Politecnico di Torino

CORSO DI LAUREA MAGISTRALE IN INGEGNERIA ELETTRONICA

GUIDING ELECTROMAGNETIC SYSTEMS

Design project

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1 Introduction

The goal of this project was to design a low-pass filter using *stepped impedance* technique.
Stepped impedance represents an easy way to realize low-pass filters in microstrip and stripline. Its behaviour is based on an approximation for which a short length of transmission line having a very large characteristic impedance implies a series inductor, while a short length of line with small characteristic impedance implements a shunt capacitors.
Therefore, thanks to this approximation we can design a low-pass filter simply by alternating sections of very high and very low characteristic impedance lines.
These filters are easy to realize but, on the other hand, because of the approximations involved their electrical performances are not excellent.
The design specifications provided to us are the following:

- fixed electrical length of transmission line segment, equal to 45°;
- response type is *Equal-ripple*$(0.5\ dB)$;
- cutoff frequency is $2.4\ GHz$;
- reference impedance is $50\ \Omega$;
- more than $30\ dB$ insertion loss at $4.8\ GHz$.

In order to do this project we used three different softwares:

1. *Matlab* to compute the value of the lumped element equivalent circuit and transmission line's characteristic impedance, width and physical length;
2. *AWR* to simulate the lumped element equivalent circuit, analyze the stepped impedance realization and design its layout;
3. *Puff* to make another simulation of the circuit in order to compare the previous results.

In the following sections the steps that we have followed are shown.

2 Lumped Element Filter

2.1 Prototype Filter

First of all using the information of insertion loss and cutoff frequency we found the filter's order and the normalized element values of the low-pass prototype filter. In this step the plot of attenuation versus normalized frequency and the table of element values for equal-ripple (0.5 dB ripple level) have been used. The results are that the order of the filter is equal to 5 and the values of the normalized elements are shown in (Tab.1).

N	g1	g2	g3	g4	g5
5	1.7058	1.2296	2.5408	1.2296	1.7058

Table 1: Element values for low-pass filter prototypes of fifth order

2.2 Filter Transformations

As a second step we designed our lumped element filter starting from the prototype filter. Prototype filters are normalized designs having a reference impedance of $R_0 = 1\ \Omega$ and a cutoff frequency of $\omega_c = 1\ rad/sec$. So we scaled in terms of impedance and frequency in order to obtain the filter which respects the design specifications showed before (Sec.1). To realize this we exploited the following equations:

$$L_n = \frac{g_n \cdot R_0}{\omega_c} \tag{1}$$

$$C_n = \frac{g_n}{\omega_c \cdot R_0} \tag{2}$$

The circuits which we obtained were two: one for *PI-network*, one for *T-network*. The simulation's results of these two kinds of filter are shown below.

2.2.1 PI-network

The circuit schematic and the values of the lumped elements are shown in (Fig.1), while its frequency response in (Fig.2).

2.2.2 T-network

The circuit schematic and the values of the lumped elements are shown in (Fig.3), while its frequency response in (Fig.4).

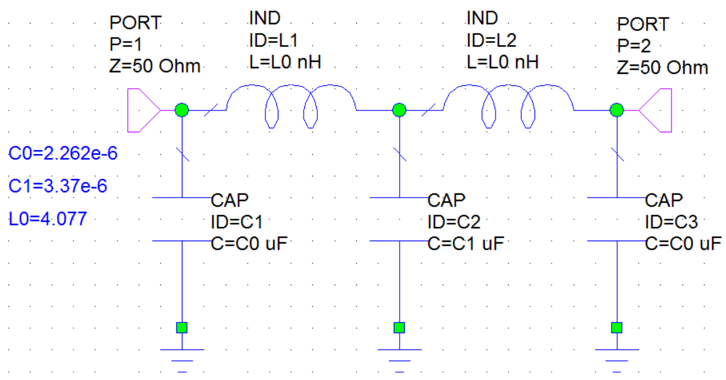

Figure 1: Circuit schematic of lumped element filter of fifth order using a PI-network

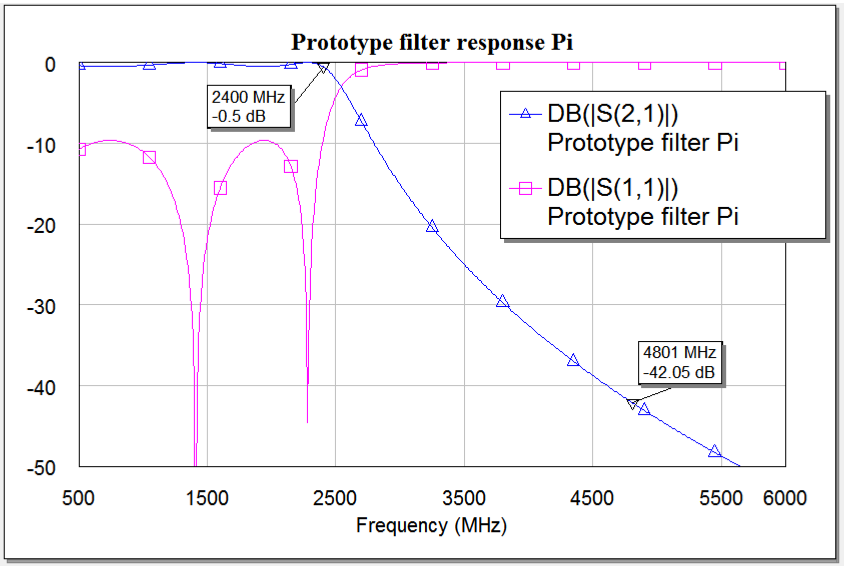

Figure 2: Frequency response of lumped element filter of fifth order using a PI-network

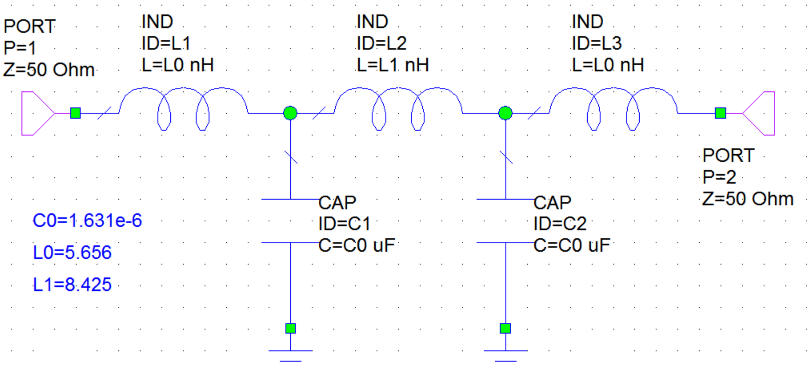

Figure 3: Circuit schematic of lumped element filter of fifth order using a T-network

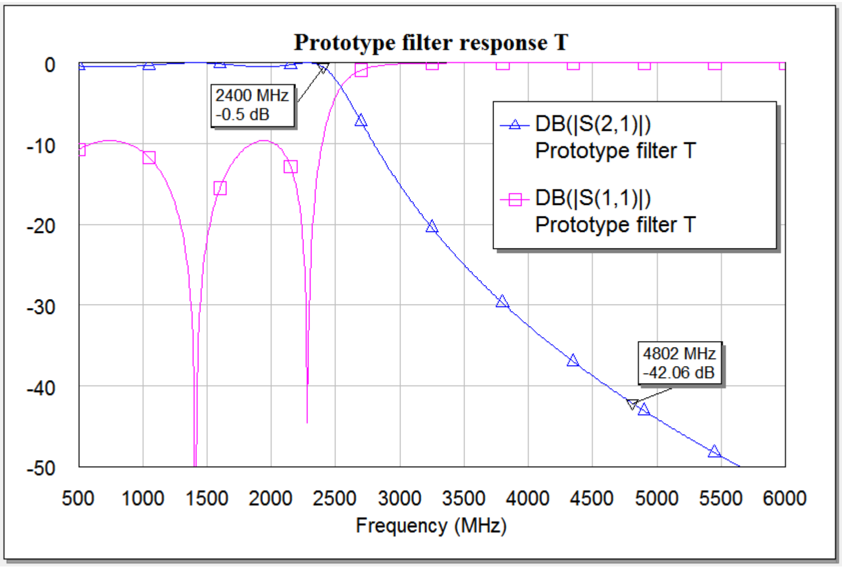

Figure 4: Frequency response of lumped element filter of fifth order using a T-network

In both types of networks it can be seen that the design specifications are satisfied.

3 Design of Microstrip

At this point, using the approximations which we mentioned in the introductive section (Sec.1), we exploited the (Eq.3) and (Eq.4) in order to determine the characteristic impedance of each transmission line's section.

$$\theta_n = \frac{g_n \cdot R_O}{Z_{hn}} \tag{3}$$

$$\theta_n = \frac{g_n \cdot Z_{ln}}{R_O} \tag{4}$$

Using the microstrip's equations (Eq.5), (Eq.6) and (Eq.7) we finally found the physical dimensions of each section of transmission line.

$$\varepsilon_{eff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2} \cdot \frac{1}{\sqrt{1 + 12 \cdot d/W}} \tag{5}$$

$$\frac{W}{d} = \begin{cases} \frac{8e^A}{e^{2A}-2}, & \text{if } \frac{W}{d} < 2 \\ \frac{2}{\pi}\left[B - 1 - ln(2B-1) + \frac{\varepsilon_r - 1}{2\varepsilon_r}\left(ln(B-1) + 0.39 - \frac{0.61}{\varepsilon_r}\right)\right], & \text{if } \frac{W}{d} > 2 \end{cases} \tag{6}$$

Where:

$$A = \frac{Z_0}{60}\sqrt{\frac{\varepsilon_e + 1}{2}} + \frac{\varepsilon_r - 1}{\varepsilon_r + 1}\left(0.23 + \frac{0.11}{\varepsilon_r}\right)$$

$$B = \frac{377\pi}{2Z_0\sqrt{\varepsilon_r}}$$

$$l = \frac{\theta \cdot c}{\omega_c \cdot \sqrt{\varepsilon_{eff}}} \tag{7}$$

So, finally the results that we obtained for the PI and T networks are shown in (Tab.2) and (Tab.3) respectively.

Number of Step	**1**	**2**	**3**	**4**	**5**
Impedance $[\Omega]$	23.021	78.279	15.456	78.279	23.021
Width $[mm]$	6.50	1.05	10.48	1.05	6.50
Length $[mm]$	10.365	10.991	10.218	10.991	10.365

Table 2: Physical quantities of PI-network

Number of Step	**1**	**2**	**3**	**4**	**5**
Impedance $[\Omega]$	108.59	31.937	161.75	31.937	108.59
Width $[mm]$	0.516	4.384	0.157	4.384	0.516
Length $[mm]$	11.181	10.506	11.408	10.506	11.181

Table 3: Physical quantities of T-network

In order to verify these results we used *TXLine*, a simple tool of *AWR* which gives us physical characteristics starting from material parameters and electrical characteristics. The quantities which we found from this step aren't exactly the same previously shown but they are close enough to those.

4 Simulation

After the check step we simulated the two different networks (using *AWR*). The following figures (Fig. 5) and (Fig.6) show the plots of the frequency response of the filters.

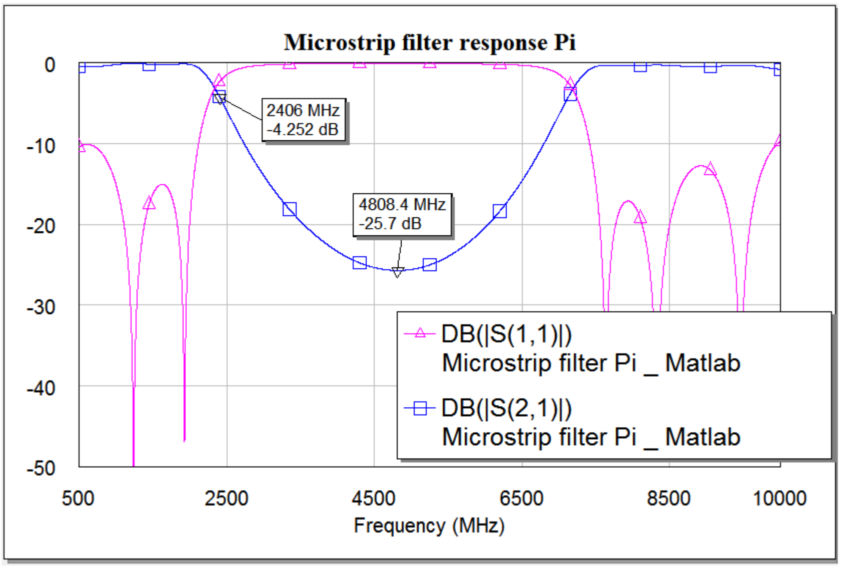

Figure 5: Frequency response of stepped impedance filter of fifth order using PI-network

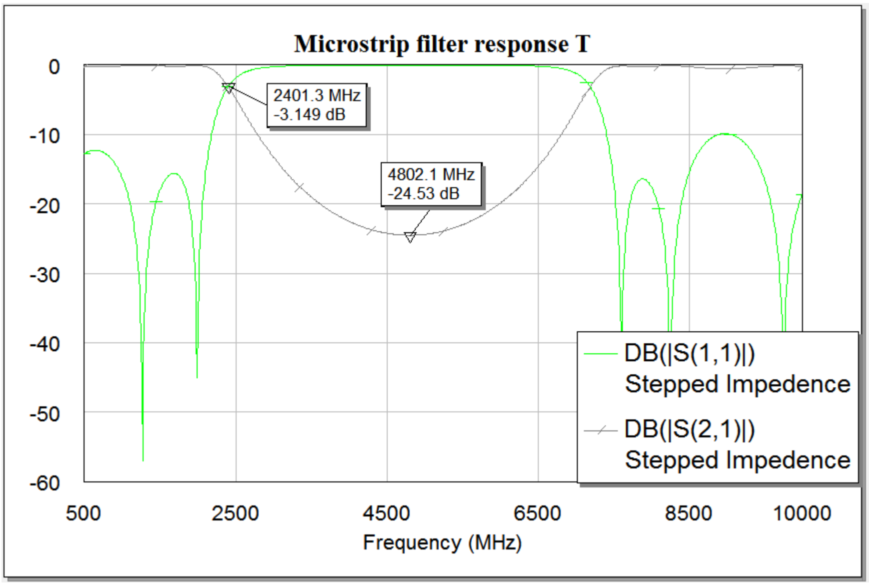

Figure 6: Frequency response of stepped impedance filter of fifth order using T-network

Unfortunately, the simulation shows that these stepped impedance filters don't satisfy the design specifications.

What we can immediatly see is that the lumped-element filter gives more attenuation out of the passband. This is due to two different phenomenas:

- the stepped-impedance filter elements differs from the corresponding lumped-element values at higher frequencies;
- the stepped-impedance filter's response is periodic, in fact there are other passbands at higher frequencies.

So, we tried to satisfy the specification realizing a seventh order filter. Repeating the same steps as above for both networks, the filters obtained meet the specification about the insertion loss at 4.8 GHz but they have a ripple in bandwidth bigger than 0.5 dB and at cutoff frequency the response has an insertion loss too high.
The (Fig.7) shows what has just been said for the *Pi-network*.

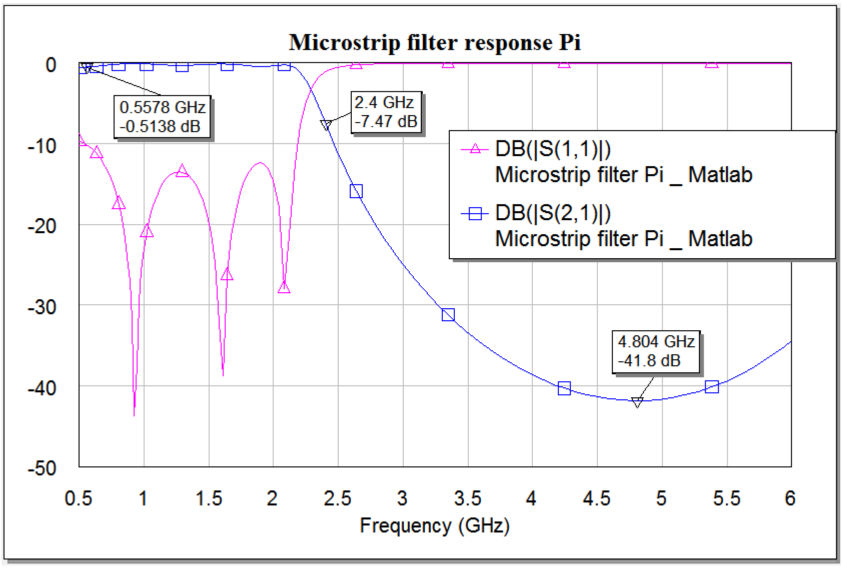

Figure 7: Frequency response of stepped impedance filter of seventh order using Pi-network

4.1 Optimizer

In order to try to obtain a better result we also performed an optimization using the AWR's built-in optimizer. This optimizer works in a really simple way: starting from our project (microstrips width) it tries different values for the selected parameter (running for every attempt the complete simulation), according to different possible algorithms, and stops when it finds a combination of values which make the design satisfy the given constraints. We used the gradient algorithm which is slower than others but more accurate. It starts from the current values and modifies them a little bit in every direction (in the state variables space) in order to find the direction in which the cost function decreases, then it follows this direction until it finds the minimum of the cost function. The result is a structure that respects very well the constraint on the insertion loss at 4.8GHz but starts to cut before 2.4GHz. More over it has an higher reflection coefficient in-band and it is no more symmetric, so we chose not to use this optimized design.

4.2 Simulation with Puff

Before drawing the circuit layout, we did another circuit simulation with *Puff* in order to observe if the results which we had previously obtained with AWR were correct.
The *T-network* type can't be simulated with this CAD software because it requires too narrow transmission lines (this is the reason why we chose to realize the layout of *Pi-network* type).
The simulation's screen is shown in (Fig.8).

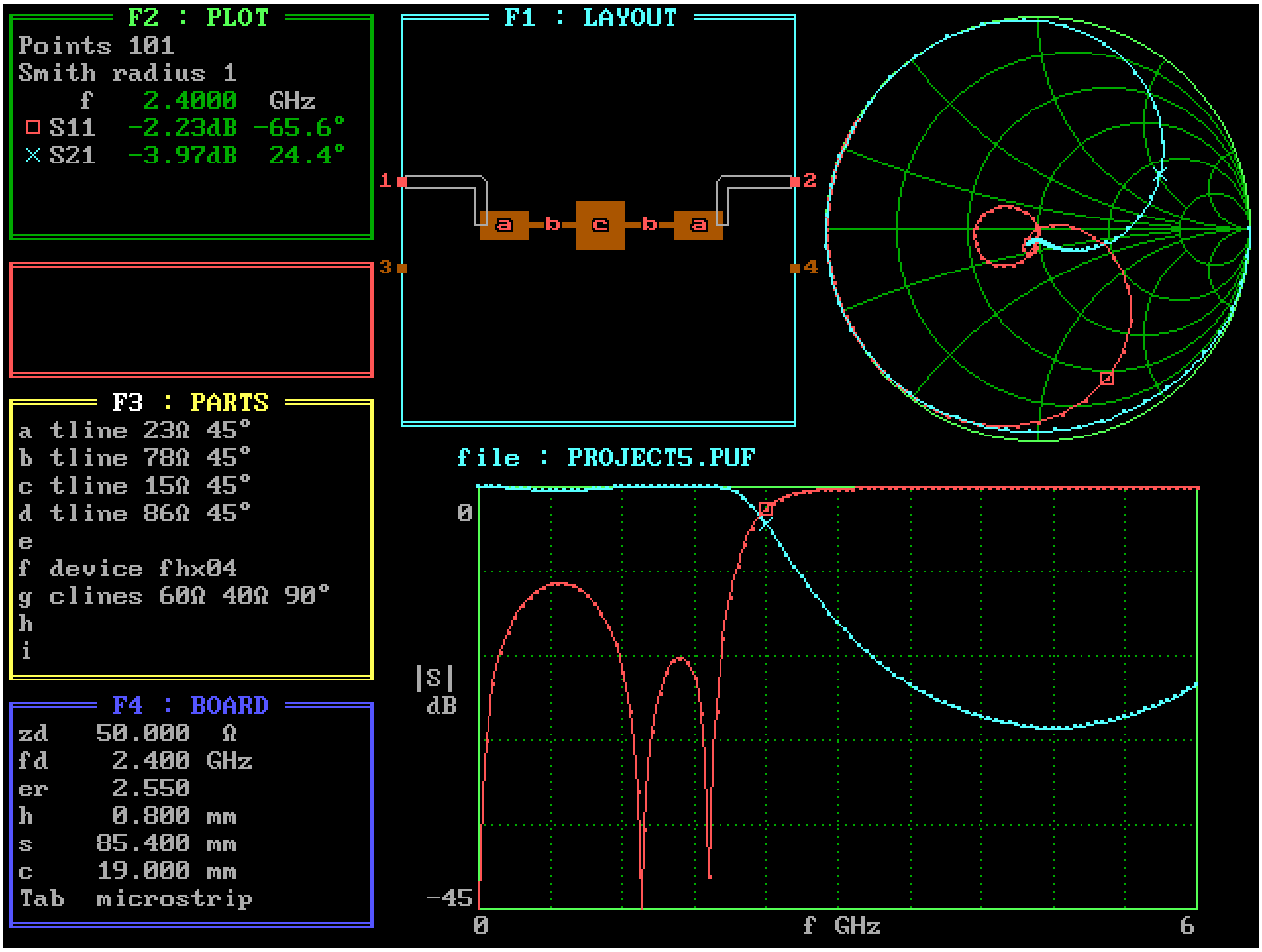

Figure 8: Circuit simulation with Puff

5 Layout

The last step which we made on the computer is to draw the layout of transmission line.
As previously said, we chose the fifth order filter using *Pi-network* type.
The layout is shown in (Fig.9) and it has been designed again using *AWR*.

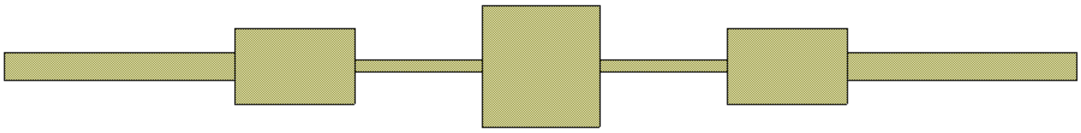

Figure 9: Layout of stepped-impedance filter

6 Measures and Conclusions

During the lab session we had the chance to measure the performances of the physical microstrip low-pass filter that we've designed in this project. The filter is shown in (Fig.10).

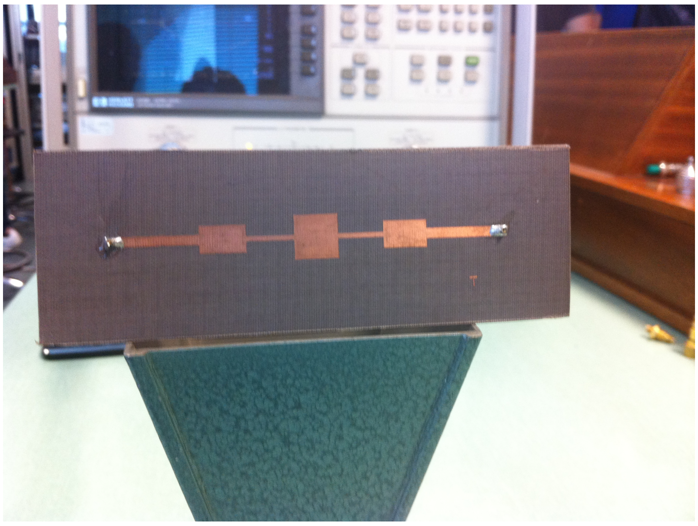

Figure 10: Microstrip Low-Pass Filter.

First of all, we made sure that the physical dimensions of the transmission line were the same calculated in the design section (Sec.3). After this fast check, we set the network analyzer's frequency between 1 and 6 GHz, and after the calibration of the equipment we were able to start the measurements. Finally, we connected the filter as shown in (Fig.11).

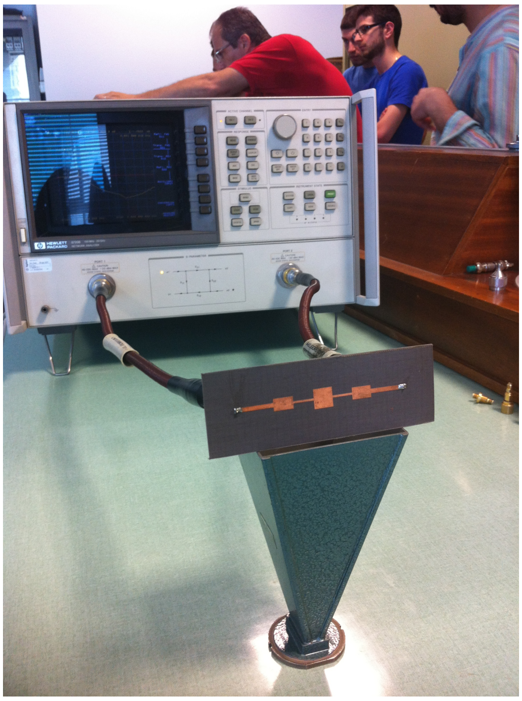

Figure 11: Network analyzer HP-8720B connected to the Low-Pass Filter.

The first required specification that we checked was the 3dB cutoff frequency. This measurement, which was made by checking the scattering matrix parameter S21, is shown in (Fig.12).

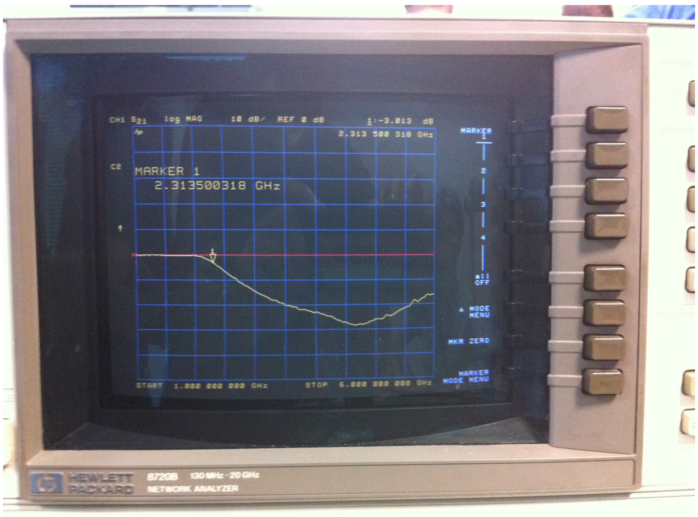

Figure 12: Scattering parameter S21.

As the picture shows, the 3dB cutoff frequency is about 2.31GHz.
Then we found the 0.5dB cutoff frequency to be approximately 2.08GHz, due to the non-idealities of the stepped impedance technique. However, this was forecast by the previous simulations.
The next specification checked was the insertion loss. The (Fig.13) shows a 28dB insertion loss at 4.8GHz. We expected to get 30dB insertion loss at the same

frequency, so the circuit approximates well the expectations.

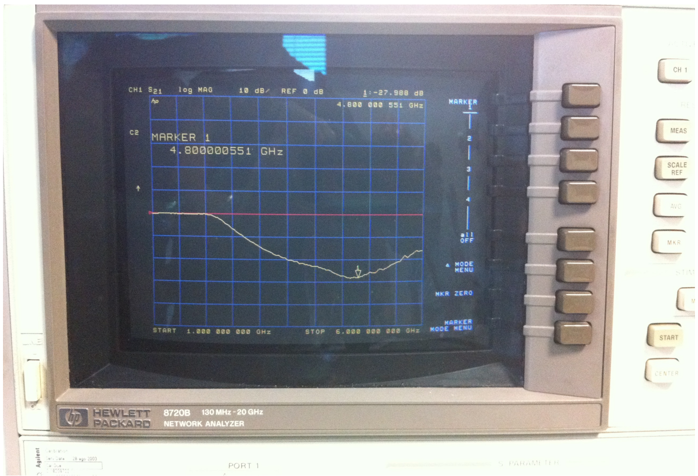

Figure 13: Insertion loss measurement.

The last thing we checked was the scattering matrix parameter S11. The network analyzer screen of this case is shown in (Fig.14).

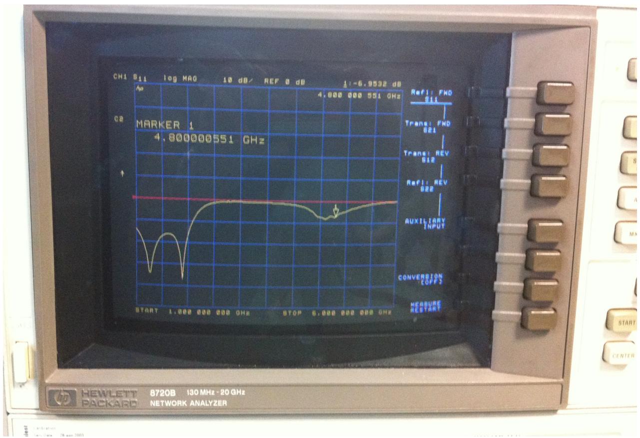

Figure 14: Scattering parameter S11.