distribution of the cells along the line.

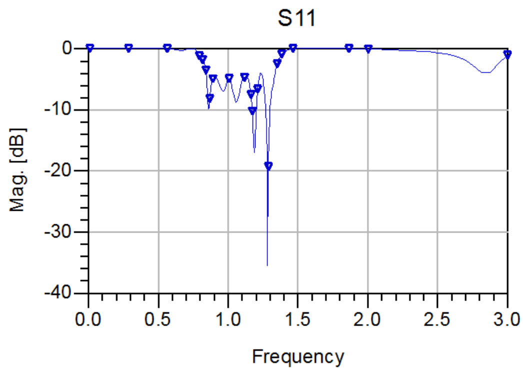
Chapter 5: V model

As we have seen in the previous chapter the main problem resides in the hard change of transition at the beginning of the model. Most of the energy of the wave is reflected when it crashes with the corner described by an angle of 90º.

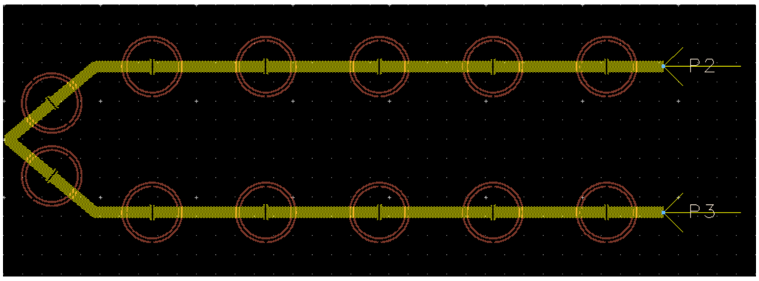
The purpose is to soften this angle and bring higher homogeneity starting with a cell, instead only a line section, describing an acute angle with the axis of symmetry in an upper vision. We have to take care about the collapse of the rings if the angle is not bigger enough.

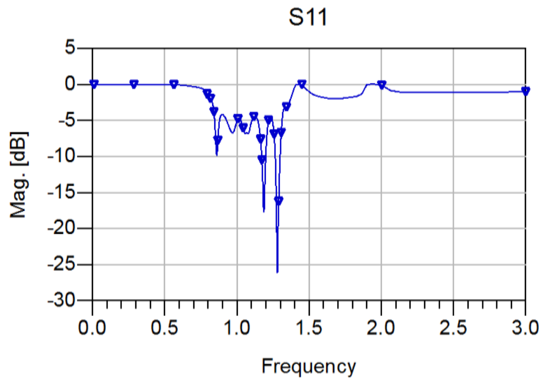
The next images show models with the line of 5.8 cm and the ring with 16 mm of radius in different angles tested to improve the bandwidth of the signal transferred.



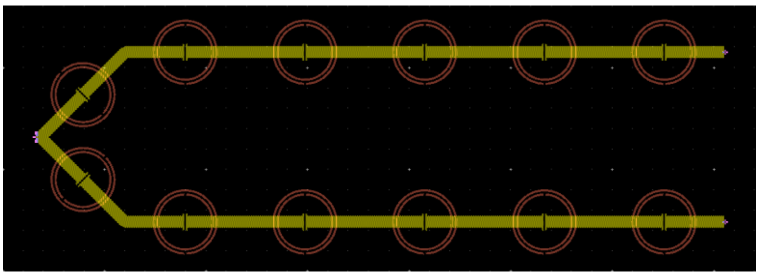


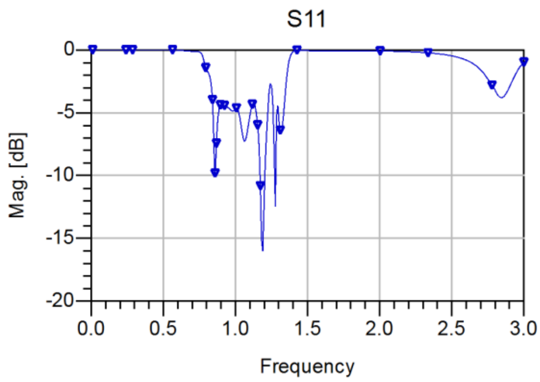
35º The smallest angle without collision of the rings.



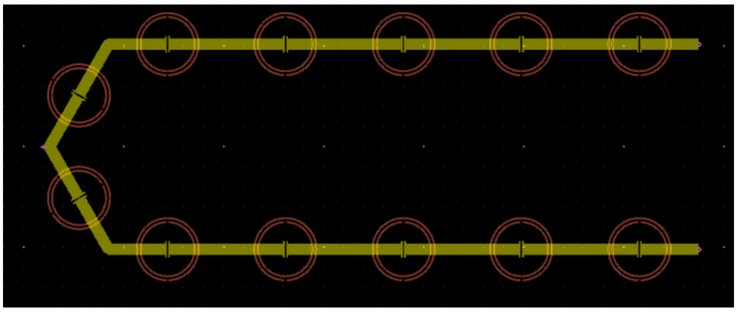


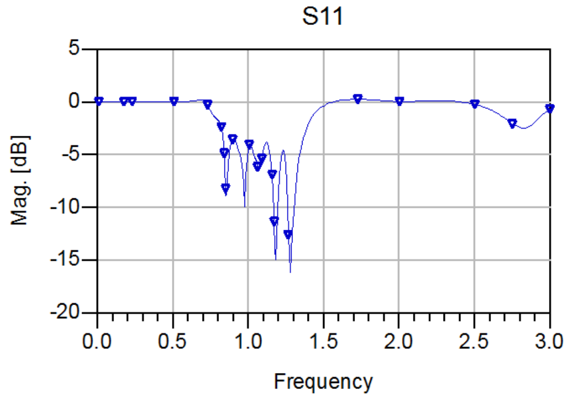
40º



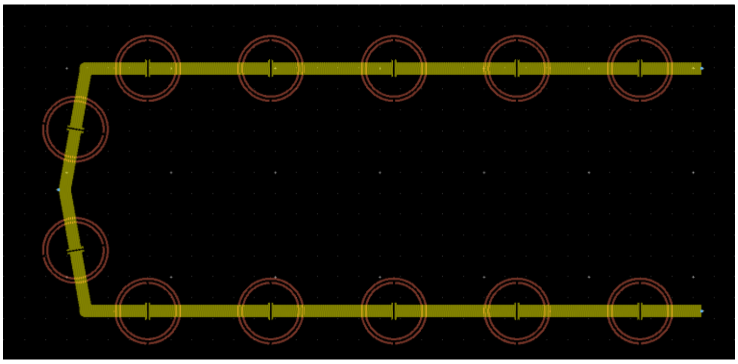


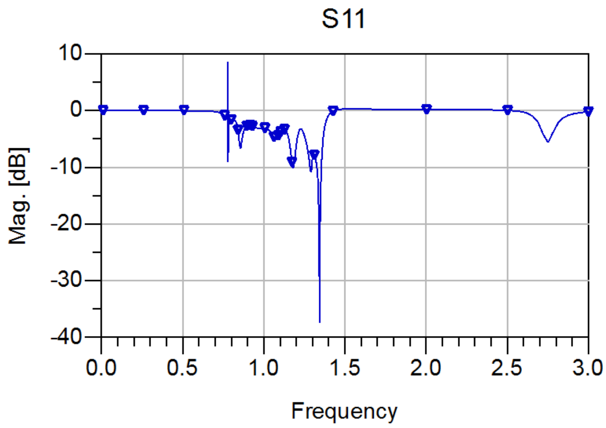
45º





60º

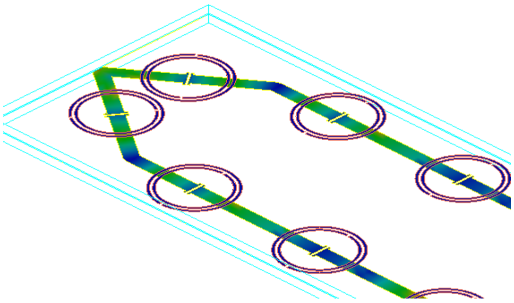


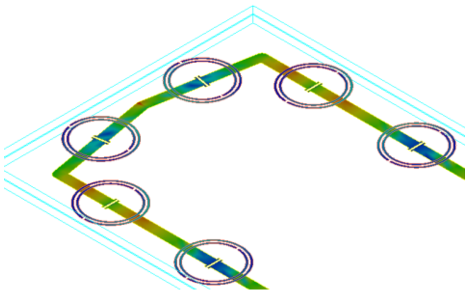


70º

At this case we have a conflict between: as acute is the angle better will be the flow of the wave but, the arms of the model will be closer, generating more electromagnetic interference between that.

If the transmission response is not good, we don't have enough bandwidth under the values of -10 dB, only a few peaks. If we analyze with the momentum post-processing we can see the same problems that we have in the first designs of the Dual Model: the transitions between angles are not soft enough to keep the wave flowing along the line.



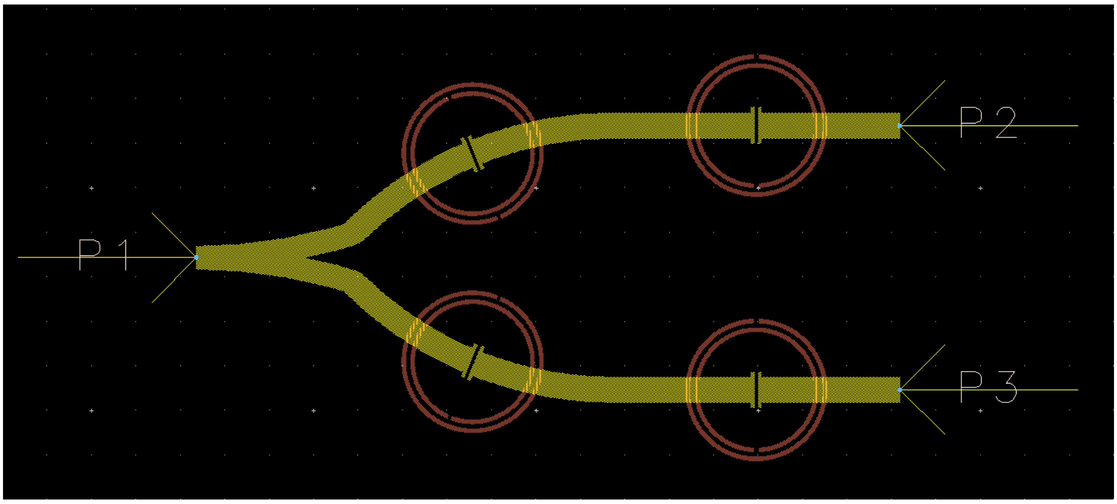


In the next steps we'll try to make a model with segments of a circumference, this transitions will be softer that any angle formed by the cut of two lines.

V model improved

At this part of the project we will only work with the lines that are close to the desired parameters. We have extracted enough analysis in the previous chapters to know which are the values which achieve the best values of impedance, adaptation and range of the evanescent wave. With this data, we will take the line of 7.77 cm with the ring of 20 mm of radius and try to give it a better input design for the input signal.

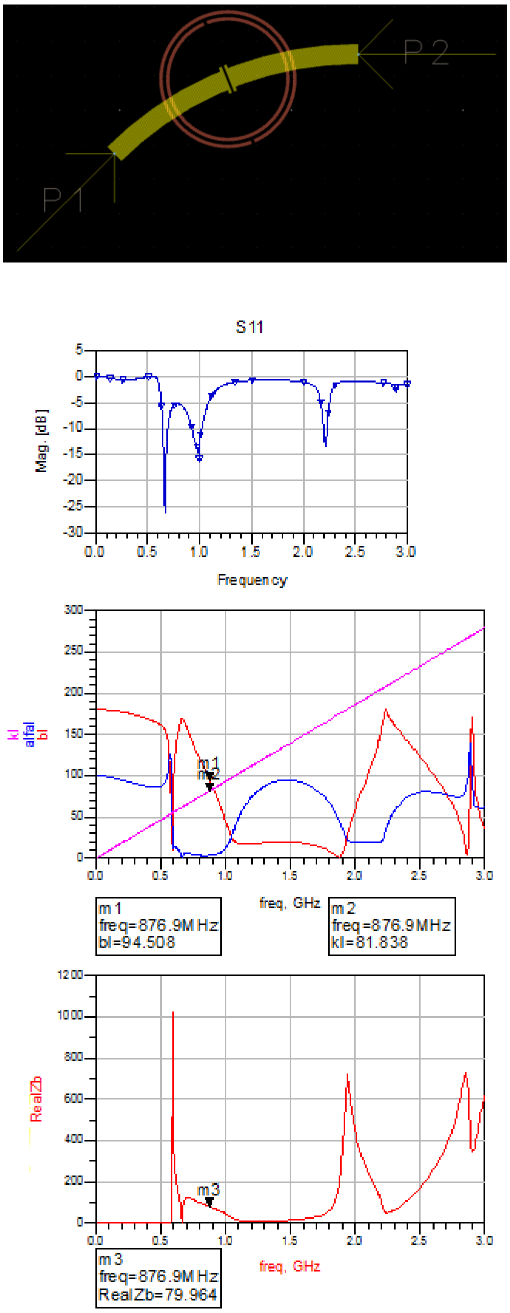
To make easier the purpose and understanding of the idea, the next image shows an advanced step of the design of this V model:

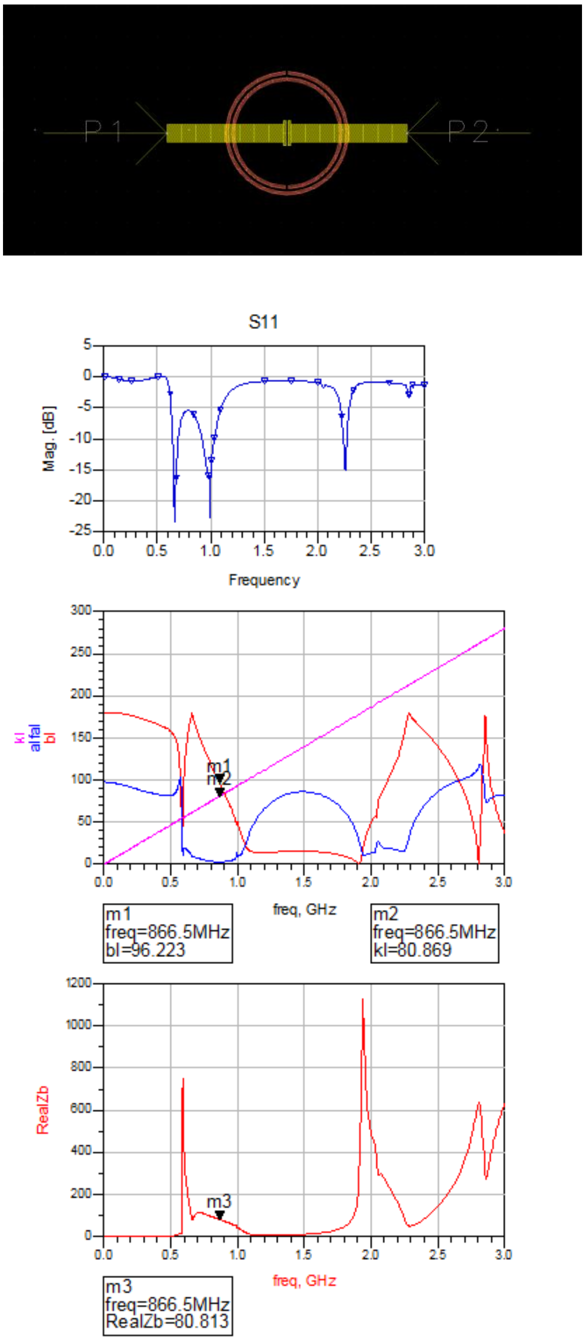


As we can see now the entry is composed by two fragments of a circumference, the first one is the birth of the model in the port 1, and finishes in the transition of the cell with a "circumference-orientation". The second one is the length of this cell until it touches a normal cell.

With a tool of the design menu we copy these steps symmetrically along the horizontal axis, as long as the radius of this two circumferences of entry, softer is the transition of the displacement of the wave, however, the branches of the model will be closer, with their corresponding electromagnetic interference.

One basic testing is checkup if the basic cell in a "circumference-orientation" responds equal to the simulation of the S-Parameters. In theory there will not be any problem, and if we apply the Momentum Simulation, we can see in the next analysis that the supposition is correct.



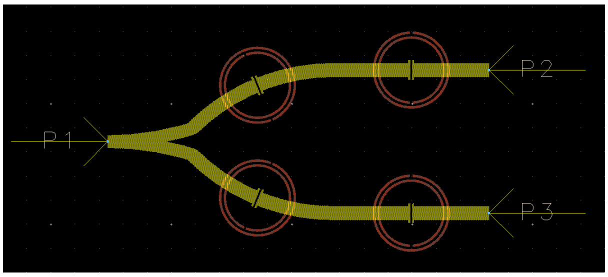


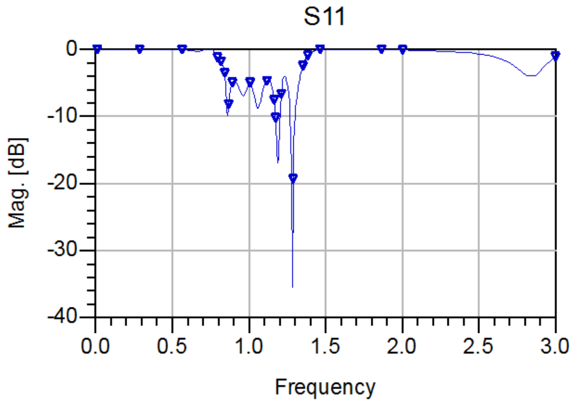
As we can see, the values don't change (only a little for the properties and margin errors inside the capability of the simulator). With this data, we can design cells with a line, which is a fragment of a circumference, preserving the length of the line with different trigonometric relations.

In this case, knowing previously the length desired, and an elected radius, we can extract the angle inside the circle needed for the design.

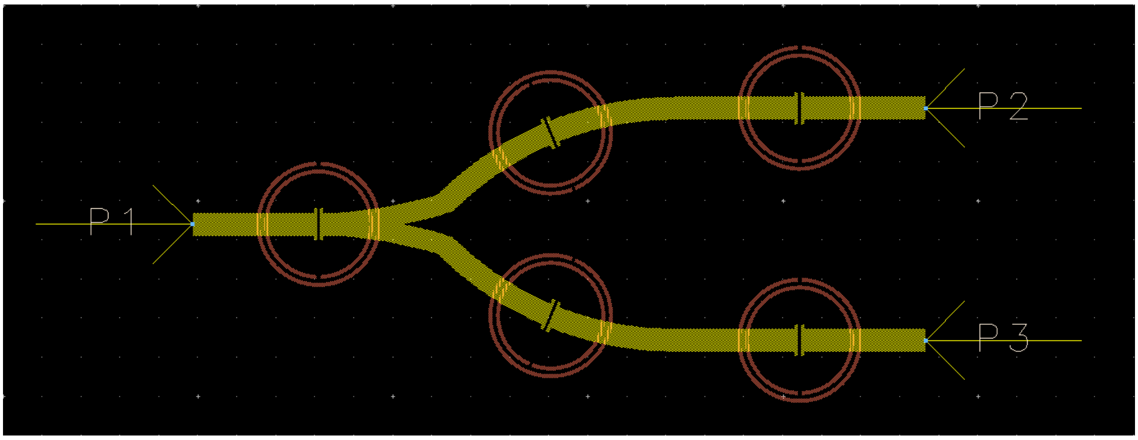
The process will be completely described later, when the design of the lines with the best results achieved is described. Now, we'll elude it to no repeat the same operations with different values along the document.

This first-model-improved has a line of entry without any length in concrete, and no cell in this part. This model was discarded quickly to improve the conditions of this "line of entry". The results for this model we're not satisfactory.





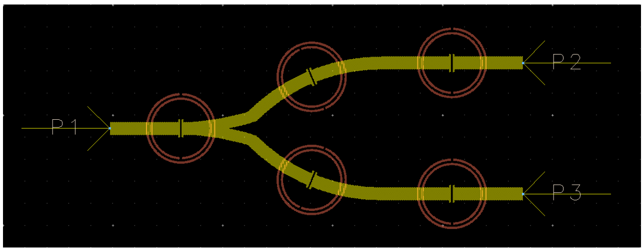
So, adding a cell at the beginning of the project, with the same parameters than the others (length, radius, design), but with a split at the end of one of this extremes to connect every branch. The next image shows one of the models to understand the idea:

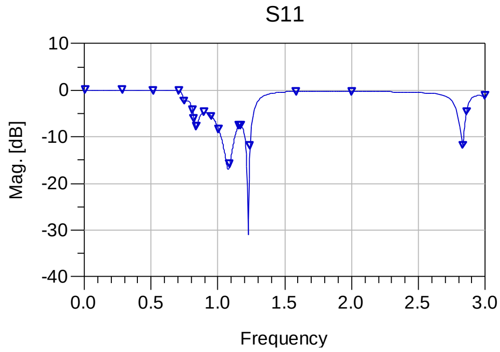


With this kind of entry, where part of the line is a segment of a circumference, the results improve due the capability of the first cell to act as an adapter of impedances and respecting the flow of the wave along the line.

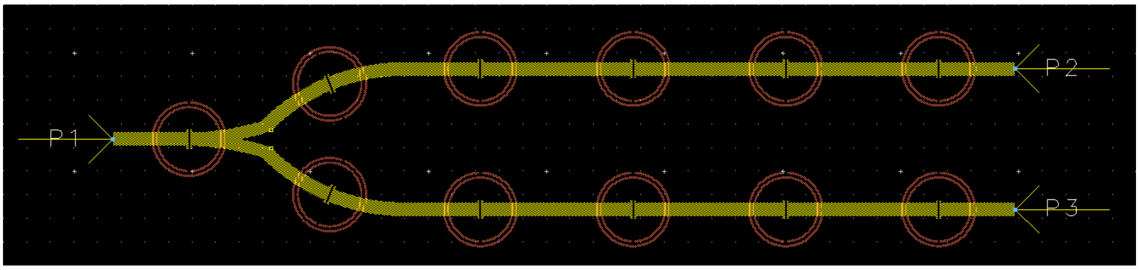
The next pages show a list of the models with little changes between them to see the behavior in this improved features.

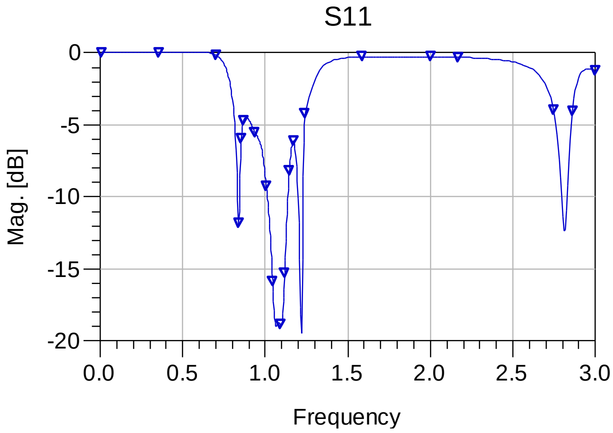
Model with 3 cells, length of 63 mm, ring of 16 mm, and 63 mm of distance between branches:



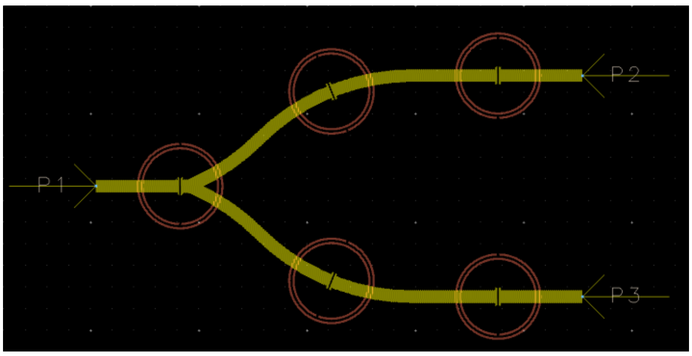


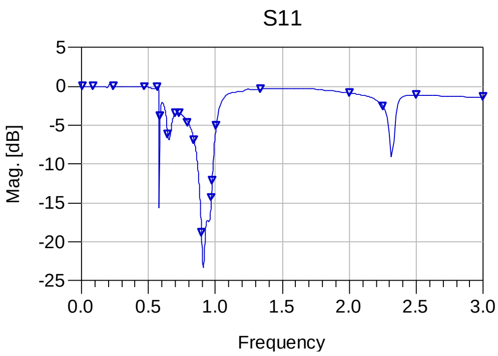
Model with 6 cells (max allowed), length of 63 mm, ring of 16 mm, and 63 mm of distance between branches:



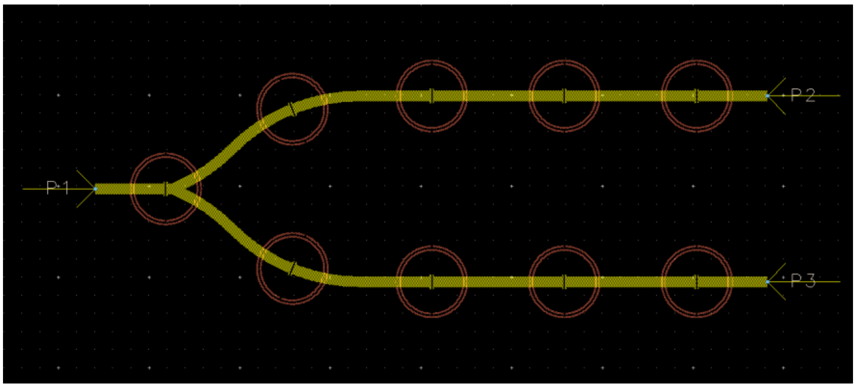


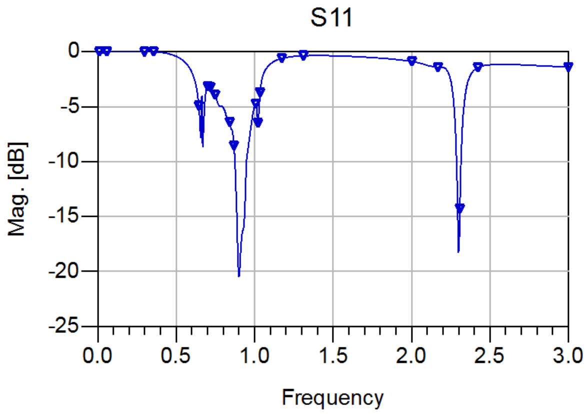
Model with 3 cells, length of 77 mm, ring of 20 mm, and 96 mm between branches:



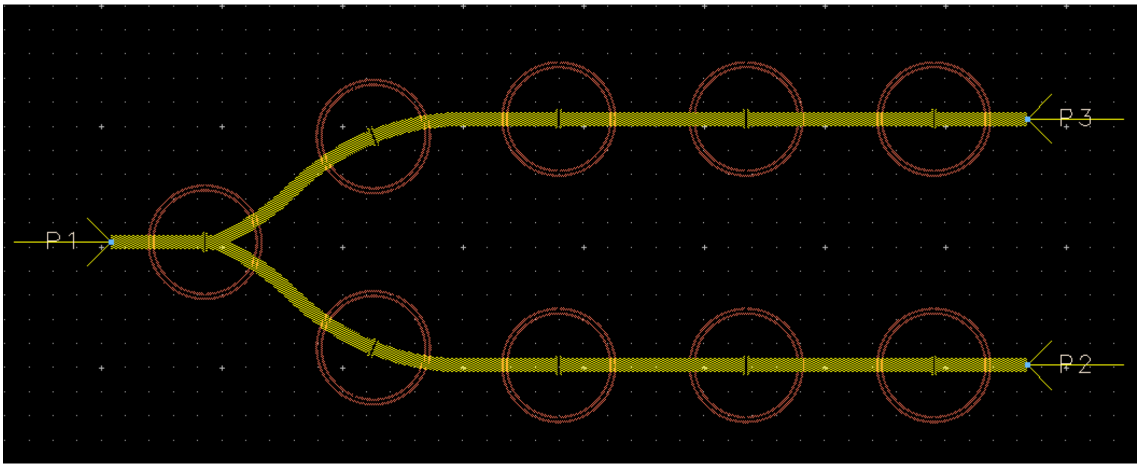


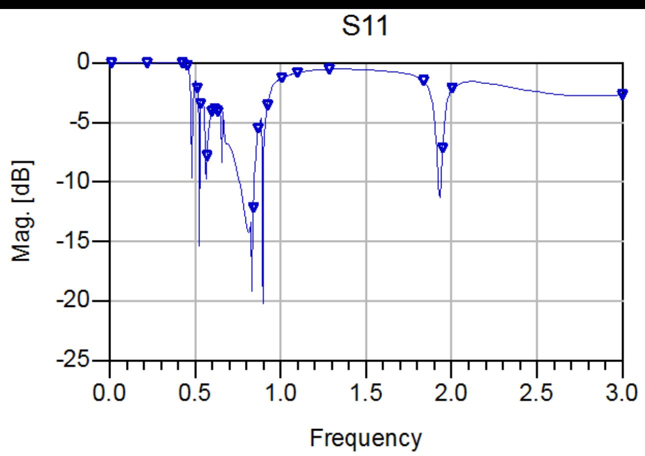
Model with 5 cells, length of 77 mm, ring of 20 mm, and 96 mm between branches:



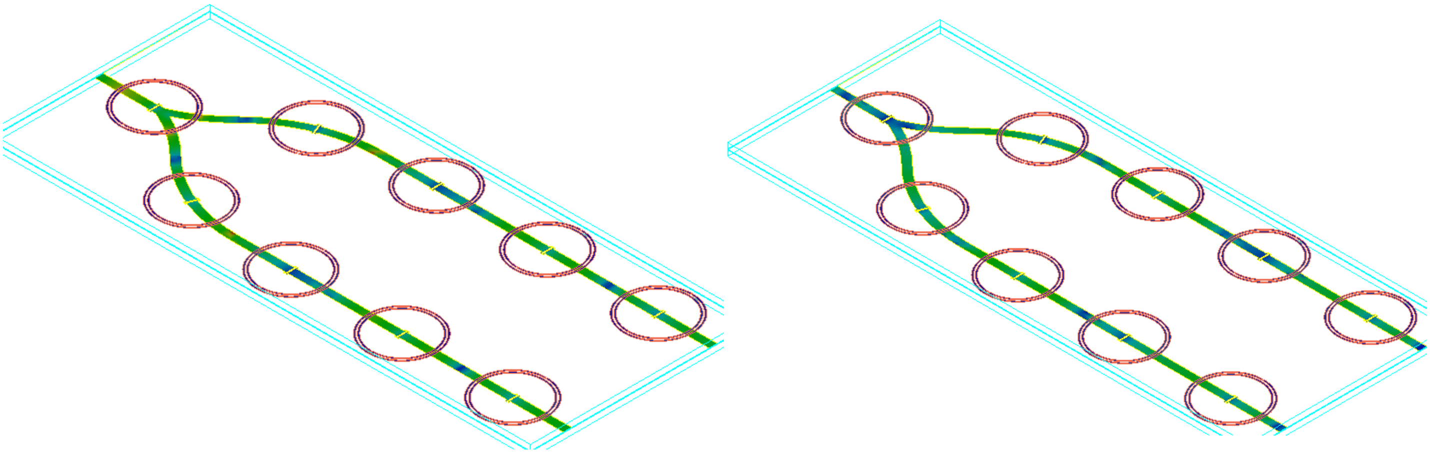


Model with 5 cells, length of 77 mm, ring of 24 mm, and 96 mm between branches:





As we can see, we're reaching bandwidths of 100 Mhz below the -10 dB of reflection, enough to work with RFID devices. Now we're going to apply the post-processing simulation to see how electromagnetic wave goes without collisions along the model:



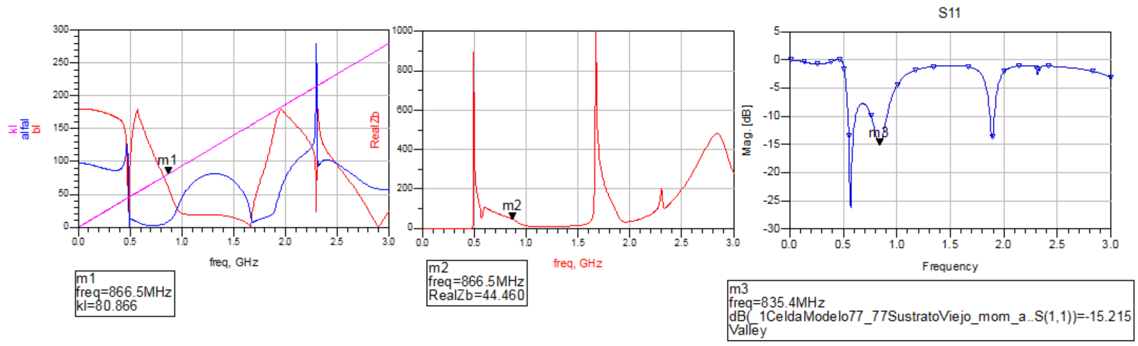
Now we can see how the wave travels with uniformity along the model and without death angles which disperse most part of the energy. The design works also without electromagnetic interference between branches. It's time to design a perfect cell model which allows us great values of impedance, max. frequency of adaptation and a good value of read range for the evanescent wave.

Optimal Cell implemented in V model:

Knowing at this moment the valid design of the V model, it's time to extract and synthesize conclusions from the chapters of analysis of the model in function of the length and radius of the circle of the SRR. The modification of the original lines at this point includes, not only the previous ones, the width of the line, the separation in the half of the cell and a change of the substrate available in the laboratory for the construction of the model.

We'll start pretending to reduce the distance between the values of βl and kl to improve the range of the evanescent wave. As we can see, as bigger is the length of the line in every cell the values of βl and kl become closer and the impedance tends to be bigger, so we start with the line of 77.773 mm, the second longer that we've studied.

We'll take the bigger radius studied, giving priority to get higher results for α in detriment of the Bloch impedance, as starting point.

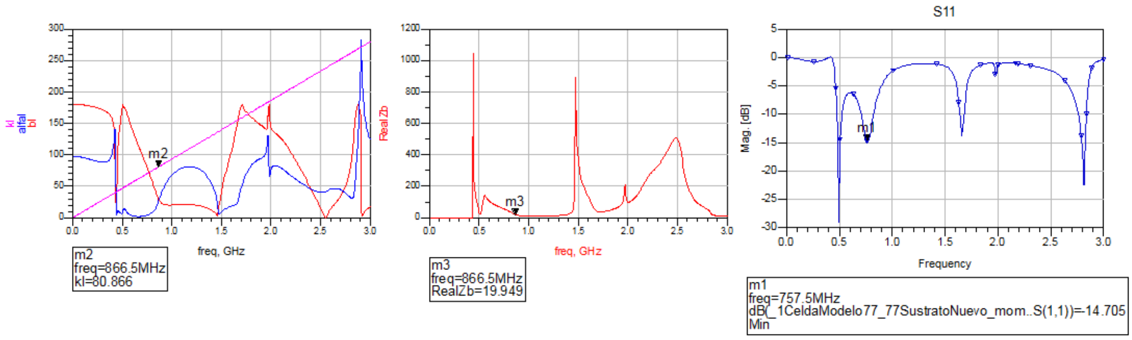


We have exaggerated taking the highest possible values, The impedance is lower than half of the value we need, and the value of βl has decreased to a very low range. We need to make some changes, but first, we'll apply the change inside the substrate and see how the results change.

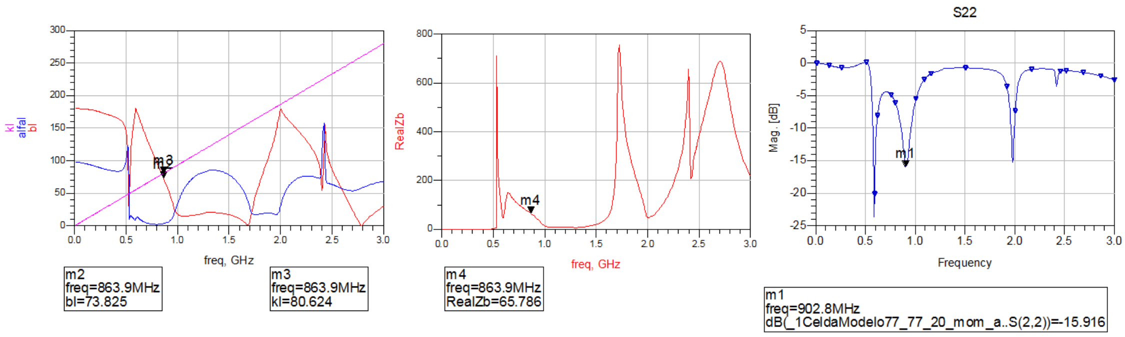
	Thickness	Er	Loss Tangent
Old Substrate	20 mil	2.33	0.009
New Substrate	30 mil	3.5	0.009

Making higher the permittivity of the substrate we'll make the phase coefficient even lower. At this point the impedance of the model is drastically low, we'll reduce the radius of the ring to improve this fact.

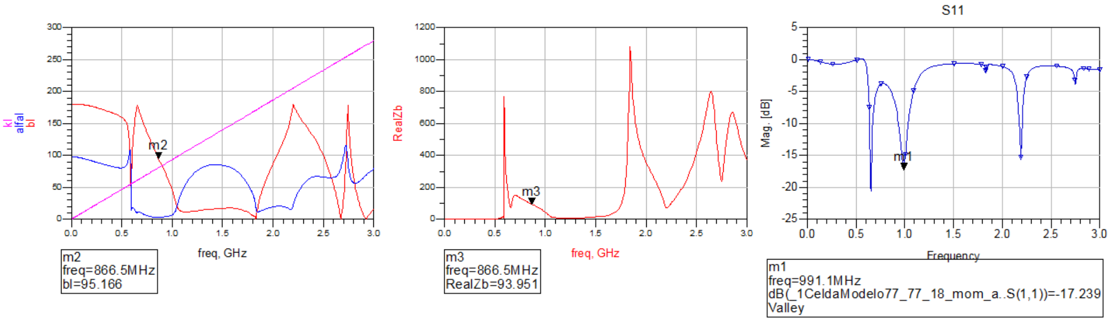
This are the results with the new substrate:



This are the results now with a ring of 20 mm of radius:

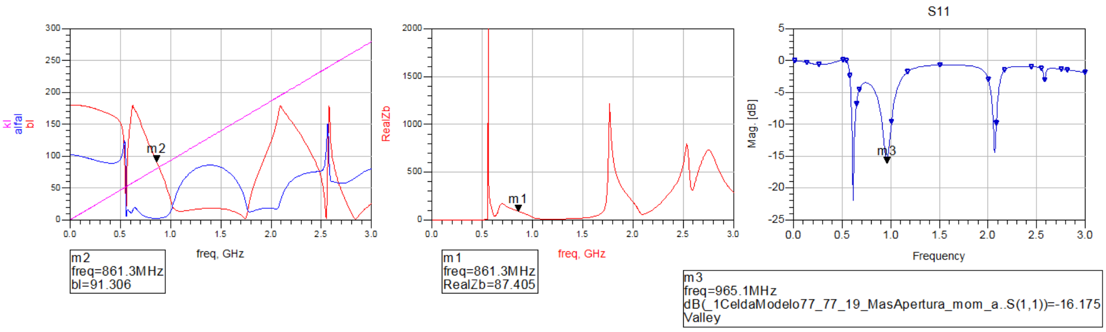


This are the results with a ring of 18 mm of radius:



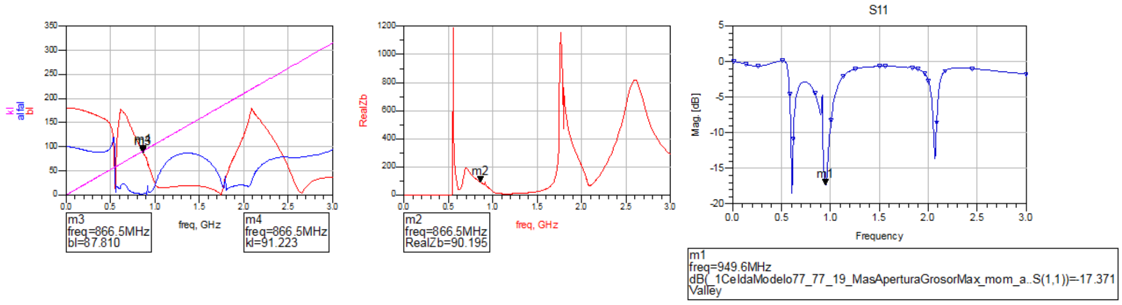
At this point, we're suffering the same problems that we have been trying to avoid before, the Zb is tending to 100, which is correct, but the phase coefficient and the frequency of maximum adaptation are getting higher. We'll try to make transformations in other parts of the design.

In this model, the ring has 19 mm of radius and the aperture inside the half of the line has been duplicated (1.45 mm).

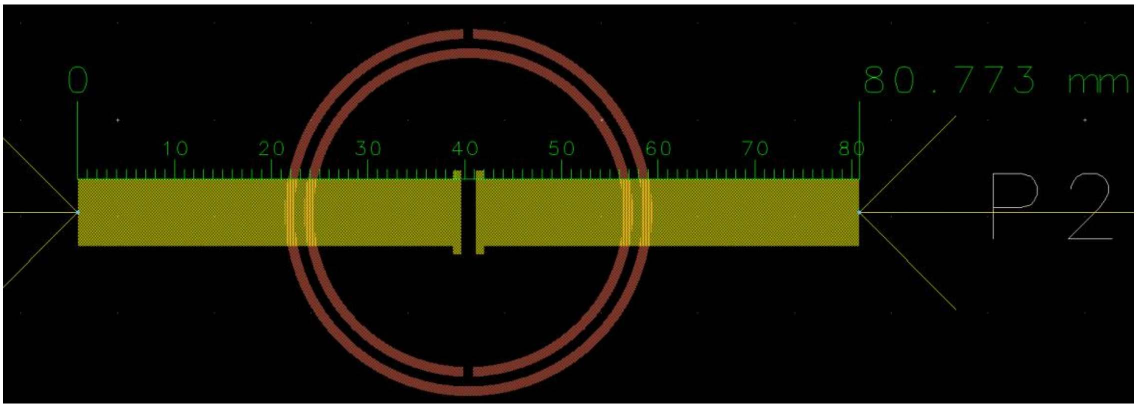


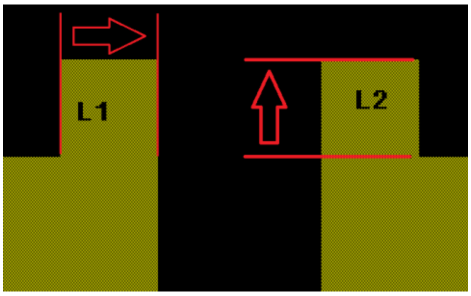
We have made bigger the width of the line from 5.82 mm to 6.984 mm, and we have updated the length of the line to 80.77 mm, a length which let us use all the space inside a V model with 40 cm available (milling machine maximum capability) and 5 cells with a little margin for maneuver.

These are the results obtained:



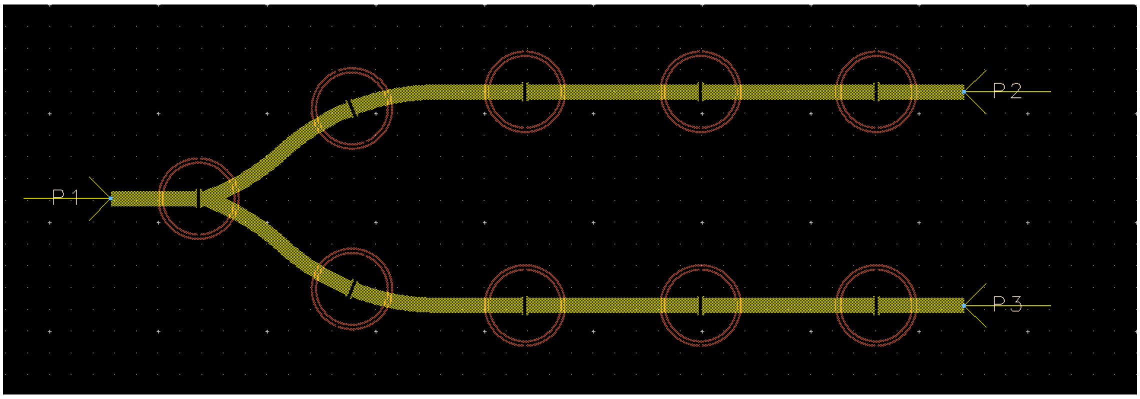
With a range near the 3 cm and a good value of impedance, we have the cell already prepared for the implementation of the V model. The frequency is higher than the desired one, but let's see how responds inside the dual model because in previous analysis tends to be lower.



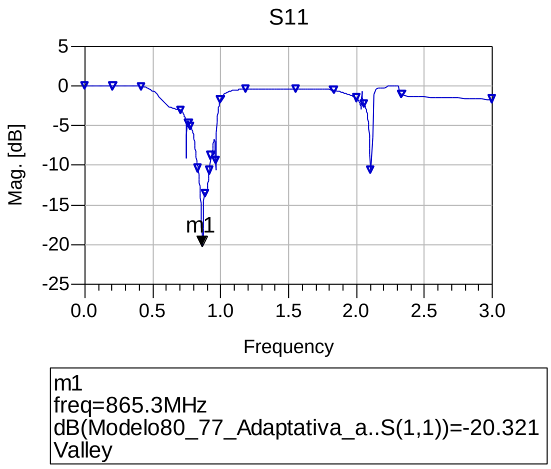


L1 = L2 = 0.872 mm

Applying this cell to the improved V-model we obtain:

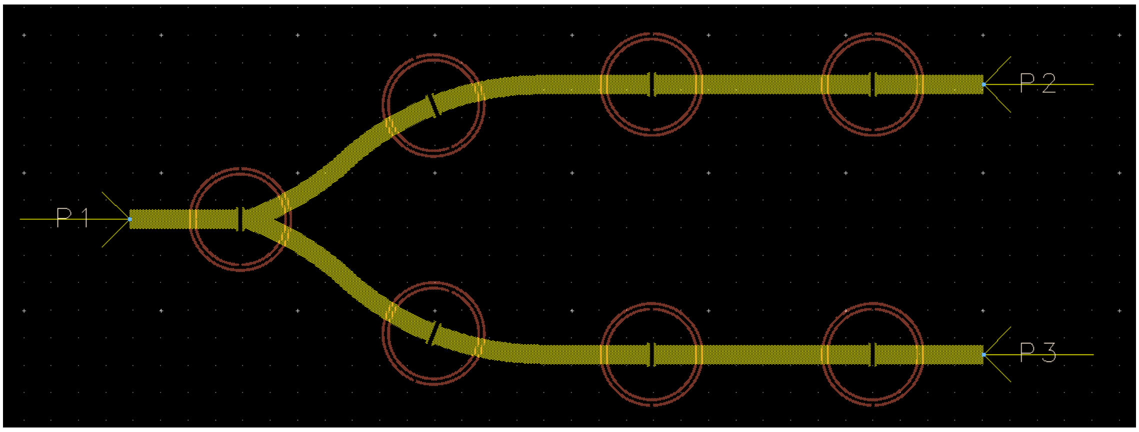


We're their S11 obtains a perfect adaptation at 865 Mhz with a bandwidth of already 100 Mhz.



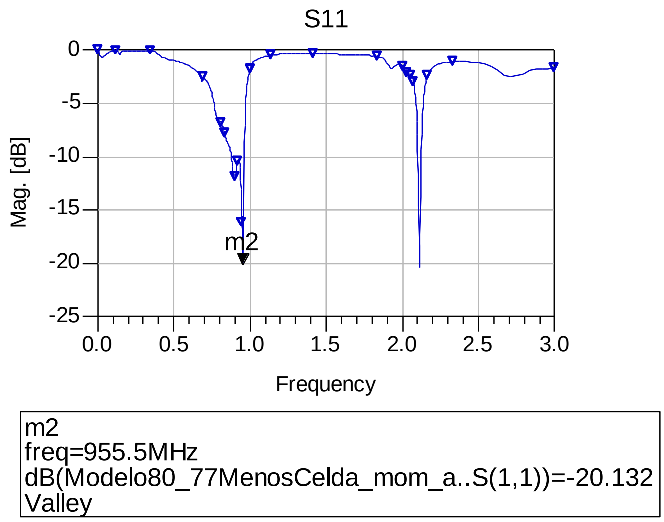
Fabrication of the model

Finally, the project has been made in the laboratories of the CIMITEC. Due to problems with the space available inside the milling machine, one cell has been eliminated from the original design. Let's evaluate this mishap of the model inside the ADS Momentum simulator, this is the model designed in the previous section *"Perfect Cell implemented in V model"* with only four cells instead five.



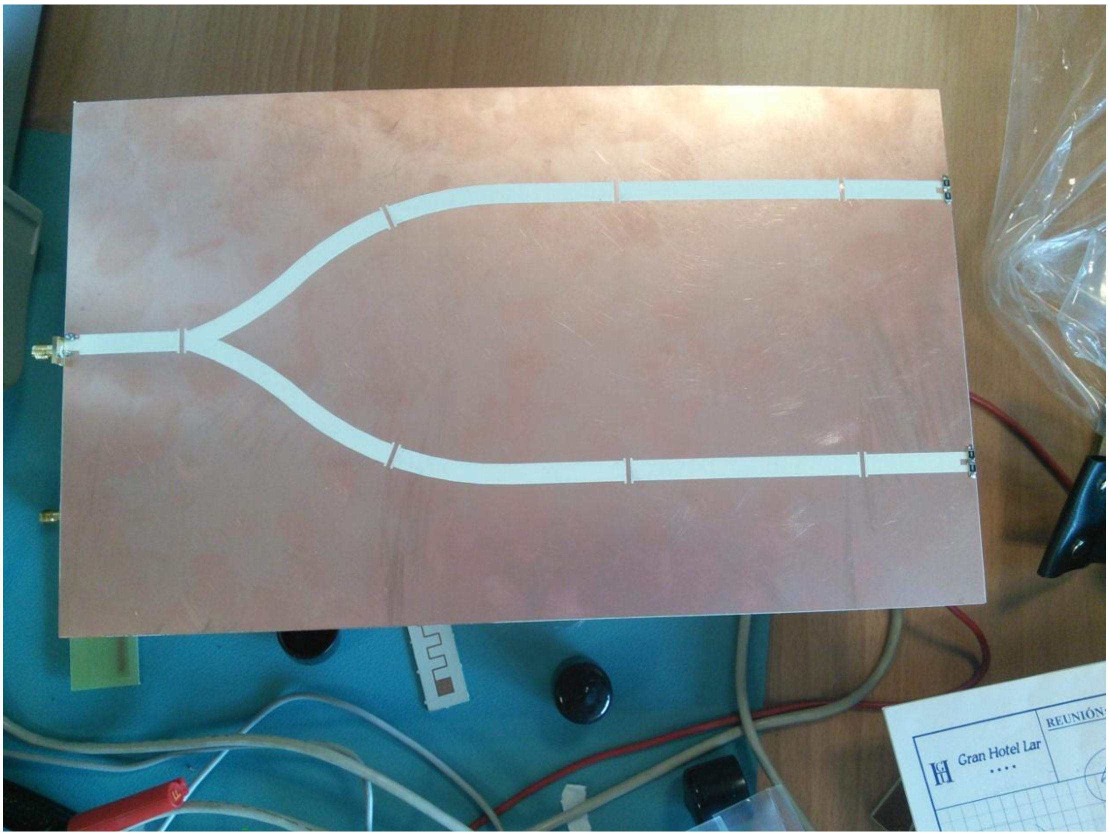
.

This is the response of the reflection matrix evaluated:

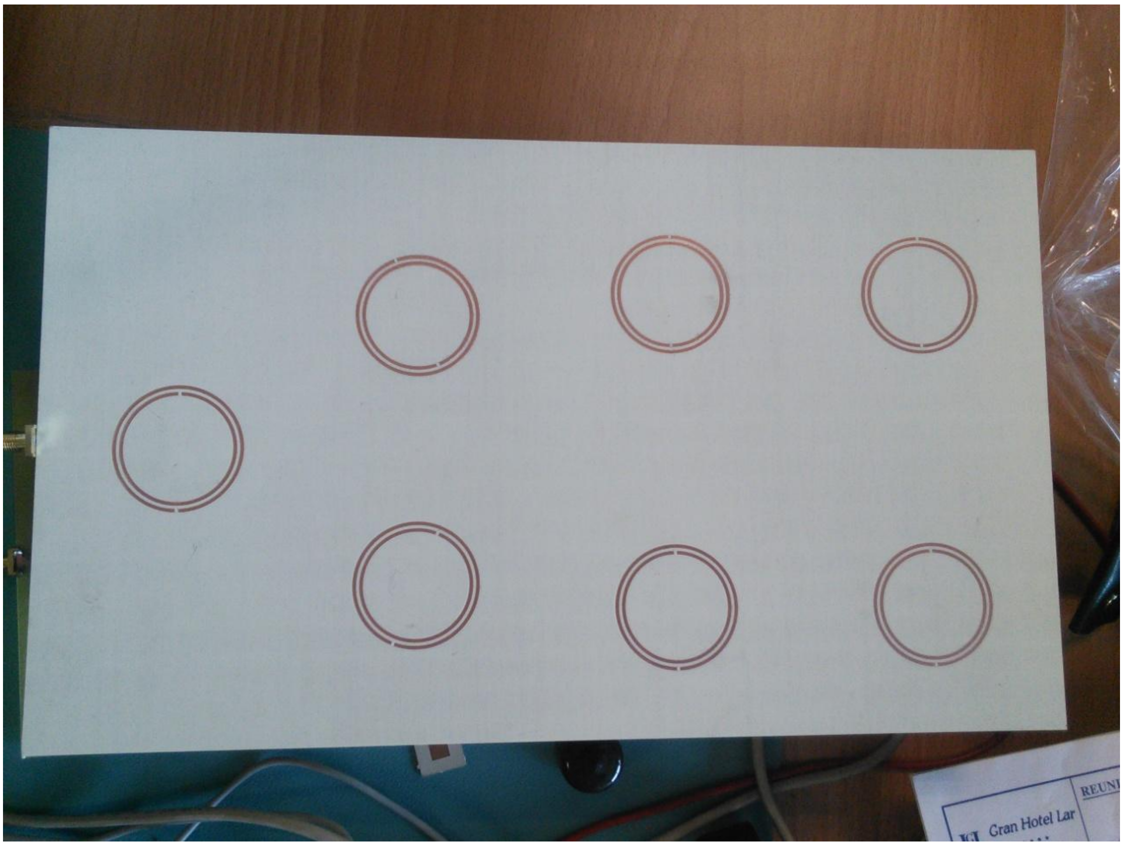


The response has a good bandwidth (values under -10 dB) but is a little high in frequency that the value that we're following. Let us hope that the manufacture of the model makes the frequency peak decreases, as often happens.

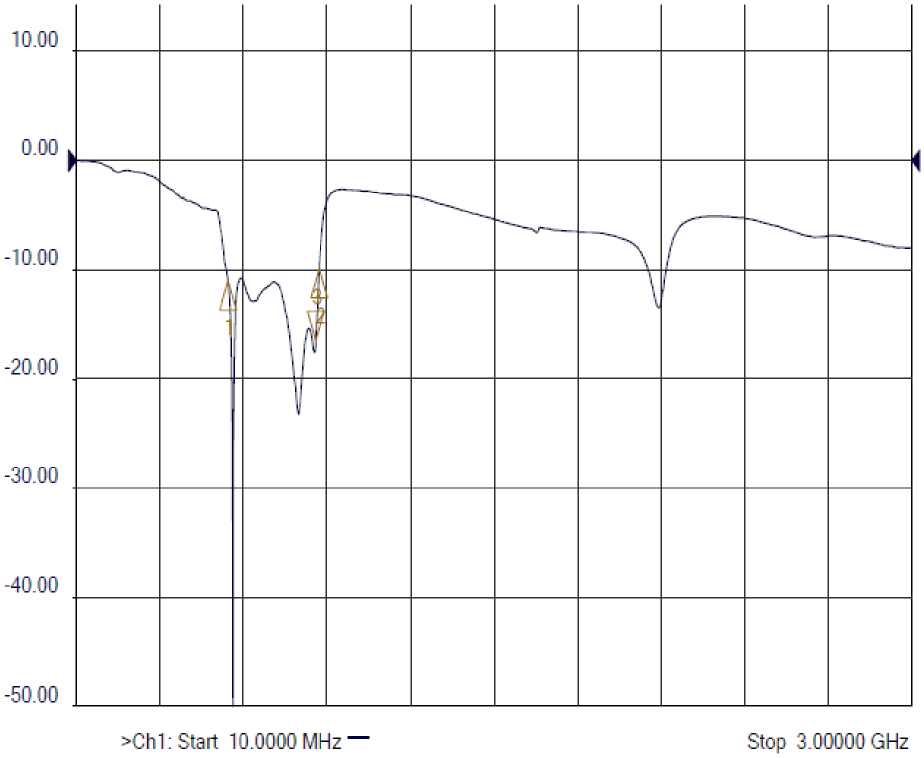
Here we have the designed reader:



The other face of the reader with the rings:



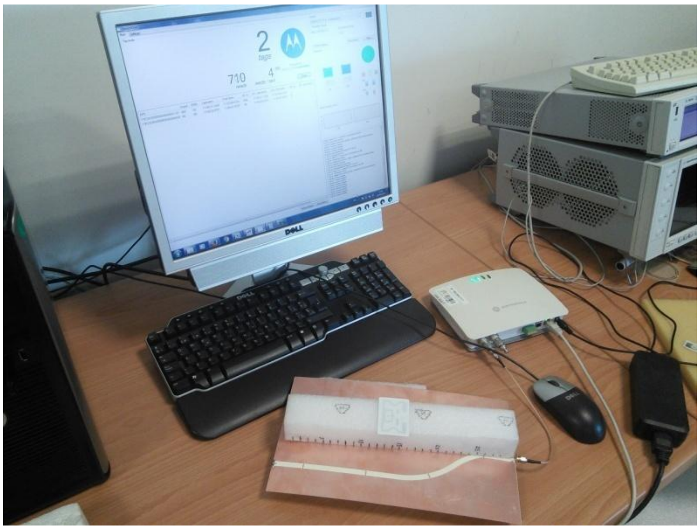
Let's taste the S11 matrix with the network analyzer of the lab:

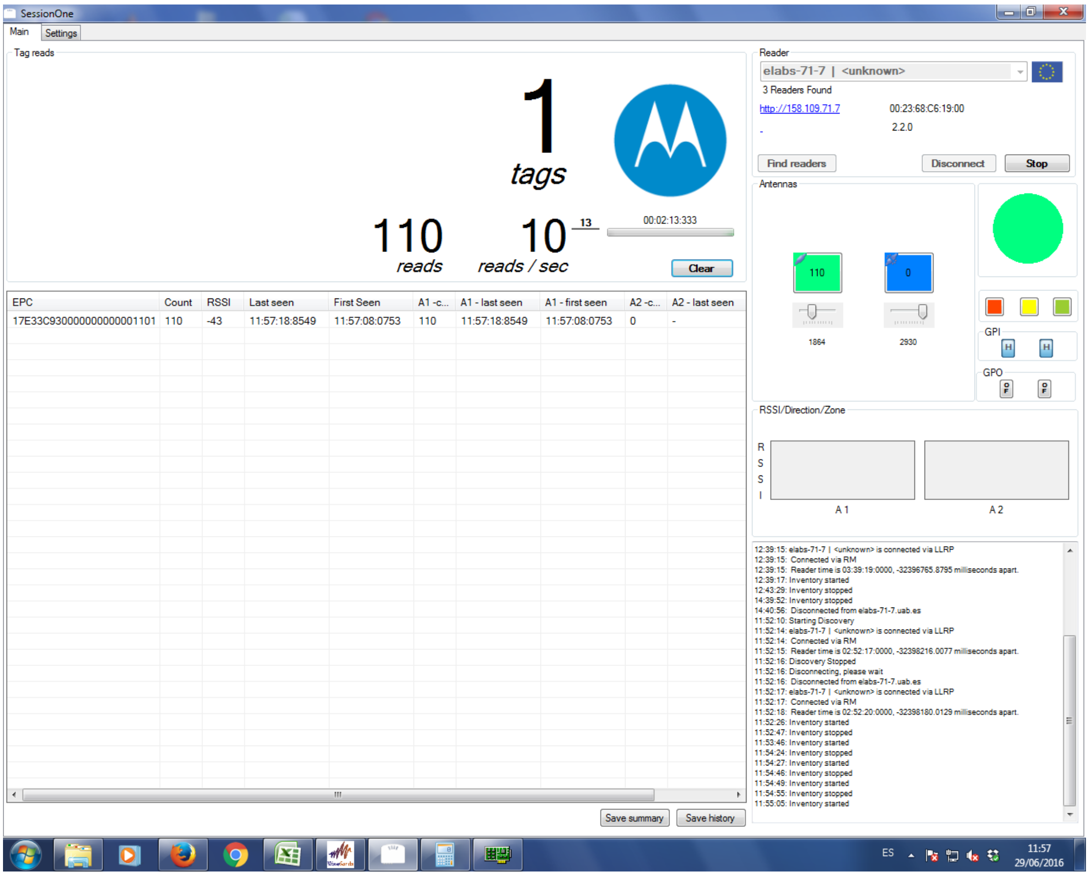


1:	553.672	MHz	-11.02 dB
2:	879.582	MHz	-9.90 dB
> 3:	867.622	MHz	-16.45 dB

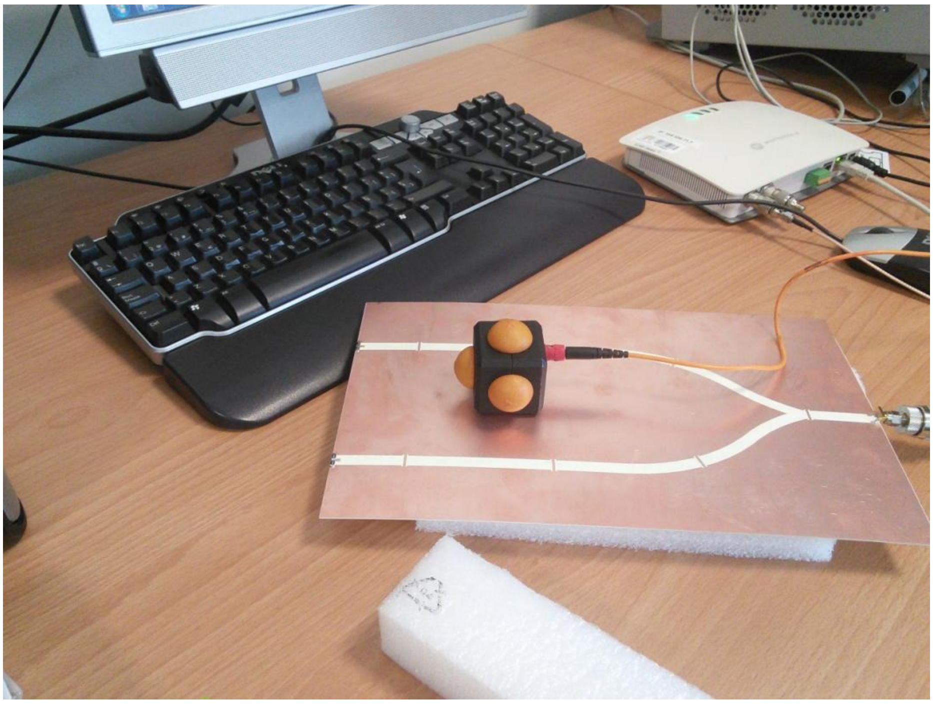
As we can see the values are not very similar to the momentum simulator ones. The frequency, as we prevent, has been decreased, but we have a bandwidth of already 300 MHz with a good transmission values.

Now let's prove if the tags are excited by the model attached to the lector:





The tag is detected, let's analyze with the field probe the range of the evanescent wave:



Evaluation of the fields at 867 MHz:

Distance (cm)	Field (V/m)
2	4.56
4	4
6	2.5
8	1.3
10	0.82
12	0.65

Evaluation of the fields at 850 MHz:

Distance (cm)	Field (V/m)
2	5.6
4	4.43
6	3.36
8	2,6
10	1.2
12	0.98

The values of the dispersion relation have been modified in the real model. Like the frequency band, the values have been decreased, but not a critical distance. Once we have passed the maximum length were the field will be present (12 cm) we have values near the 1 V/m which correspond to a residual camp radiated by the model.

Conclusions:

Here there's a synthesis of the facts achieved along the design of the project:

- We have achieved a S11 of -10 in a long range of frequencies (aprox. 300 MHz) which are below the simulated parameters but are in the range of interest too.
- The range of the evanescent wave is lower than the one calculated. However the range achieved is good.
- V model allows us to put solution to the problem of energy dispersion that appears on the corners of the dual model.

Finally we must synthesize all the experiences collected in the development of the project and the possible improvements that potential future modifications can do with the device explained along this pages.

- It's important to become familiar with the tools available in the simulator, to work with more velocity and precision.
- Without a complete study of parameters like impedance or phase coefficient in the models with more than one cell, we need to begin with a solid analysis of the working parameters in the one-cell models.
- Pay attention on the post-processing simulation, which give us another perspective of flowing waves along the model to detect stationary conditions in the design.

Potential future modifications that can be studied are:

- Don't get stuck with the limitations of the milling machine (40 cm of max. space available), add manually more cells to improve the response of the S11 matrix.
- Study chipring techniques (the SRR circles in the model have different radius) of other kinds of SRR structures: Deformed Omega Structure, etc...
- Other dispositions of the structure of the model (maybe more separation between branches or more than 2 branches to cover more area).

Blibliography:

Microwave Engineering - David M.Pozar

Antenna Theory: Analysis and design - Constantine A. Balanis

Circuits and systems integrated for communications - Course Slides - Ferran Martín

Radio Frequency IDentification (RFID) Systems - Course Slides - Jordi Bonache

Fundamental-Mode Leaky-Wave Antenna (LWA) Using Slotline and Split-Ring-Resonator (SRR)-Based Metamaterials - Gerard Zamora, Simone Zuffanelli, Ferran Paredes, Francisco Javier Herraiz-Martínez, Member, IEEE, Ferran Martín and Jordi Bonache.

Controlling the Electromagnetic Field Confinement with Metamaterials - Jordi Bonache, Gerard Zamora, Ferran Paredes, Simone Zuffanelli, Pau Aguila & Ferran Martin

Annex 1 - RFID Basics

In the introduction a short description of the RFID devices has been made. To understand more the basics about some points described along the project (like the work frequency band) this annex will describe some information about RFID devices.

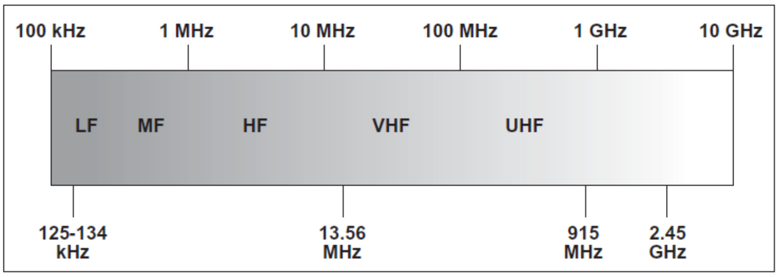
As we've said before, an RFID system is composed by the tag, the reader and the host-controller which administrates the info contained in the tags. In RFID there are both low frequency and high frequency bands:

Low frequency bands:

- LF: 125 - 134 KHz
- HF: 13.56 KHz

High frequency bands:

- UHF: 860 -960 KHz
- Microwave: 2.5 GHz



The work frequency used in the project is the Ultra-High Frequency Band (UHF), regulated by the UE (865.6 - 867.7 MHz).

<u>Backscatter</u>

An reader sends information to one or more tags by modulating an RF carrier. Tags receive their operating energy from this same modulated RF carrier and sends the information to the reader by means of a backscatter modulation of the rader's carrier.

Tag backscatter use ASK and/or PSK modulation. The tag manufacturer selects the modulation format.

<u>Performance Criteria</u>

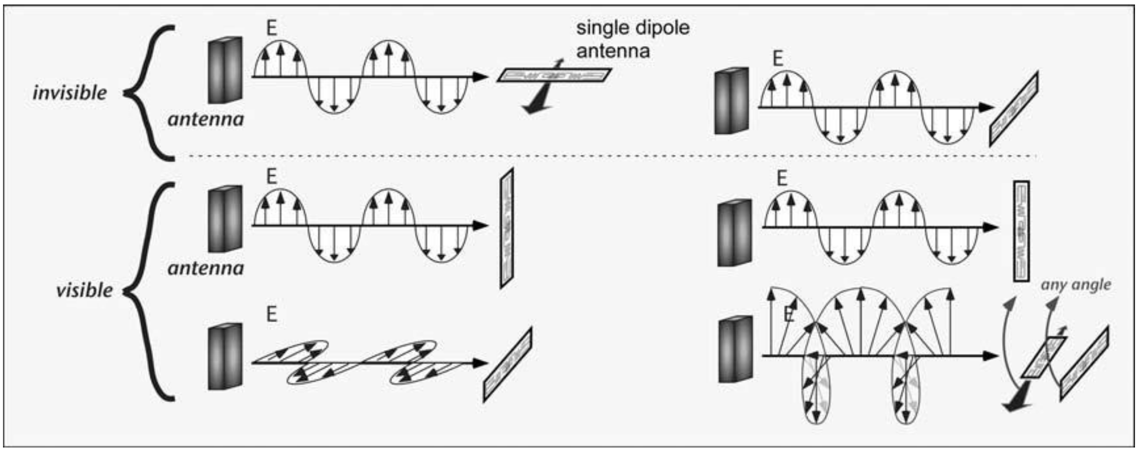
Inside the tag performance characteristics one of the most determinant is the read range (maximum distance at which RFID reader can detect the backscattered signal from the tag). Because reader sensitivity is typically high in comparison with tag, the read range is defined by the tag response threshold:

$$r = \frac{\lambda}{4\pi}\sqrt{\frac{P_t G_t G_r \tau}{P_{th}}}$$

The product $P_t G_t$ is regulated by country regulations (EIRP) and P_{th} is defined by the IC features.

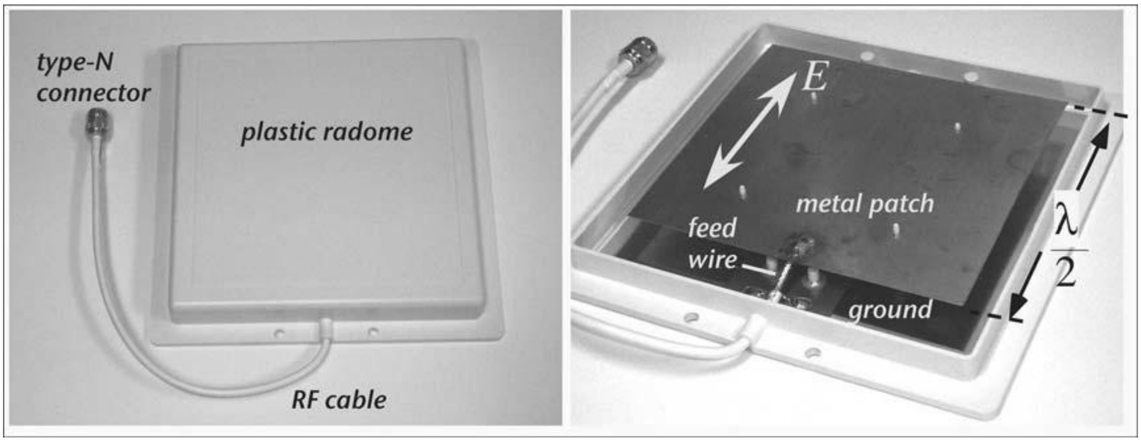
Polarization

Tag antennas are necessarily made of thin conductors and usually will have no sensitivity to radiation perpendicular to their plane. This means that some combinations of polarization and orientation will enable tags to be read, and other combinations will result in tags that are invisible to the reader's illumination.



RFID Readers

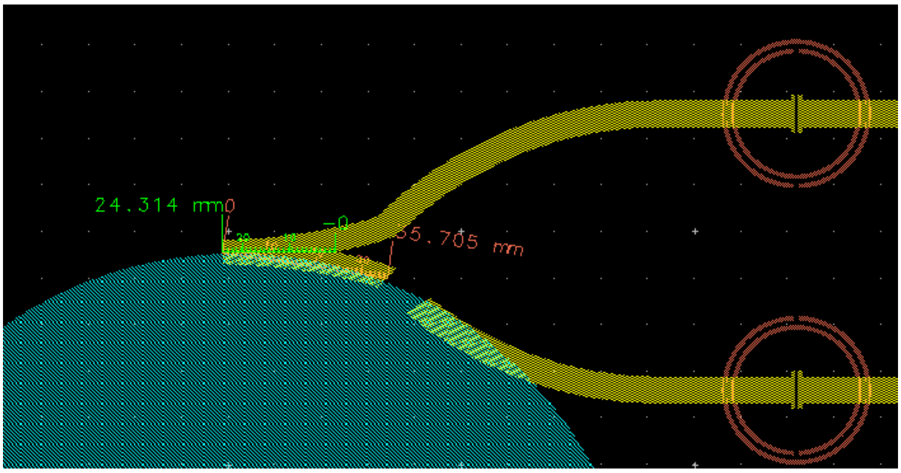
A very popular antenna for RFID reader application is the patch or panel antenna. A patch antenna gains its name from the fact that it basically consists of a metal patch suspended over a ground plane.



Annex 2 - Circumference Segments

In many parts of the design of the V model we're operating with transmission lines which are not in a straight line. There are parts of more or less large girth which, in most cases, needs to be equal to the original dimensions of the line.

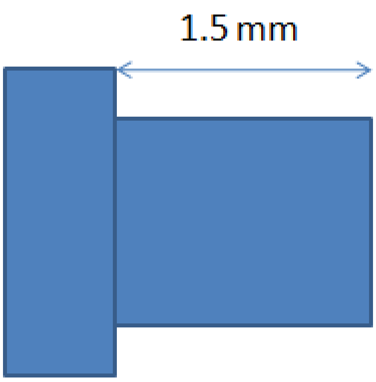
ADS2009 has tools to operate with advanced rotation angles different that the usual values (90º, 45º), these pages show the process of calculus used to implement the described line.



In the project all the models are implemented with two segments of a circumference, concatenated between them, with a big radius value to make the slope of the model be more soft. Taking the values of the line of 80.77 mm of length:

We select a radius which satisfies the conditions described in the paragraph above (106.17 mm), and knowing the length of the line we have:

- Perimeter of the entire circle: $2\pi r$ = 667.083 mm which corresponds to 360º
- With a relation of three we have that a length of 80.77 mm has an angle of α=43.6º



For the part in the beginning we take a value as a safeguard (1.5 mm) as the image shows. Now, subtracting the value from the rest of the length we have 38.787 mm. With another relation of tree we have that this corresponds to an angle of 38.8º