

# Project of microwave filter for RADAR systems

André Silva

*Instituto Superior Técnico*  
*andre.silva@tecnico.ulisboa.pt*

**Abstract**— The current project fits the theme of microwave filters. Using as base the subject of the design and synthesis of these filters, a microwave filter focused on radar systems was designed.

This subject is relevant due to the great use of these types of structures in modern telecommunications systems like air surveillance radar systems.

Multiple sources were examined, so that a waveguide filter with resonant cavities could be designed. The designed structure was then tested using the software CST Studio Suite®, where we could observe that, after optimization, the structure could be used as a microwave filter working in the frequency band of the air surveillance radar systems.

At the end of this project, a concise and complete procedure for the design and synthesis of waveguide cavity filters could be presented. Said procedure could be used for other projects that could use waveguide cavity filters.

**Keywords**— Pass-band filters, Microwave, Resonant cavities, Iris, Periodic structures, Waveguides.

## I. INTRODUCTION

Microwave and millimetric waves are used in various areas such as telecommunications, military systems, medicine, etc. During World War II, with the emergence of high-resolution radar systems, its importance became evident.[1]

Due to the various uses of microwave and millimetric waves, the design of filters gains a great importance. This importance is also increased due to the expansion of mobile telecommunications systems in recent years, which led to a demand of microwave filters with higher precision and slimmer bandwidths. As such with this project an example of a microwave filter for an air control system will be developed, and a process for the development of such filters may be achieved for future applications.

## II. WAVEGUIDES AND RESONANT CAVITIES

Waveguides are structures that allow electromagnetic waves to propagate along a certain route. These structures are of particular use in high frequency systems such as microwave systems. [2] Depending on their dimensions and format, different propagation modes can be present inside those waveguides. In this work we will make use of rectangular waveguides, since they are most useful for the construction of microwave filters. [2]

Each propagation mode has a cut-off frequency that can be determined by:

$$f_{cmn} = \frac{1}{2\pi\sqrt{\mu\epsilon}} k_c c \quad (1)$$

Where:

$$k_c = \sqrt{\left(\frac{m\pi}{a}\right)^2 + \left(\frac{n\pi}{b}\right)^2} \quad (2)$$

If you close one of the sides of the waveguide you get a resonant cavity, that allows to store energy under the form of stationary waves, since this allows the possibility of the waves being reflected and traveling in the opposite direction. Like the rectangular waveguide, depending on the dimensions of the cavity, each cavity has a resonant frequency that can be computed by:

$$f_{mnl} = \frac{1}{2\pi\sqrt{\mu\epsilon}} k_{mnl} \quad (3)$$

Where:

$$k_{mnl} = \sqrt{\left(\frac{m\pi}{a}\right)^2 + \left(\frac{n\pi}{b}\right)^2 + \left(\frac{l\pi}{d}\right)^2} \quad (4)$$

Microwave resonant cavities can be represented and thought of as simple LC circuits. For a microwave cavity, the stored electric energy is equal to the stored magnetic energy at resonance as is the case for a resonant LC circuit. As such filter design techniques can be used to make microwave filters.[3]

### III. INSERTION LOSS METHOD AND FILTER DESIGN

In the design of filters using the insertion loss method, the response of the filter is defined by its insertion loss or by its power loss ratio  $P_{LR}$  [4].

It's possible to obtain the insertion loss from the power loss ration using the expression below:

$$IL = 10 \log P_{LR} \quad (5)$$

For Chebyshev filters we have:

$$P_{LR} = 1 + k^2 T_N^2 \left( \frac{\omega}{\omega_c} \right) \quad (6)$$

where  $T_N^2 \left( \frac{\omega}{\omega_c} \right)$  is the  $N$  order Chebyshev polynomial and  $c$  is the cut-off frequency.

We can then say that the insertion loss is:

$$IL \approx 10 \log \left( \frac{k^2}{4} \left( \frac{2\omega}{\omega_c} \right)^{2N} \right) \quad (7)$$

With  $N$  being the filter order.

Knowing the filter order, it is possible to design a low pass prototype filter as shown in the figure below.

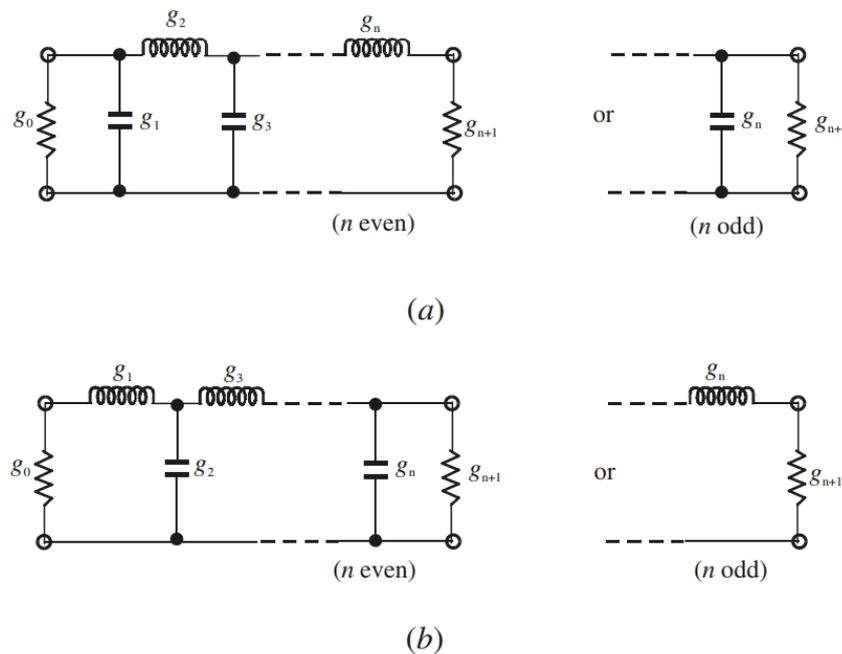


Figure 1: Low pass prototype filter: (a) Pi scheme; (b) T scheme [5].

$$g_{N+1} = \begin{cases} 1 & N \text{ ímpar} \\ 2k^2 + 1 - 2k\sqrt{1+k^2} & N \text{ par} \end{cases} \quad (8)$$

With

$$k = \sqrt{10^{L_{Ar}/10} - 1} \quad (9)$$

and  $L_{Ar}$  is the bandpass ripple.

The rest of the parameters are computed following the expressions below:

$$g_k = \frac{4a_{k-1}a_k}{b_{k-1}g_{k-1}} \quad (10)$$

$$a_k = \sin \frac{2k-1}{2N} \pi \quad (11)$$

$$b_k = \sinh^2 \frac{\beta}{2N} + \sin^2 \frac{k\pi}{N} \quad (12)$$

$$\beta = \ln \frac{\sqrt{1+k^2}+1}{\sqrt{1+k^2}-1} \quad (13)$$

$$g_1 = \frac{2a_1}{\sinh \beta/2N} \quad (14)$$

The values can also be obtained through tables that were compiled by other authors.

The values obtained are for a prototype lowpass filter normalized with source impedance of  $1\Omega$  and cut-off frequency  $1 \text{ rad/s}$ , like the one represented in the figure below, therefore it is necessary to transform the prototype lowpass filter into a bandpass filter.

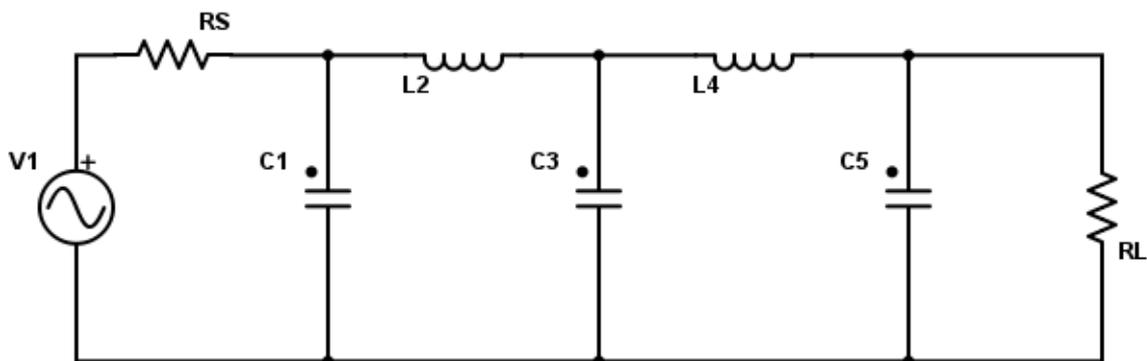


Figure 2 – Low pass filter.

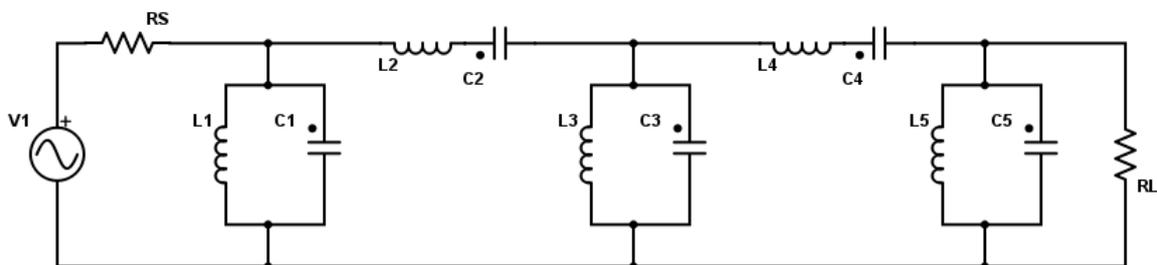


Figure 3 – Bandpass filter.

The transformations possible are impedance and frequency scaling, transform from lowpass to highpass filter and from lowpass to bandpass or stopband filter [6].

From the lowpass prototype filter we can obtain a bandpass filter as the one shown below.

The series inductors are switched to an inductor and a capacitor in series, and the shunt capacitors are switched to a shunt inductor and capacitor. The values of these new elements can be obtained following the expressions presented below:

$$L'_k = \frac{L_k}{\Delta\omega_0} \quad (15)$$

$$C'_k = \frac{\Delta}{\omega_0 L_k} \quad (16)$$

$$L'_k = \frac{\Delta}{\omega_0 C_k} \quad (17)$$

$$C'_k = \frac{C_k}{\Delta\omega_0} \quad (18)$$

Where the values  $L_k$  and  $C_k$  are the elements we are switching from the lowpass prototype filter and the fractional bandwidth obtained by:

$$\Delta = \frac{\omega_2 - \omega_1}{\omega_0} \quad (19)$$

The filter design until this point uses lumped elements, but for high frequencies

like the ones used in microwave systems it is necessary to implement the desired circuit in distributed elements.

#### IV. IMPLEMENTATION

One of the strategies used for the implementation of microwave filters is the use of impedance or admittance inverters. This allows the representation of our filter as a network of shunt or series LC resonators. As we can see in figure 4.

For admittance inverters you would have the same network but with shunt LC resonators.

The idea behind the use of these inverters is to get a network where all elements are either in series or shunt. For this a series LC resonator between two impedance inverters, as show in the picture, is the same as a shunt LC resonator as we had previously from our filter design.

The value of the impedance inverters is related to the resonator we want to change to a series element and can be computed by the following expression:

$$K = \sqrt{\frac{L}{C_1}} \quad (20)$$

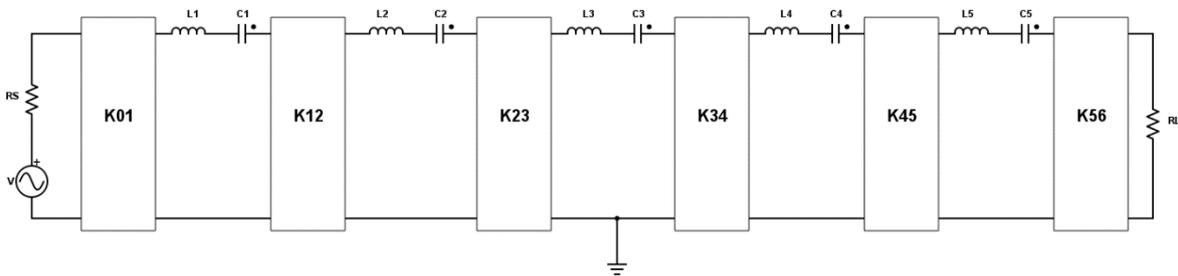


Figure 4 – Bandpass filter with impedance inverters.

One approach that makes use of these impedance and admittance inverters is the case where waveguide resonators are modeled with transmission lines, while the coupling inductive waveguide windows are modeled by ideal impedance inverters.

To model the waveguide resonators with transmission lines we need to calculate the slope parameter  $X_i$  of the transmission line, in order to replace the LC resonator. The slope parameter can be determined by:

$$X_i = \frac{\omega_0}{2} \frac{dX}{d\omega} \text{ when } \omega = \omega_0 \quad (21)$$

That applied to a resonant cavity in waveguides takes can be simplified as:

$$X = \frac{\pi}{2} Z_0 \left( \frac{\lambda_{go}}{\lambda_0} \right)^2 \quad (22)$$

So, for a waveguide the normalized values of our impedance inverters take the form of: [3]

$$\frac{K_{01}}{Z_0} = \frac{\sqrt{R_S x \Delta}}{g_0 g_1} \quad (23)$$

$$\frac{K_{j,j+1}}{Z_0} = \frac{\Delta x}{g_j g_{j+1}} \quad (24)$$

$$\frac{K_{n,n+1}}{Z_0} = \frac{\sqrt{R_L x \Delta}}{g_n g_{n+1}} \quad (25)$$

The last step in the filter design is to obtain the physical dimension of the structure we want to build. With normalized values of the impedance inverters it is possible to compute the  $S_{21}$  parameter, using the following expression:

$$|S_{21}| = \frac{2Z_0}{K + \frac{Z_0^2}{K}} = \frac{2}{\frac{K}{Z_0} + \frac{Z_0}{K}} \quad (26)$$

This parameter is of relevance because it allows us to determine the physical dimension of the iris as shown in figure 5.

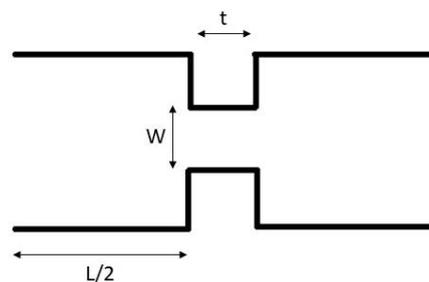


Figure 5 – Iris structure.

Making use of simulation software like CST Studio Suite®, a structure like the one in figure 5 is used, to obtain the parameter  $S_{21}$ . That value is compared to the theoretical value computed using equation 26. If the value obtained through simulation is larger than the one obtained theoretically you increase the width of the iris, and if it is inferior that width is decreased. This iterative process is repeated until you obtain the theoretical value.

Now we will determine the length of each cavity present in the structure.

If we have a cavity, and it is charged by a short circuit, then the length will be  $l = \lambda_g/2$  and its phase will be  $\beta l = \frac{2\pi}{\lambda_g} \frac{\lambda_g}{2} = \pi$ .

Since the iris are considered complex impedances, the phase and the central frequency of the cavities will be altered with the introduction of the cavities. In order for the resonance frequency to be desired, the length of the cavity must be changed. The electrical length in this case will be:

$$\beta l = \frac{2\pi l}{\lambda_g} = \pi - \alpha_1/2 - \alpha_2/2 \quad (27)$$

Where  $\alpha_1$  is the length in cavity degrees due to port 1 and  $\alpha_2$  is the length of the cavity due to port 2.

In this way we can say that the length of the cavity is obtained by the following relationship:

$$l = \frac{\lambda_{g0}}{2\pi} (\pi - \alpha_1/2 - \alpha_2/2) \quad (28)$$

Since the relationship between the phase of  $S_{11}(\varphi)$  and  $\alpha$  is  $\alpha = \pi - \phi$ , then the cavity length will be of the form [7]:

$$l = \frac{\lambda_{g0}}{4\pi} (\phi_1 + \phi_2) \quad (29)$$

Where  $\phi_1$  is the phase of  $S_{11}$  for the first iris and  $\phi_2$  is the phase of  $S_{11}$  for the second iris, since we are counting that each cavity has two iris.

## V. SIMULATION

For this work the filter designed was a filter for aviation RADAR systems. These systems operate in the 2.7 GHz to 2.9 GHz band, and currently work with bandwidths in the order of 30 MHz. For this reason, it was chosen a center frequency of 2.8GHz and a bandwidth of 30 MHz. For the topology it was chosen that a rectangular waveguide would be used since these structures are more suitable for the order of power present in aviation RADAR systems. The waveguide chosen followed the WR 284 standard and as such as the following dimensions:

$$\begin{aligned} a &= 72.136 \text{ mm} \\ b &= 34.036 \text{ mm} \end{aligned}$$

Also, this waveguide has cutoff frequency of the mode  $TE_{10}$  at 2.08 GHz.

The type of filter was a Chebyshev filter with ripple of 0.2 dB and attenuation of -50 dB at 2.7GHz.

Following the insertion loss method, a low pass filter with order 5, shown in figure 6,

was designed with the following parameters present in table 1.

TABLE 1  
VALUES FOR THE LOW PASS FILTER.

Parameter	Value
$C_1$	1.3395 pF
$L_2$	1.3370 nH
$C_3$	2.1661 pF
$L_4$	1.3370 nH
$C_5$	1.3395 pF

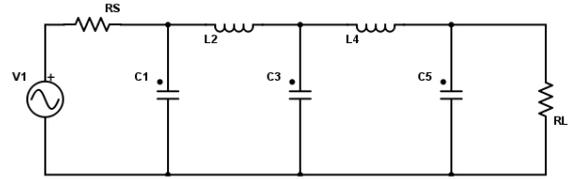


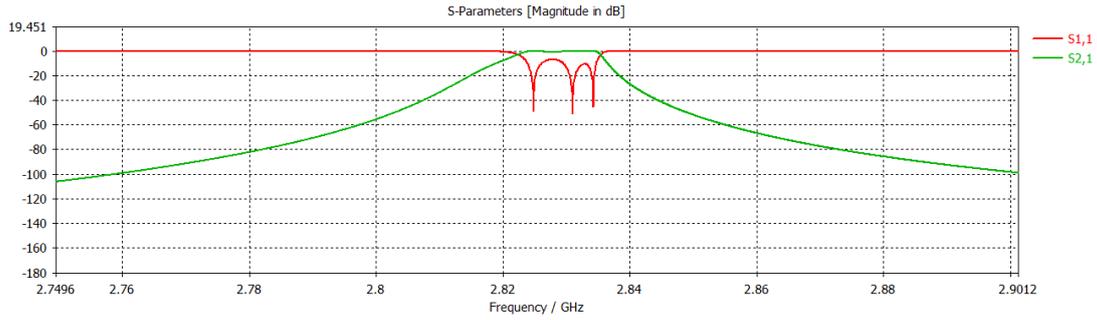
Figure 6: Lowpass filter.

Since a passband filter is needed for these kinds of systems, the lowpass filter was transformed into a bandpass filter with the following parameters.

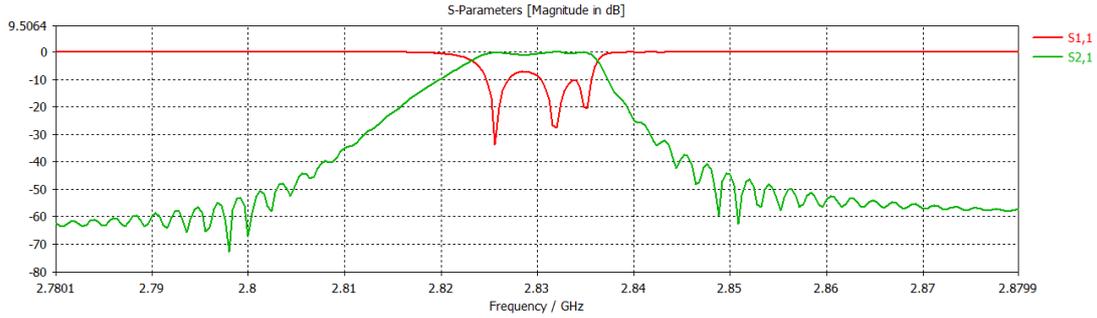
TABLE 2  
BANDPASS FILTER VALUES

Parameter	Value
$C_1$	142.11951 pF
$L_1$	27.734437 pH
$C_2$	0.00911 pF
$L_2$	354.655 nH
$C_3$	229.8254 pF
$L_3$	14.05849 pH
$C_4$	0.00911 pF
$L_4$	354.655 nH
$C_5$	142.11951 pF
$L_5$	27.734437 pH

As presented previously, these bandpass filters need to be converted to a format where it can be made with resonant cavities waveguides. As such, impedance inverters must be computed in order to transform the circuit in a network of series LC resonators. So using the equations 23, 24 and 25 we get the following values.



(a)



(b)

Figure 7: Response of the designed filter: (a) Frequency Domain Solver; (b) Time Domain Solver.

TABLE 3  
K PARAMETERS VALUES.

Parameter	Value
$\frac{K_{01}}{Z_0}$	0.1446256
$\frac{K_{12}}{Z_0}$	0.0209541
$\frac{K_{23}}{Z_0}$	0.0129569
$\frac{K_{34}}{Z_0}$	0.0129569
$\frac{K_{45}}{Z_0}$	0.0209541
$\frac{K_{56}}{Z_0}$	0.1446256

For the physical dimensions of the cavities the procedure explained in previous section permitted to obtain the width of the iris of each cavity and its length, as show in the next two tables.

TABLE 4  
IRIS WIDTH

Iris	Width (mm)
1	24.512
2	9.974
3	7.918
4	7.918
5	9.974
6	24.512

TABLE 5  
CAVITY LENGTH

Cavity	Length (mm)
1	73.769
2	77.093
3	77.296
4	77.093
5	73.769

Using the simulations software CST Studio Suite®, the structure designed was then simulated, using the Time Domain solver and the Frequency Domain solver and the response obtained is present in figure 7.

How we can verify the response obtained is Chebyshev type with a ripple level equal to the intended, but the central frequency and bandwidth are not the desired. The sized structure has the central frequency 2.83 GHz and a bandwidth of 15 MHz. It is therefore clear that the model needs optimization in order to meet the desired requirements.

For the optimization process each cavity was built in the simulation software and altered individually. After each cavity the

whole structure was simulated with the changes made to the cavity. By changing the length, it is possible to change the central frequency up and down, and by changing the width of the irises it is possible to change the bandwidth. Each cavity was altered so that the central frequency would be at the 2.8 GHz and the irises widths were changed so that the bandwidth would match the desired value. After the optimization process the following values were determined.

TABLE 7  
IRIS WIDTH AFTER OPTIMIZATION

Iris	Width (mm)
1	27.892
2	13.514
3	11.348
4	11.348
5	13.514
6	27.892

TABLE 6  
CAVITY LENGTH AFTER OPTIMIZATION

Cavity	Length (mm)
1	73.828
2	78.227
3	78.390
4	78.227
5	73.828

With the new values the whole structure was simulated, and the following response was obtained.

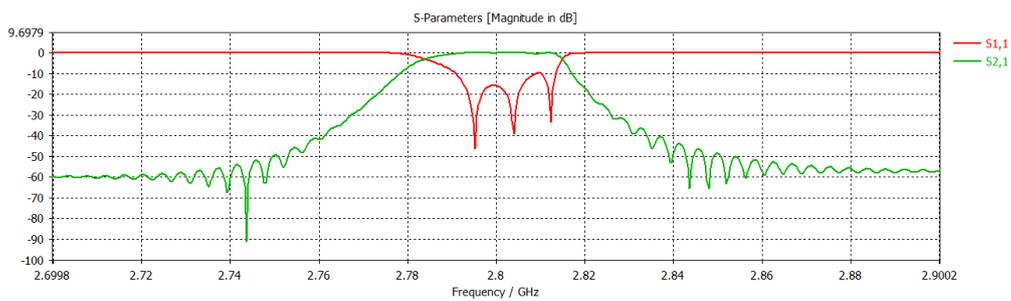
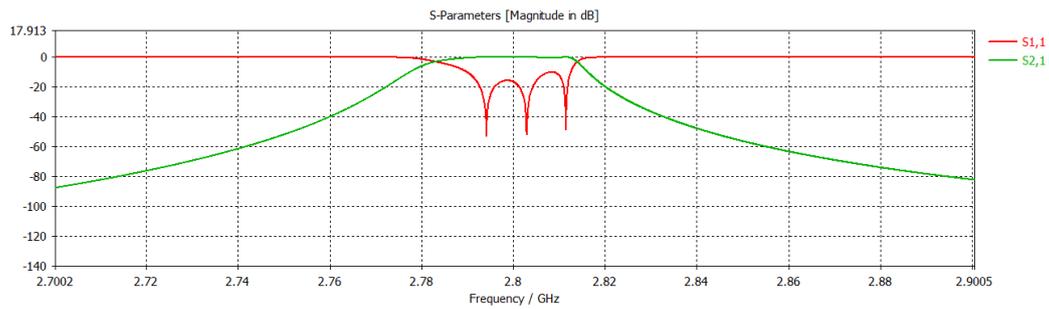


Figure 8: Response of the designed filter after optimization: (a) Frequency Domain Solver; (b) Time Domain Solver.

## VI. CONCLUSIONS

After this work a concise and coherent design process was determined for the design of microwave filters based in resonant cavities. The process allows to obtain a structure close to the desired specifications but after simulation it is obvious that a certain degree of optimization is required so that the filter designed meets those same specifications. With this work it was possible to have a broad idea of the various factors and disciplines to be taken into account during the process of design and synthesis of microwave filters, from the choice of material, to the dimensioning of structures, to the determination of operating conditions and the importance that simulation software has in this type of projects.

## REFERENCES

- [1] Merrill I. Skolnik. "*Introduction to Radar Systems*", McGraw-Hill Education; 3rd Edition, 2002
- [2] David M. Pozar. "*Microwave Engineering*". John Wiley & Sons, Inc., 4th edition, 2011.
- [3] Afonso Barbosa "Microondas". Seção de Folhas-AEIST, 2015
- [4] Ralph Levy, Richard V. Snyder, and George Matthaei. "*Design of microwave filters*". IEEE Trans. Microwave Theory Tech., 50(3):783–793, September 2002.
- [5] J.S. Hong, M.J. Lancaster, "*Microstrip filters for RF/Microwave Applications*", John Wiley & Sons, 2004.
- [6] Robert E. Collin. "*Foundations for Microwave Engineering*". IEEE Press, 2nd edition, 2001.
- [7] F. M. Vanin, D. Schmitt, and R. Levy, "*Dimensional synthesis of wideband waveguide*"