Semester S1

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Foundations of electromagnetic wave propagation

Practical Work PW2

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Design and analysis of a two pole filter using "Momentum" software

I.INTRODUCTION

The purpose of this practical work is to produce a two-pole planar filter in microstrip technology by studying the electromagnetic parameters of the circuit.
This study will make it possible to know the different couplings between elements, and thus to determine the geometric parameters of the circuit.

Filter specifications:

Center frequency f_0 = 3.6 GHz

Bandwidth Δf = 100 MHz

Ripple = 0.1 dB in the band

Thebycheff type two-pole filter (np=2)

II. STUDY OF THE *TWO*-POLE FILTER

The two-pole filter consists of two planar "H" shaped resonators excited by two microstrip lines (Figure 1).

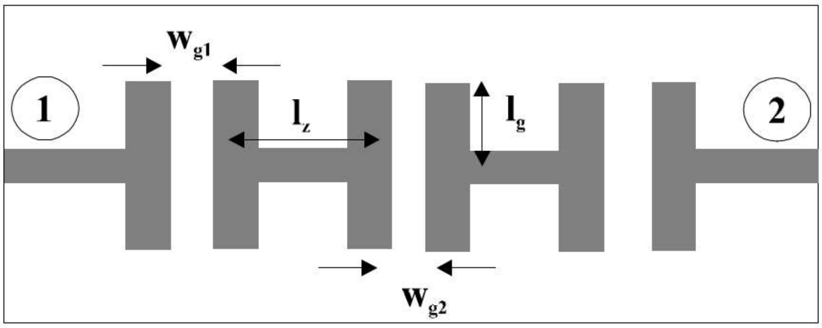


Figure 1

The circuit is made on a dielectric substrate with a thickness of 0.5 mm and permittivity ε_r = 9.6. The operating frequency of the circuit is the resonance frequency of the H resonator which depends both on the lengths l_z and l_g and the characteristics of the substrate. The coupling between the access line and the resonator is fixed by the width of the gap w_{g1}. This coupling is related to the external quality coefficient Q_{e1} for line 1 and Q_{e2} for line 2. The coupling k between resonators depends on the gap w_{g2}. This parameter affects the bandwidth filter and on the ripple of the transmission parameter.

The synthesis of this type of filter can be performed using an equivalent circuit model with localized elements (Figure 2).

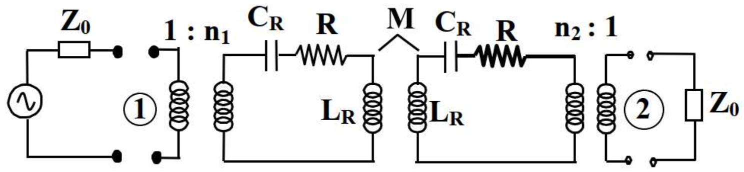


Figure 2

L_R, C_R and R characterize the resonators. The resonator frequency is therefore:

$$f_0 = \frac{1}{2\pi\sqrt{L_R C_R}} \tag{1}$$

⇨ R is representative for the resonator losses. We will have two cases :

- R= 0 : no loss calculation
- $R = \frac{L\omega_0}{Q_0}$ with Q_0 the unloaded quality factor of the resonator. (2)

⇨ The inter-resonator coupling is characterized by the mutual inductance M.

⇨ The coupling of the resonator with the access lines depends on parameters n_1 and n_2 of the perfect transformers.

1. CALCULATION OF FILTER ELEMENTS

a. External quality factor

It is calculated from the impedance Z_0 of the source or the load brought back into the resonator plane (Figure 3).

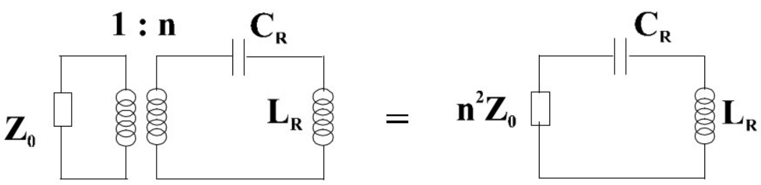


Figure 3

$$Q_e = \frac{L_R\omega_0}{n^2 Z_0} \tag{3}$$

The analysis start with the study of one resonator modelled by a circuit composed of a resonator coupled to two lines (Figure 4) which gives the transmission response in Figure 5.

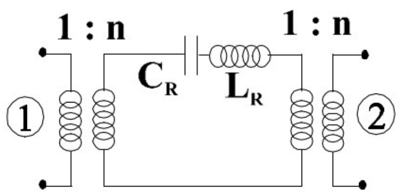


Figure 4

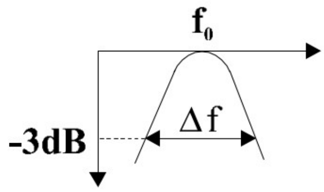


Figure 5

Then, the underload quality factor QL is given by:

$$Q_L = \frac{f_0}{\Delta f} \tag{4}$$

With $$\frac{1}{Q_L} = \frac{1}{Q_{e1}} + \frac{1}{Q_{e2}} + \frac{1}{Q_0} \tag{5}$$

Considering the structure with no loss, Q_0 is infinite

the structure is symmetrical so $Q_{e1} = Q_{e2} = Q_e$.

We then obtain:

$$Q_L = \frac{f_0}{\Delta_f} = \frac{Q_e}{2} \tag{6}$$

b. Coupling coefficient k

It corresponds to the inter-resonator coupling coefficient. The model is given in the set-up presenting figure 6.

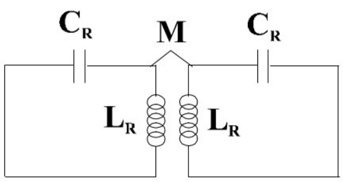


Figure 6

The coupling coefficient is given by:

$$k = \frac{M}{\sqrt{L_R L_R}} = \frac{M}{L_R} \tag{7}$$

This coefficient can also be calculated by replacing the set-up in Figure 6 by that of Figure 7, where P represents a symmetry plane.

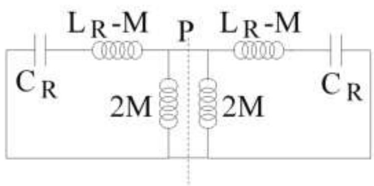


Figure 7

If P is an open circuit, the resonance frequency of the odd mode is written:

$$f_{co} = \frac{1}{2\pi\sqrt{(L_R + M)C_R}} = \frac{1}{2\pi L_R^2\sqrt{(1+k)C_R}} \tag{8}$$

If P is a short circuit, the resonance frequency of the even mode is written:

$$f_{cc} = \frac{1}{2\pi\sqrt{(L_R - M)C_R}} = \frac{1}{2\pi L_R^2\sqrt{(1-k)C_R}} \tag{9}$$

Then, the coupling coefficient k is given by:

$$k = \frac{f_{cc}^2 - f_{co}^2}{f_{cc}^2 + f_{co}^2} = \frac{M}{L_R} \tag{10}$$

The elements of the filter k and Q_e, can therefore be determined from the elements (eq.(3), eq.(7)) or from electromagnetic parameters (eq.(6), eq.(10)).

2. SYNTHESIS OF THE FILTER ACCORDING TO THE SPECIFICATIONS

Defining the specifications of a filter consist in given the characteristics of the transmission response.

The characteristic parameters are:

- the central frequency of the filter,
- the filter's bandwidth and ripple rate,
- rejection or selectivity,
- the group propagation time...

In general, a response model is also chosen. The best known are the Thebycheff, Butterworth or elliptical filters.

The synthesis consists in determining the electromagnetic parameters k and Q_e from the specifications.

In the literature, many people have worked on this subject and we will only recall here the results that allow us to synthesize a Thebycheff type two-pole filter. The results are as follows:

$$Q_e = \frac{f_0\, g_0\, g_1}{\Delta f} \tag{11}$$

$$k = \frac{\Delta f}{f_0 \sqrt{g_1 g_2}} \tag{12}$$

In these equations, f_0 is the central frequency of the filter, Δf is the bandwidth and g_0 g_1 and g_2 represent coefficients that are obtained from the filter ripple (Table 1).

At this stage of the study, the parameters Q_e and k are known and will allow us to then determine the dimensions of the circuit.

III. DETERMINATION OF THE TRANSMISSION AND REFLECTION RESPONSES OF THE EQUIVALENT CIRCUIT: ANALYSIS WITH ADS

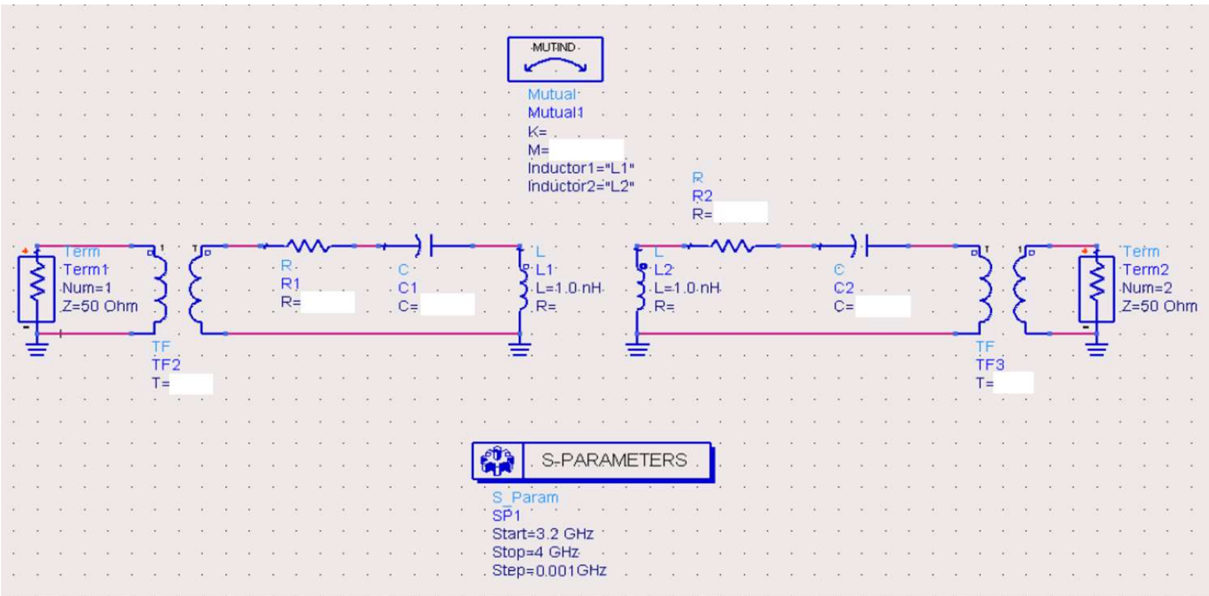


Figure 8

From the specifications of the filter, determine the values of Q_e (eq. 11) and k (eq. 12) using the tables of g_i coefficients given in the appendix. Determine the values of the localized elements of the circuit and visualize the S parameters.

- Conclusions.

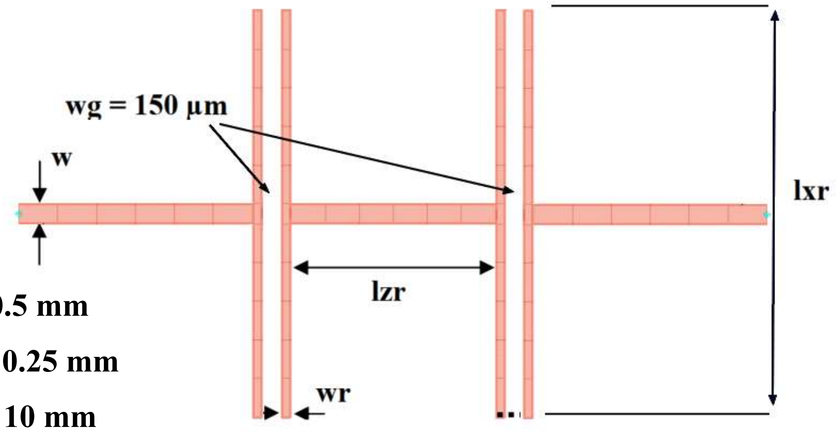
Do the calculation with R = 0 Ω (no loss) and a calculation with resonators having an unloaded quality factor Q_0 of 120.

- Conclusions.

1. FILTER COMPUTATIONS

a. Determination of the dimensions of the H-shaped resonator

The two excitation lines are positioned far enough from the resonator to do not disrupt its operation (Figure 9). The goal is then to determine lzr, lxr, wr to have a resonance frequency of 3.6 GHz corresponding to the center frequency of the filter and a high unloaded quality factor.



with **w = 0.5 mm**

wr = 0.25 mm

lxr = 10 mm

lzr = ? mm

Figure 9

b. Determination of wg1

The structure to be studied includes a single resonator excited by two lines (Figure 10).

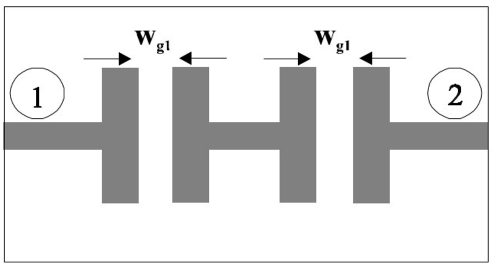


Figure 10

For a certain gap value w_{g1}, the transmission parameter S_{21} is calculated. Around the resonance frequency this parameter will present the variation shown in Figure 11.

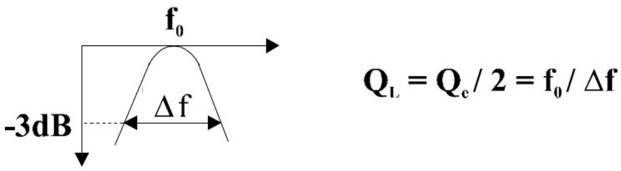


Figure 11

The calculation performed for different values of w_{g1} allows to draw the curve of the Figure 12.

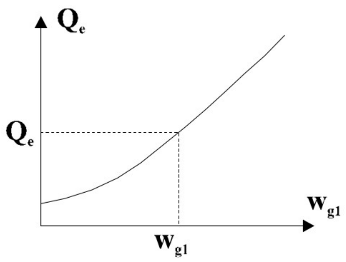


Figure 12

From the value of Q_e given by equation (11), the value of w_{g1} is determined Graphically (Excel Chart and trend curve).

c. Determination of w_{g2}

Depending on the software used, there are two methods.

1) Using free oscillations, the device is not excited. These are the natural resonance frequencies of the circuit that are calculated. In this case, the frequencies of resonance of two coupled resonators are analyzed according to the nature of the symmetry plane between the resonators (Figure 13).

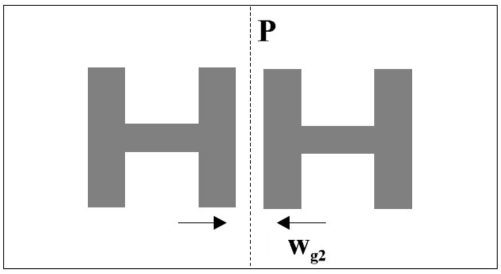


Figure 13

P = electrical short circuit (CCE). Even mode $f = f_{ce}$

P = magnetic short circuit (CCM). Odd mode $f = f_{co}$

The value of the coupling coefficient k is deduced from equation (10).

2) In forced oscillations, the device is excited. So that the excitement does not disturb resonances, access lines are placed to have a weak coupling, or a large value of wg1 (Figure 14). In this case, the resonance frequencies f_{ce} and f_{co} are determined from the layout of the module of S_{21} or S_{11}.

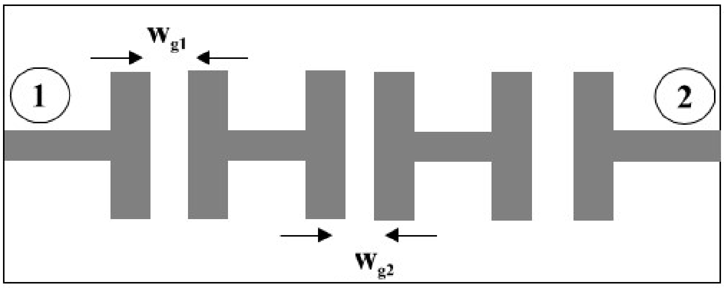


Figure 14

This calculation is performed for different values of w_{g2} and the curve in Figure 15 is traced.

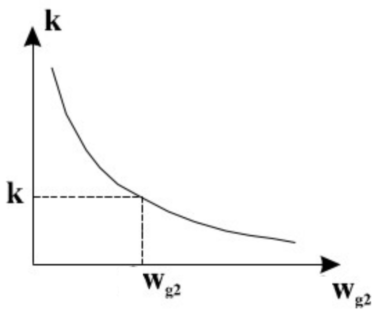


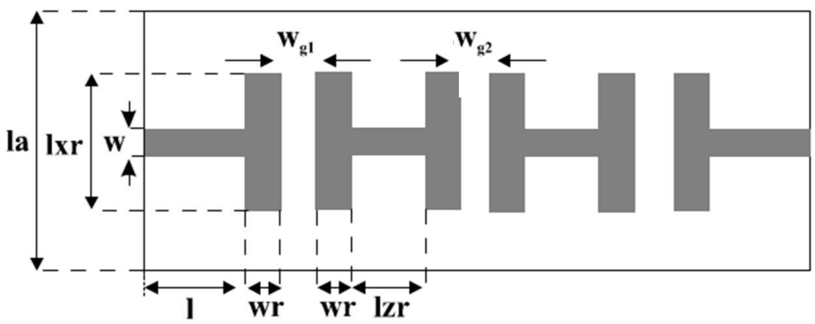
Figure 15

Equation (10) gives the value of k. From there, it is then possible to graphically determine the width of the corresponding w_{g2} gap.

At the end of the segmented electromagnetic study, we know how approximated the totality of the filter dimensions. The last step then consists in studying the overall structure and checking if specifications are respected.

IV. MANIPULATIONS

The analysis is performed in the 3.2 GHz - 4.0 GHz frequency band. The proposed filter has the following dimensions (Figure 16).



la = 16 mm **wr** = 0.25 mm
lxr = 10 mm **l** = 3 mm
w = 0.5 mm **lzr** = 5 mm

Cavity height = 3.5 mm
Substrate thickness = 0.5 mm
Permittivity = 9.6
Metallization thickness = 10 um

Figure 16

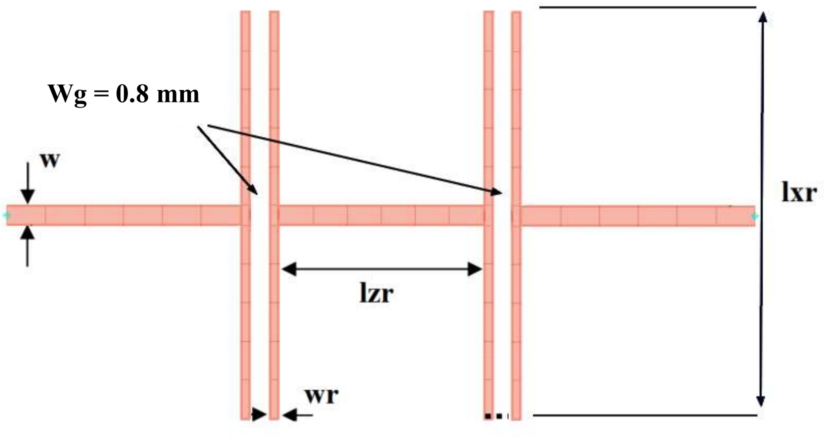
The dimensioning of the filter will come in 3 main steps, before considering the whole structure :

- resonator dimensioning
- resonator's access coupling
- resonator to resonator coupling

1. STUDY OF THE RESONATOR

Determine the resonance frequency and unloaded quality factor of the structure figure 17 (analysis band 3.5 GHz - 3.7 GHz).

➢ Conclusions.



with **w = 0.5 mm**
wr = 0.25 mm
lxr = 10 mm
lzr = 5 mm

Figure 17

2. STUDY OF THE EXTERNAL QUALITY COEFFICIENT Q_E

The structure with no loss (infinite conductivity, zero loss tangent) in Figure 7 with two access lines and only one resonator is simulated. For values of w_{g1} from 10µm to 200 µm, measure parameter S_{21}. Then calculate the Q_L and deduce the value of the external quality factor Q_e from it.

Calculate for each value of wg1 the value of Q_e and plot the Q_e curve in function of w_{g1}. Give the value of w_{g1} to meet the specifications.

3. STUDY OF THE INTER-RESONATOR COUPLING

The overall structure with 2 access lines and two resonators (Figure 18) is used. The input-output coupling is chosen low either w_{g1} = 800 µm. For values of wg2 equal to 100 µm, 300 µm, 500 µm, 700 µm, calculate the values of the resonance frequencies from the modulus of S_{21} and deduce the value of the inter-resonators coupling coefficient k for each value of w_{g2}.

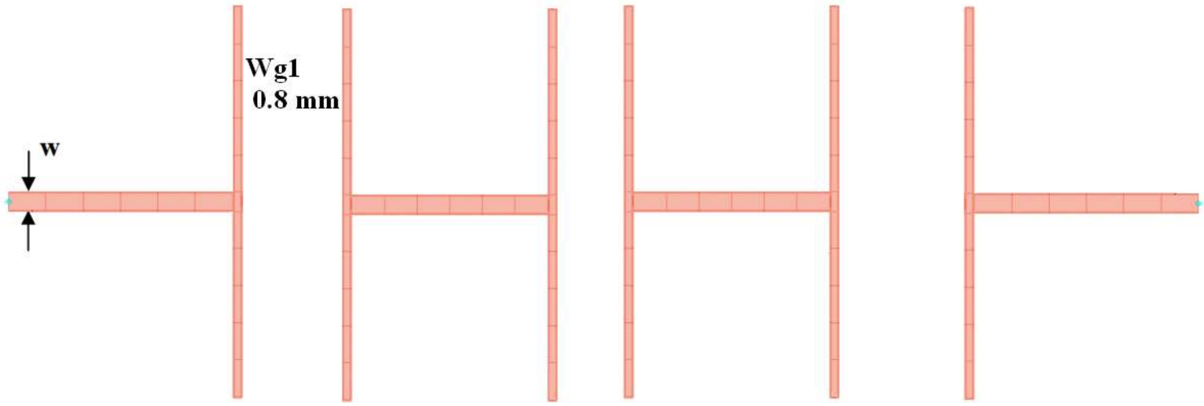


Figure 18

Trace the variations of k as a function of w_{g2}. Give the value of w_{g2} that satisfies the specifications.

4. STUDY OF THE OVERALL STRUCTURE OF THE FILTER

Perform the layout of the global filter from the approximate dimensions determined previously and analyze its behavior in the band 3.2 GHz - 4 GHz.

5. CONCLUSION

Check if the template is respected and plan the modifications to be made to optimize the filter (visualize on the same curve the responses of the circuit in localized elements and the overall filter structure). If necessary, carry out another simulation.

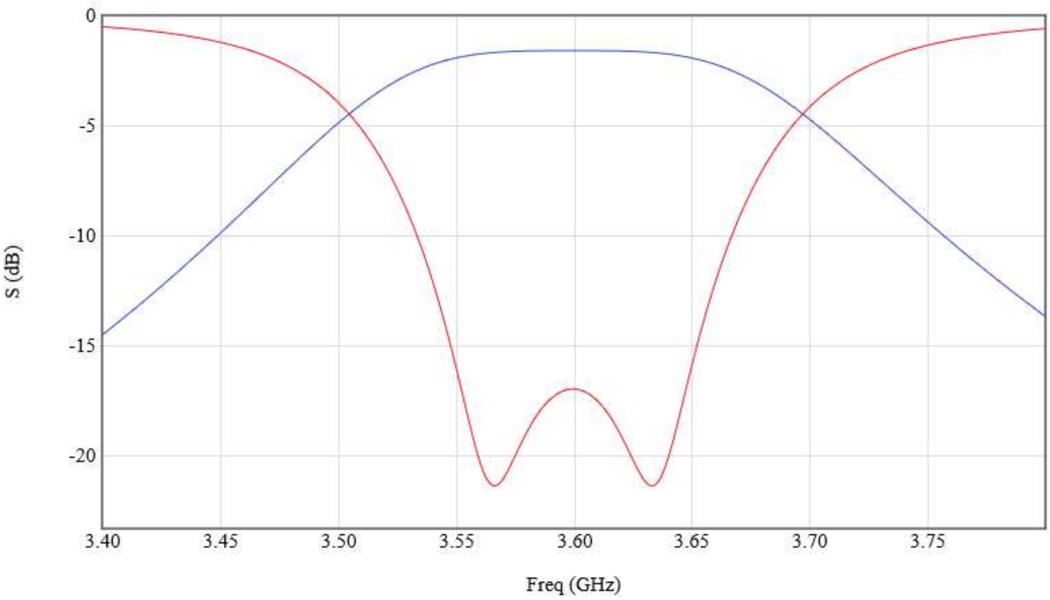


Figure 19: realistic response of the synthesis with $Q_0 = 150$

Table 1: Values of the Chebychev elements with $g_0 = 1$, $\omega'_1 = 1$

np	g1	g2	g3	g4	g5	g6	g7	g8	g9	g10	g11
0,01 dB ondulation (ripple)											
1	0,0960	1,0000									
2	0,4489	0,4078	1,1008								
3	0,6292	0,9703	0,6292	1,0000							
4	0,7129	1,2004	1,3213	0,6476	1,1008						
5	0,7563	1,3049	1,5773	1,3049	0,7563	1,0000					
6	0,7814	1,3600	1,6897	1,5350	1,4970	0,7098	1,1008				
7	0,7970	1,3924	1,7481	1,6331	1,7481	1,3924	0,7970	1,0000			
8	0,8073	1,4131	1,7825	1,6833	1,8529	1,6193	1,5555	0,7334	1,1008		
9	0,8145	1,4271	1,8044	1,7125	1,9058	1,7125	1,8044	1,4271	0,8145	1,0000	
10	0,8197	1,4370	1,8193	1,7311	1,9362	1,7590	1,9055	1,6528	1,5817	0,7446	1,1008
0,1 dB ondulation (ripple)											
1	0,3053	1,0000									
2	0,8431	0,6220	1,3554								
3	1,0316	1,1474	1,3159	1,0000							
4	1,1088	1,3062	1,7704	0,8181	1,3554						
5	1,1468	1,3712	1,9750	1,3712	1,1468	1,0000					
6	1,1681	1,4040	2,0562	1,5171	1,9029	0,8618	1,3554				
7	1,1812	1,4228	2,0967	1,5734	2,0967	1,4228	1,1812	1,0000			
8	1,1898	1,4346	2,1199	1,6010	2,1700	1,5641	1,9445	0,8778	1,3554		
9	1,1957	1,4426	2,1346	1,6167	2,2054	1,6167	2,1346	1,4426	1,1957	1,0000	
10	1,2000	1,4482	2,1445	1,6266	2,2254	1,6419	2,2046	1,5822	1,9629	0,8853	1,3554
0,2 dB ondulation (ripple)											
1	0,4342	1,0000									
2	1,0379	0,6746	1,5386								
3	1,2276	1,1525	1,2276	1,0000							
4	1,3029	1,2844	1,9762	0,8468	1,5386						
5	1,3395	1,3370	2,1661	1,3370	1,3395	1,0000					
6	1,3598	1,3632	2,2395	1,4556	2,0974	0,8838	1,5386				
7	1,3723	1,3782	2,2757	1,5001	2,2757	1,3782	1,3723	1,0000			
8	1,3804	1,3876	2,2964	1,5218	2,3414	1,4925	2,1349	0,8972	1,5386		
9	1,3861	1,3939	2,3094	1,5340	2,3728	1,5340	2,3094	1,3939	1,3861	1,0000	
10	1,3901	1,3983	2,3181	1,5417	2,3905	1,5537	2,3721	1,5066	2,1514	0,9035	1,5386
0,5 dB ondulation (ripple)											
1	0,6987	1,0000									
2	1,4029	0,7071	1,9841								
3	1,5963	1,0967	1,5963	1,0000							
4	1,6704	1,1925	2,3662	0,8419	1,9841						
5	1,7058	1,2296	2,5409	1,2296	1,7058	1,0000					
6	1,7254	1,2479	2,6064	1,3136	2,4759	0,8696	1,9841				
7	1,7373	1,2582	2,6383	1,3443	2,6383	1,2582	1,7373	1,0000			
8	1,7451	1,2647	2,6565	1,3590	2,6965	1,3389	2,5093	0,8795	1,9841		
9	1,7505	1,2690	2,6678	1,3673	2,7240	1,3673	2,6678	1,2690	1,7505	1,0000	
10	1,7543	1,2721	2,6755	1,3725	2,7393	1,3806	2,7232	1,3484	2,5239	0,8842	1,9841