École Polytechnique de Louvain

LELEC2700 - Microwaves

Group 2: Low Pass Tchebytchev Filter

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Contents

1 Introduction

This project threat with the design of a Tchebyshev open stubs low-pass filter with the following specifications:

1. Cutoff freq: 10 GHz
2. Maximum ripple: 1dB
3. Attenuation of 30 dB at 20 GHz
4. The following substrate is used : RO4350B 0.5mm
   See (1)

The project is structured as follows:

- Design of the element based on the simulation of its **frequency response**
- Design of circuit **layout** for fabrication
- Measurement of its **frequency response** (S-parameters)
- **Performances versus specifications** analysis

2 Theoretical analysis

2.1 Order of the filter

The following equations describe the properties of a Tchebytchev filter of order N:

$$L = 1 + k^2 T_N^2(\omega') \approx \frac{k^2}{4}(2\omega')^{2N} \tag{1}$$

$$Ripple = 1 + k^2 = 10\log(1+k^2)\ [dB] \tag{2}$$

with $T_N(\omega')$ the Tchebytchev polynom of order N, L the insertions losses (ratio between the power available at the source and the power delivered to the load), a factor linked to the ripple and $\omega' = \frac{\omega}{\omega_c}$.
Matching it with the specification of the wanted filter we get k=0.5088 and then $N \geq 3.4787$. The design of a Tchebytchev filter is then a trade-off between a low ripple and a high attenuation beyond the cut-off.

We decided to implement a filter of order 5, allowing a good compromise between slope of the filter after the cut-off frequency and limited ripple in the band-pass zone. Furthermore the Tchebytchev filter of odd order allow a matching in the band-pass.

2.2 Choice of lumped components

The order of the filter having been determined, it is possible for first approximation to get the circuit based on lumped ideal components such as capacitances and inductors.
For a Tchebytchev low pass filter of order 5, with maximum ripple of 1 [dB], looking in the tables from Reference (3) we get the following circuit :

1.00 db ripple											
1	0.5088	∞									
2	0.9110	0.9957	∞								
3	1.0118	1.3332	1.5088	∞							
4	1.0495	1.4126	1.9093	1.2817	∞						
5	1.0674	1.4441	1.9938	1.5908	1.6652	∞					
6	1.0773	1.4601	2.0270	1.6507	2.0491	1.3457	∞				
7	1.0832	1.4694	2.0437	1.6736	2.1192	1.6489	1.7118	∞			
8	1.0872	1.4751	2.0537	1.6850	2.1453	1.7021	2.0922	1.3691	∞		
9	1.0899	1.4790	2.0601	1.6918	2.1583	1.7213	2.1574	1.6707	1.7317	∞	
10	1.0918	1.4817	2.0645	1.6961	2.1658	1.7306	2.1803	1.7215	2.1111	1.3801	∞

Figure 1: 1 dB ripple Tchebytchev low pass filter
Components Normalised values

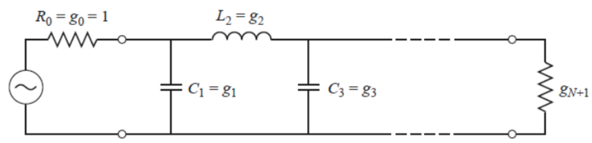

Figure 2: Lumped Circuit
Model

Denormalising the components as followed :

$$\begin{cases} C_i = \frac{g_i}{R_0 \omega_c} \\ L_i = \frac{g_i \, R_0}{\omega_c} \end{cases}$$

We finally simulated the circuit on ADS getting the following curves (Figure 4).

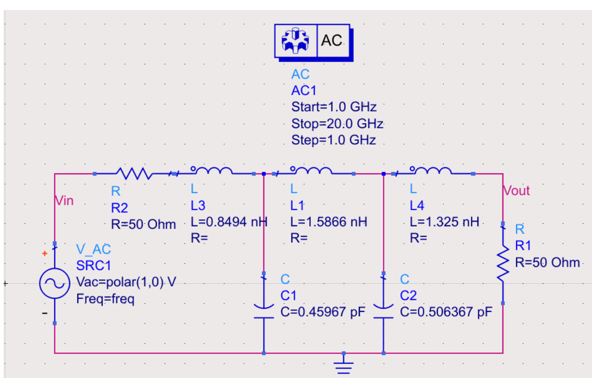

Figure 3: Lumped Circuit
ADS Simulation

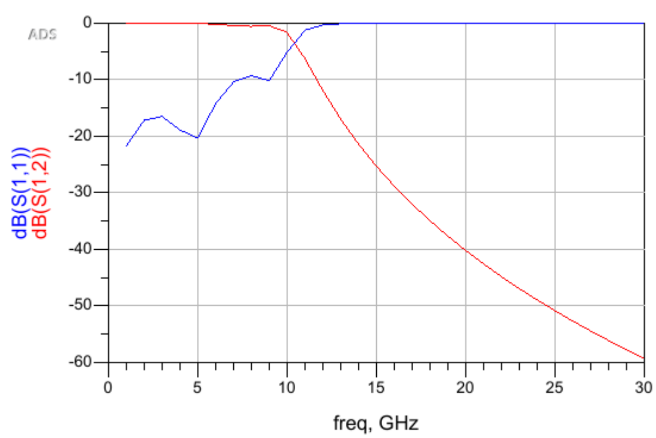

Figure 4: Lumped Circuit S-parameters
ADS Simulation

We see on figure 4 that the specifications are respected as the attenuation is of ≈ -3 [dB] at 10 [GHz] and of -40 [dB] at 20 [GHz]. There is no ripple in the passband zone.

2.3 Conversion to Microstrip

Now that the lumped components were chosen, we can begin implementing them in microstrip technology. The statement requires to implement the inductances as transmission lines, and the capacitors as open-stubs.

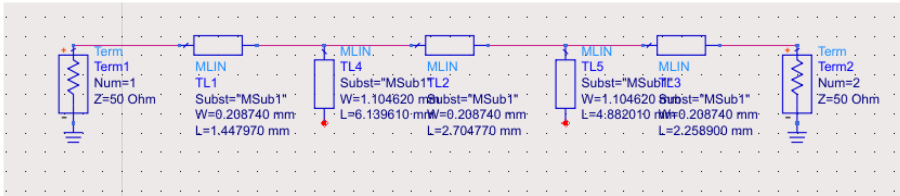

Figure 5: ADS circuit

2.3.1 Inductances

A transmission line can be modelled as

$$\frac{X}{2} = Z_c tan(\frac{\beta l}{2}) \tag{3}$$

If we assume Z_c is high, and $\beta l << \frac{\lambda}{4}$, we can approximate equation 3 by $X \approx Z_C \beta l$ and $B \approx 0$, which translates as a purely inductive transmission line.

Since the goal is to make an inductance, it becomes

$$\omega L = Z_c \beta l \tag{4}$$

ω is set to the cut-off frequency, 10[GHz]. Z_c is set to it's maximum implementable value by the factory. Indeed the higher is Z_c, the narrower is the microstrip. An intuitive way to understand it is thinking in term of effective permittivity of the line. If we widen it, the effective permittivity increases and tends towards the value of the permittivity in the substrate. An increasing permittivity means a lower caracteristic impedance as for a TEM mode : $Z_c = \sqrt{\frac{\mu}{\epsilon}}$.
The machine generating the final product has a limited resolution which prevents it from making strips that are too thin. The maximum value we could take is 120Ω, so we chose $Z_c = 110\Omega$ to have a little margin. The last unknown parameter from equation 4 is βl which defines the resulting inductance of the microstrip.

2.3.2 Capacitors

Capacitors are modelled using open-stubs. Under the assumption of a lossless transmission line, the following equation can be used to model the TL.

$$Z_{in} = Z_0 \frac{Z_L cos(\beta l) + jZ_0 sin(\beta l)}{Z_0 cos(\beta l) + jZ_L sin(\beta l)} \tag{5}$$

Open stub means $Z_L = \infty$, the ideal transmission lines follows this equation

$$Z_0 = \frac{tan(\beta l)}{\omega C} \tag{6}$$

Z_0 was chosen arbitrarily to be 50Ω, ω fixed to 10GHz which leaves βl to be set in order to get the wanted capacitance value of the line.

Once all the parameters have been chosen, we can model them using computer software. LineCalc, a tool from the ADS software sutie, was used to compute the physical parameters of the microstrips based on the mathematical parameters (β l, Z_c, ω) and those of the substrate used. The circuit is on figure 5, and the layont on figure 6

2.4 Analysis of microstrip simulations

Now the circuit has been modelled in ADS, we're able to simulate the S-parameters. Figure 7 show the simulated S parameters.

Figure 6: Layout of the circuit

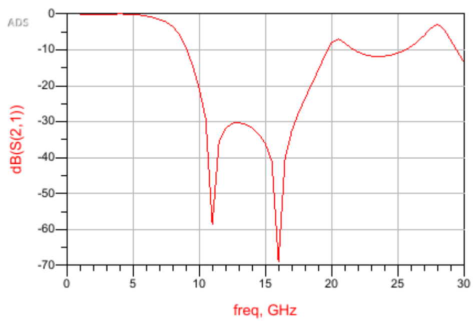

Figure 7: Microstrip circuit sized for a 1dB ripple

The shape of the curve is very different from the lumped simulation. This is mainly due to the fact that the microstrips have a specific L and C value at 10GHz. The further away from that base frequency we are, the more altered the results become. We do however notice that the cutoff frequency is slightly shifted. This is caused by the little capacitance we estimated to be zero in the previous section. In order to counter that effect, since the circuit is more capacitive than computed, we must undersize the capacitance a little. This was done through tweaking the length of the open stubs until the cutoff frequency was back to what we're expecting (both βl increased by 10 %).
When doing so, the ripple was increased: a linear attenuation is visible before cutoff (Figure 8). To counter that alteration, we decided to size the circuit for a 0.5dB ripple (using the tables in Pozar) whilst keeping the capacitances undersized.
The result can be seen in figure 9[1]. The linear attenuation before 10GHz is reduced, and as an added bonus we notice a better attenuation at 20GHz, which is asked in the statement.

[1]Comparing $S_{1,2}$ to $S_{2,1}$ seems counterintuitive. However we can assume $S_{1,2} = S_{2,1}$ since the circuit does not contain any active component or ferrite and is thus reciprocal.

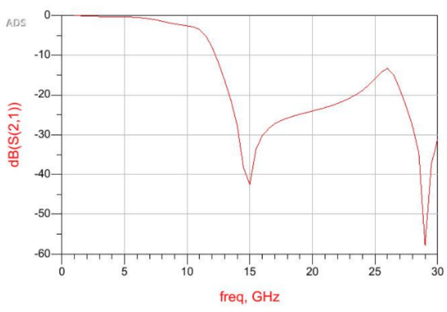

Figure 8: S-parameters with a 1dB ripple and undersized capacitances

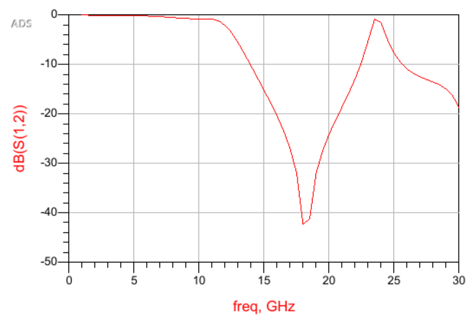

Figure 9: S-Parameters of the final circuit - 0.5dB ripple and undersized capacitances[1]

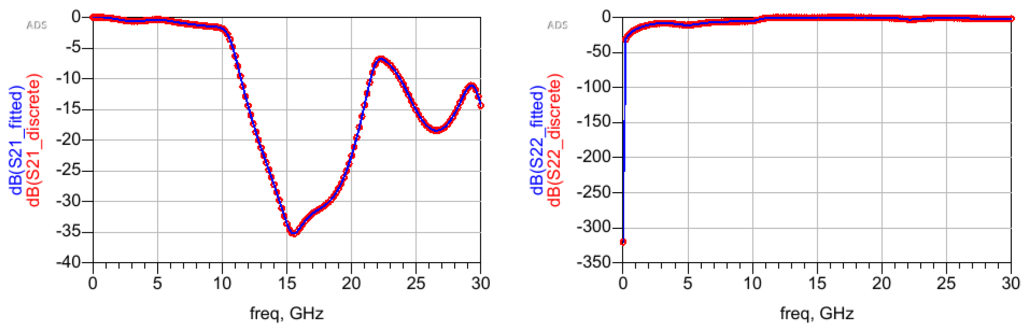

Figure 10: Momentum simulation

Lets take a look at the Momentum simulation, which takes the geometry of the substrate and the strips into effect. As you can see on figure 10, the graph is very similar to the S parameter simulation before 10GHz (figure 9). The same linear attenuation is observed before 10GHz , though it seems a little stronger. The cutoff frequency is the same. Towards the higher frequencies, the graphs start to differ. These result don't matter that much though because they are far from the design frequency of 10GHz. As stated when sizing the microstrips, the capacitance and inductance have a specific value computed for 10GHz, and are dependant on the frequency. An altered behavior is thus expected far from the design frequency.

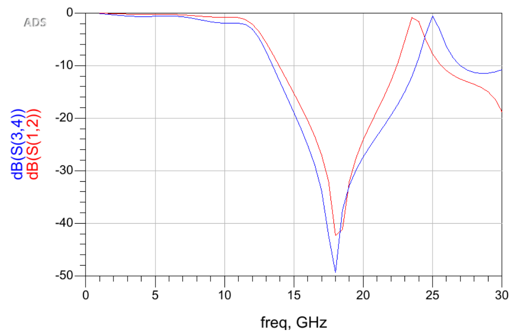

Figure 11: Simulation when altering the strip width by 10%

3 Results and discussion

Once the circuit is manufactured, we must evaluate whether it fits the specifications. Figure 12 plots the S parameters of the microstrip filter. Take the time to observe the following table which compares the specifications, the simulated parameters (figure 8) to the physical circuit (figure 12).

	Specification	Simulation	Real implementation
Cutoff frequency	10GHz	12GHz	11GHz
Ripple before cutoff	1dB	2dB	4dB
Attenuation at 20GHz	20dB	30dB	24dB

The cutoff frequency is approximatively the one expected, however we notice a strong linear attenuation from 6 GHz to 10GHz on the real circuit which was much less pronounced on the simulations. We could not find the cause to this impairment. We've tend to think it is due to the manufacturing resolution: our hypothesis is that the microstrip might be slightly too thin or too thick, which affects the ripple. To test that hypothesis, we conducted a simulation (figure 11) in which the width of the strips was altered by 10%. There is a slight impact on the ripple but not enough compared to the real circuit. Our hypothesis does not completely explain the linear attenuation.
Furthermore a ripple of 0.5 to 1 [dB] can be caused by the coaxial connectors and probably impact the microstrip implementation (Figure 13).

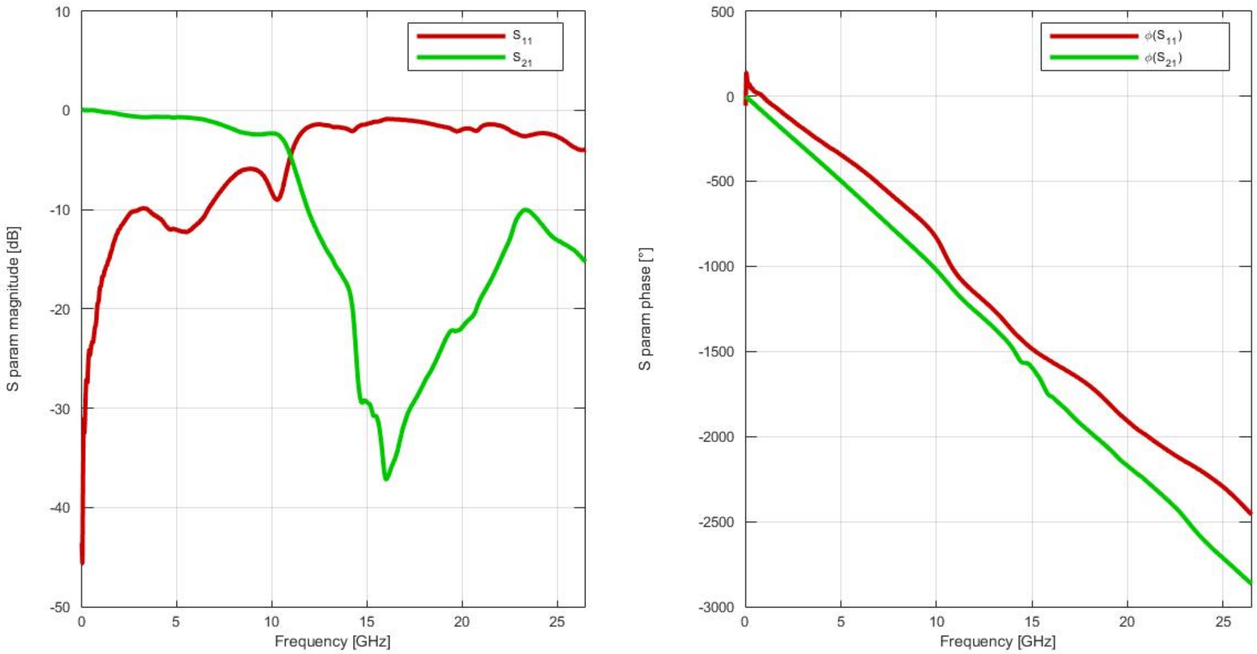

Figure 12: S parameters of the real circuit

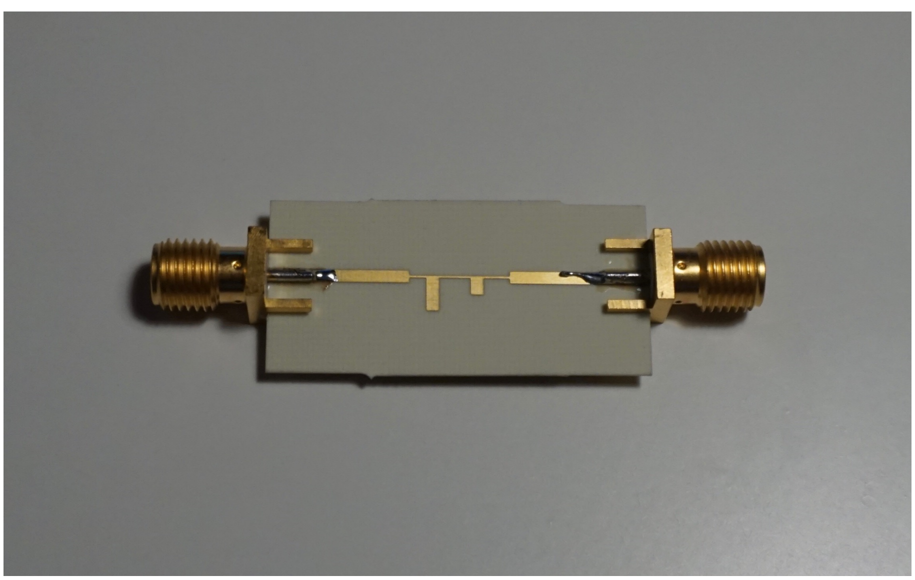

Figure 13: Microstrip implementation

4 Conclusion

Finaly our Low Pass Tchebytchev Filter partially respects the specifications:

- The **cut-off frequency** is around 11 [Ghz] but we observe an attenuation with constant slope (-0.78 [dB/dec]) between 6 and 11 [GHz] to reach -4 [dB] at 11 [GHz].
- The **bandwidth** $B \in [0; 11]$ [GHz]. We managed to limit the linear attenuation before the cut-off frequency in the simulation but it appeared in the momentum and real implementation (Figure 12).
- The **attenuation** at 20 [GHz] is equal to 24 [dB]. The specification on the attenuation at 20 [GHz] was released to 24 [dB] instead of 30[dB] to limit the ripple in a acceptable range.

After implementation from ideal lumped components to microstrip, 2 problems occured : The cut-off frequency was shifted to 7 [GHz] due to capacitances in the series microstrips and the attenuation at 20 [GHz] was higher than 10 [GHz].
In order to counter that effect, we undersized the capacitance a little. This was done through tweaking the length of the open stubs. doing this a linear attenation (in dB scale) appeared. We dealed with it recomputing the capacitance and inductance value for a 0.5 [dB] ripple. This limited the slope to -0.27 [dB/dec]. Unfortunately the slope rised to -0.78 [dB/dec] in the real microstrip implementation.
Two hypothesis were enunciated: The manufacturing resolution did not allow the implementation of such thin microstrips and an additionnal ripple can be caused by the non-ideal coaxial connectors.

References

[1] R. Sorrentino, G. Bianchi, « Microwaves and RF engineering », Wiley, 2010

[2] D. Pozar, Microwave Engineering, 4th edition, Wiley

[3] G.Matthaei,E.M.T.Jones,L.Young, MicrowaveFilters, impedance matching networks and coupling structures. p 109