EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH
ORGANISATION EUROPEENNE POUR LA RECHERCHE NUCLEAIRE

CERN − PS DIVISION

PS/BD/Note 2002−193(Tech.)

Passive low-pass filters with constant input resistance

J.M. Belleman

Abstract

Commonly, passive filters work by reflecting unwanted energy back to the source. This is sometimes undesirable. The addition of a simple input matching network can yield a constant input resistance filter, which absorbs out-of-band energy, rather than reflecting it. This paper gives circuits and element values for matching networks for Bessel, Gaussian and linear phase with equiripple filters of orders 3 to 10.

Geneva, Switzerland
November 4, 2002

1 Introduction

It is sometimes useful to have passive LC ladder filters that absorb, rather than reflect, energy in the stop band. The usual way to obtain this is by the use of diplexers, i.e., by connecting two complementary filters in parallel at their inputs. One filter accepts the band of frequencies that the other rejects. Except for Butterworth filters, there is no solution for the perfect complementary filter.

If there is no need to present all out−of−band signal power on a separate output, there is a much simpler way to obtain good input matching. The parallel combination of a series RC circuit and a series RLC resonator can efficiently absorb virtually all stop band energy. Even though this method yields only an approximation of constant resistance, it is good enough for most practical applications. For most filters treated below, the theoretical reflection coefficient is below −50dB over all frequencies.

2 Basic considerations

The starting point for the design of a filter with constant input resistance is the normalized low-pass prototype for zero source impedance. This is the filter that produces the correct response with a constant input level, which is evidently the case for any constant source connected to a load that is constant as a function of frequency.

Any such filter starts with a large series inductance. Therefore, its input impedance will tend to rise with frequency above cut-off. A series RC circuit across the filter input can restore the input impedance to unity for very high frequencies, and a series RLC resonator can be positioned over the transition region to minimize the impedance ripple (Figure 1).

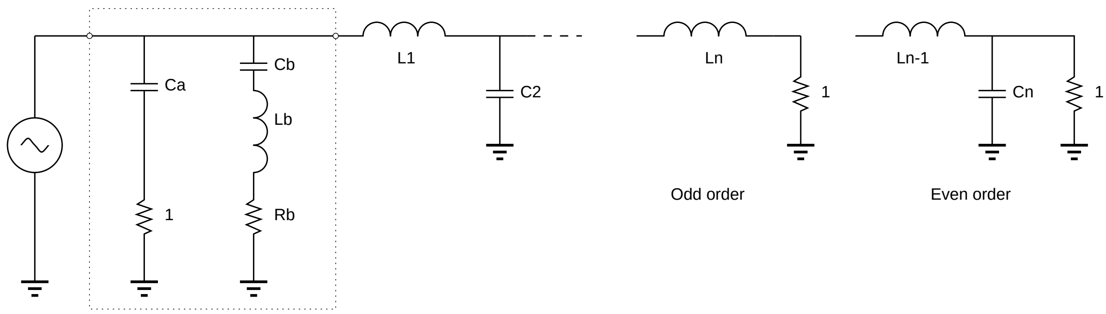

Figure 1. Low-pass filter with input matching

3 Filter tables

The following tables, taken from Zverev [1], have been complemented with the normalized element values for the input compensation network. The values have been determined using a heuristic seeking to minimize $|Z(C_a, C_b, L_b, R_b) - 1|$ over all frequencies, and may not represent the absolute optimum. This is evident from the somewhat inhomogeneous aspect of the S_{11} curves. (Figure 2, 3, 4.) They should be plenty good however, for almost all practical purposes.

Table 1. Normalized element values for Bessel filters (Maximally flat delay)

	Ca	Cb	Lb	Rb	L1	C2	L3	C4	L5	C6	L7	C8	L9	C10
3	0.5804	0.3412	0.9915	2.6161	1.4631	0.8427	0.2926							
4	0.6121	0.3143	1.0646	2.7036	1.5012	0.9781	0.6127	0.2114						
5	0.6465	0.2834	1.1613	2.8896	1.5125	1.0232	0.7531	0.4729	0.1618					
6	0.6622	0.2683	1.2094	3.0029	1.5124	1.0329	0.8125	0.6072	0.3785	0.1287				
7	0.6876	0.2452	1.2955	3.2070	1.5087	1.0293	0.8345	0.6752	0.5031	0.3113	0.1054			
8	0.7091	0.2266	1.3736	3.4024	1.5044	1.0214	0.8392	0.7081	0.5743	0.4253	0.2616	0.0883		
9	0.7206	0.2172	1.4167	3.5267	1.5006	1.0127	0.8361	0.7220	0.6142	0.4963	0.3654	0.2238	0.0754	
10	0.7270	0.2123	1.4407	3.6091	1.4973	1.0045	0.8297	0.7258	0.6355	0.5401	0.4342	0.3182	0.1942	0.0653

Table 2. Normalized element values for Gaussian filters

	Ca	Cb	Lb	Rb	L1	C2	L3	C4	L5	C6	L7	C8	L9	C10
3	0.6267	0.3093	1.1256	3.1978	1.4179	0.7167	0.2347							
4	0.6877	0.2498	1.3129	3.5644	1.4518	0.8406	0.4905	0.1642						
5	0.7149	0.2252	1.4049	3.7347	1.4655	0.8934	0.6109	0.3684	0.1239					
6	0.7256	0.2158	1.4409	3.8011	1.4713	0.9174	0.6710	0.4792	0.2915	0.0981				
7	0.7304	0.2116	1.4571	3.8334	1.4737	0.9286	0.7020	0.5412	0.3918	0.2387	0.0803			
8	0.7326	0.2096	1.4647	3.8493	1.4748	0.9341	0.7185	0.5766	0.4529	0.3292	0.2005	0.0674		
9	0.7340	0.2085	1.4695	3.8601	1.4753	0.9367	0.7273	0.5972	0.4907	0.3880	0.2822	0.1716	0.0576	
10	0.7335	0.2089	1.4671	3.8551	1.4755	0.9381	0.7321	0.6092	0.5142	0.4267	0.3381	0.2456	0.1492	0.0501

Table 3. Normalized element values for linear phase filters with equiripple error (0.05°)

	Ca	Cb	Lb	Rb	L1	C2	L3	C4	L5	C6	L7	C8	L9	C10
3	0.5981	0.3275	1.0360	2.5837	1.5018	0.9328	0.3631							
4	0.6387	0.2884	1.1425	2.7818	1.5211	1.0444	0.7395	0.2925						
5	0.7098	0.2254	1.3810	3.3266	1.5144	1.0407	0.8447	0.6177	0.2456					
6	0.7061	0.2300	1.3541	3.3652	1.5050	1.0306	0.8554	0.7283	0.5389	0.2147				
7	0.7387	0.2031	1.4877	3.7021	1.4988	1.0071	0.8422	0.7421	0.6441	0.4791	0.1911			
8	0.6892	0.2471	1.2867	3.3189	1.4953	1.0018	0.8264	0.7396	0.6688	0.5858	0.4369	0.1743		
9	0.7381	0.2037	1.4891	3.7692	1.4907	0.9845	0.8116	0.7197	0.6646	0.6089	0.5359	0.4003	0.1598	
10	0.6819	0.2545	1.2598	3.3002	1.4905	0.9858	0.8018	0.7123	0.6540	0.6141	0.5669	0.5003	0.3741	0.1494

4 Reflection coefficient graphs (S_{11})

For the frequency response, group delay and time responses, consult Zverev [1]. Below are the graphs of the theoretical value of the reflection coefficient S_{11} vs. normalized angular frequency, with the proposed compensation circuit in place.

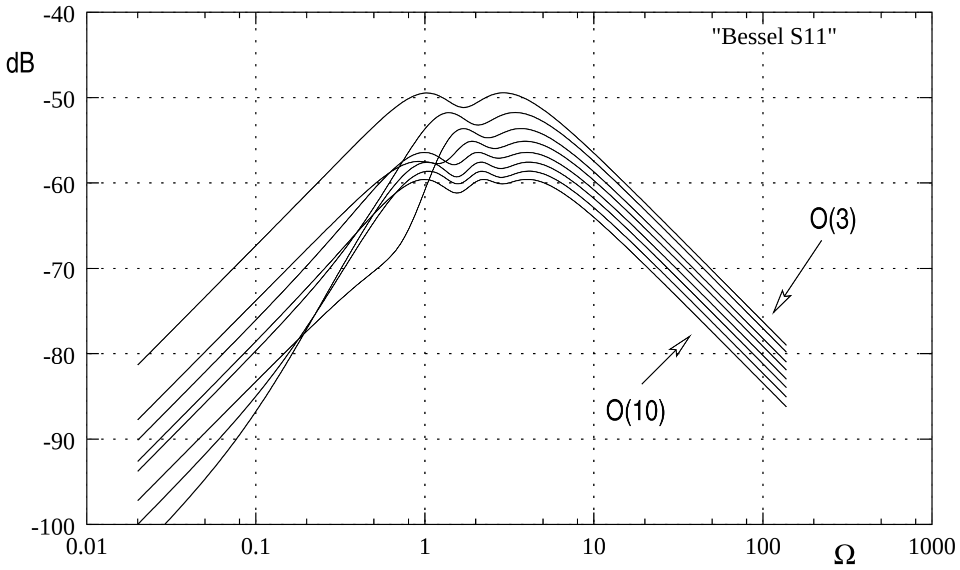

Figure 2. Bessel filter reflection coefficient (S_{11})

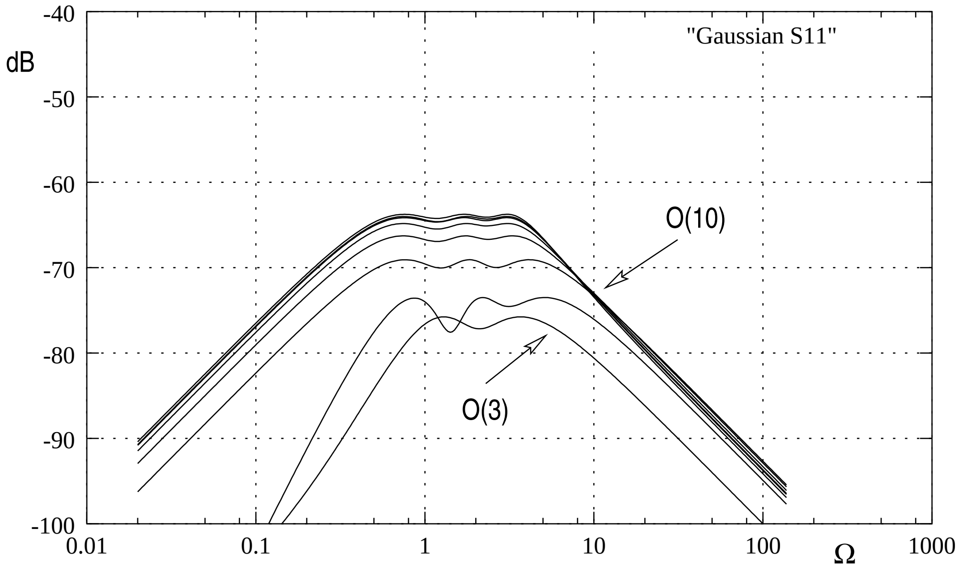

Figure 3. Gaussian filter reflection coefficient (S_{11})

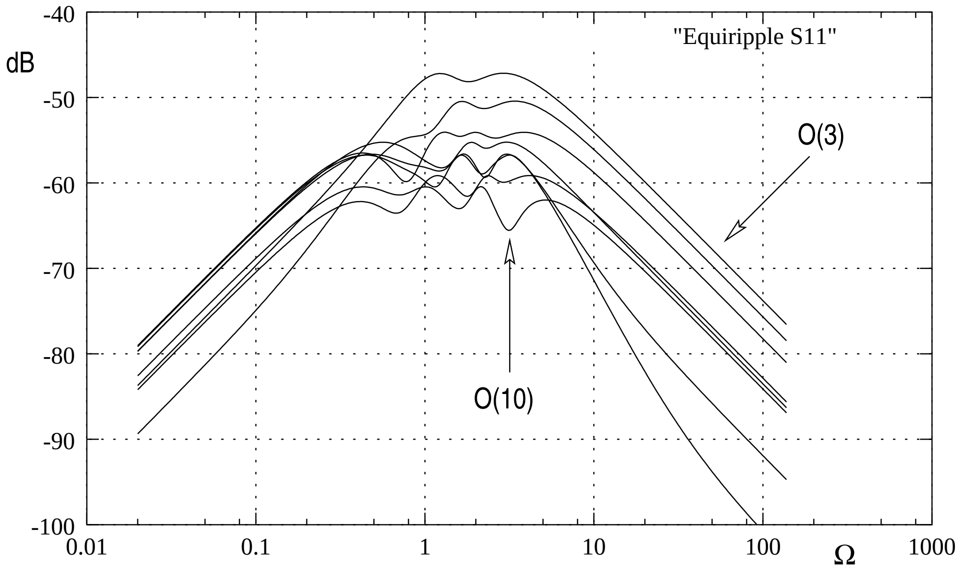

Figure 4. Linear phase with equiripple error (0.05°) reflection coefficient (S_{11})

5 A practical design example

The design concerns a 50 Ohm, 6th order Bessel low-pass filter with a 40MHz cut−off frequency. The values for the inductances, taken from the appropriate table, are denormalized by multiplying with:

$$\frac{Z_0}{\omega} = \frac{50}{2\pi \times 40MHz} \approx 199n \qquad (1)$$

Similarly, the capacitor values are obtained by multiplying with:

$$\frac{1}{Z_0 \omega} = \frac{1}{100\pi \times 40MHz} \approx 79.6p \qquad (2)$$

The resistor values are simply multiplied by 50. This yields the detailed schematic diagram shown in figure 5.

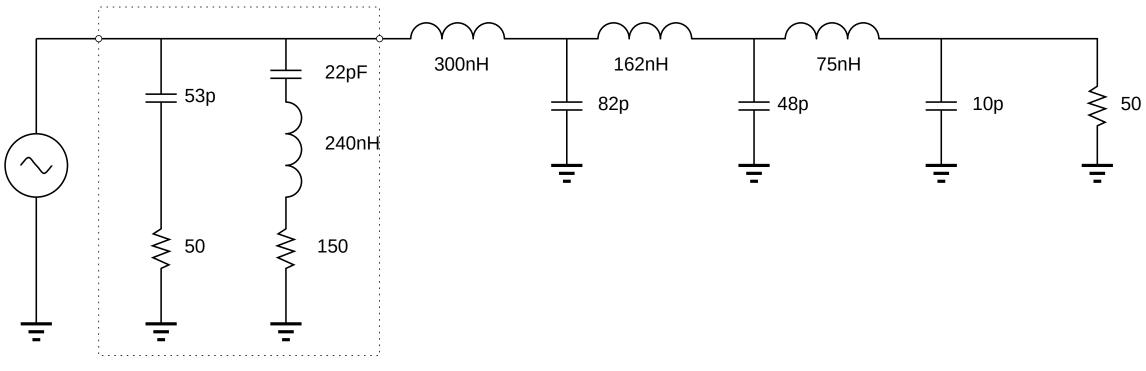

Figure 5. Sixth order 50Ω 40 MHz Bessel low−pass

The filter was constructed using hand wound coils and 5% tolerance ceramic chip capacitors on a piece of copper plated epoxy board. (Figure 6.) The coils are positioned so as to minimize mutual coupling, but no screening has been used between the filter sections.

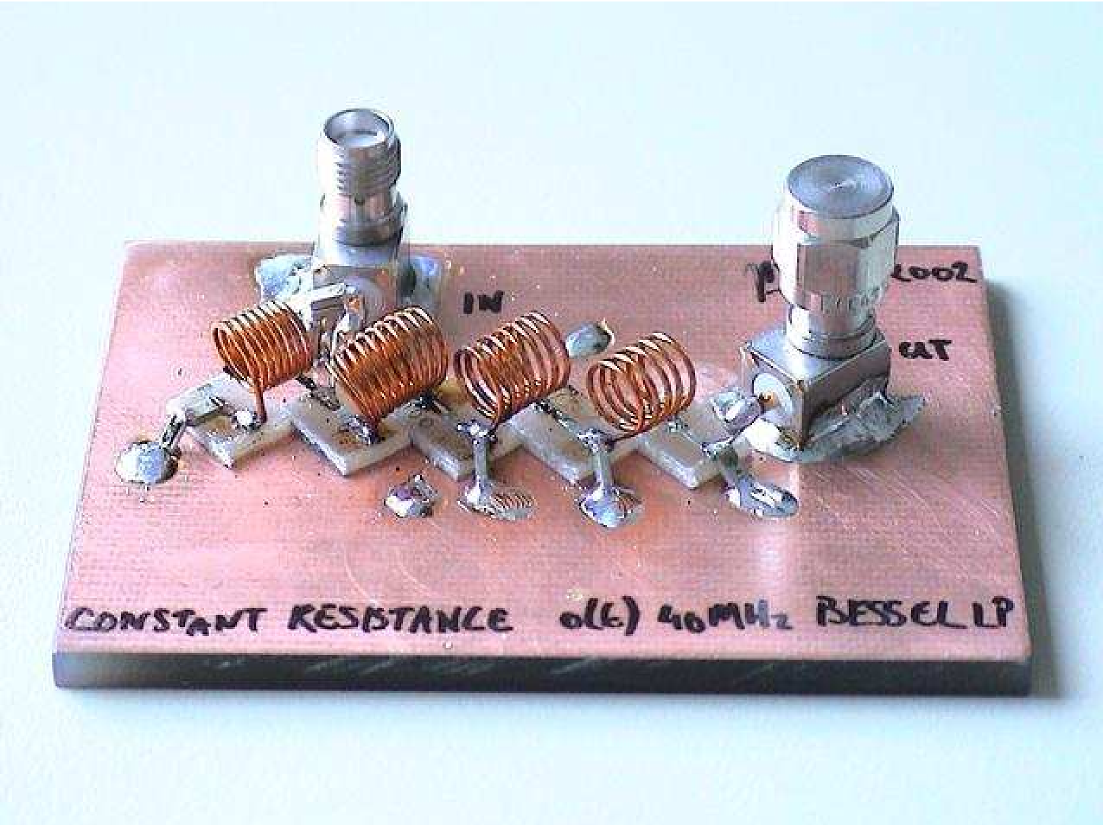

Figure 6. Practical realization of a constant resistance Bessel filter

The following plot (Figure 7), shows the theoretically possible S_{11} (lower curve), as well as the practically achieved values. These results are compatible with the expected performance for 5% tolerance components, as a Monte Carlo simulation using a circuit simulator will readily show.

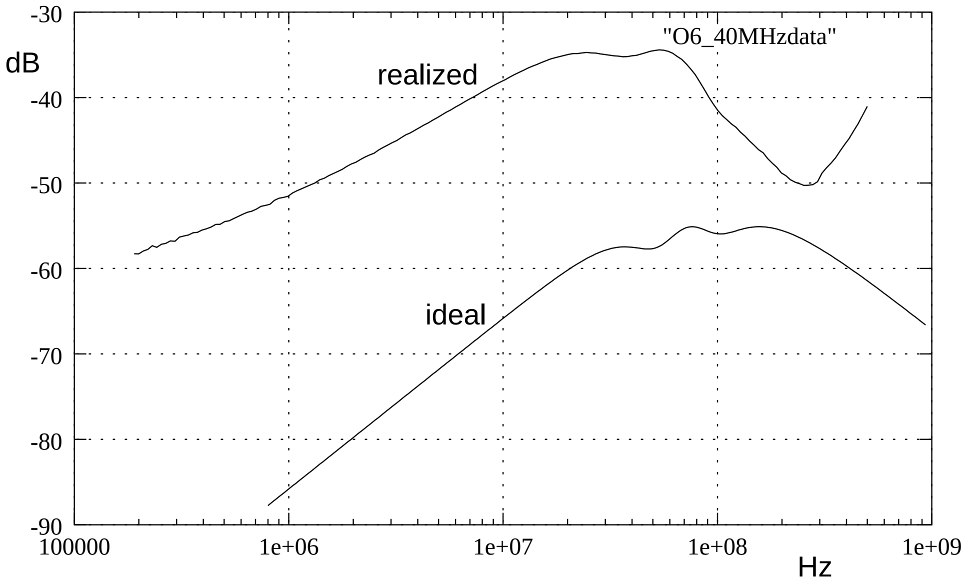

Figure 7. Reflection coefficient (S_{11}) of the realized filter

6 Conclusion

A simple method is described for obtaining low-pass filters with constant input resistance over frequency. Such filters absorb, rather than reflect, out-of-band energy. The filters are useful in applications that cannot tolerate reflections, e.g., if the signal source is strongly reactive, or connected through a long transmission line.

For most filters, the theoretical reflection coefficient S_{11} is below −50dB. This corresponds to an input resistance that deviates by no more than 0.3% from its nominal value. For practical realizations using components with 5% accuracy, and for frequencies in the MHz range, an S_{11} better than −30dB can reasonably be expected.

7 Acknowledgments

I am indebted to my colleagues, Marek Gasior and José-Luis Gonzalez, for many discussions on the subject of passive filters, and to Marek in particular, for providing the photograph of the realized filter.

References:

[1] Anatol I. Sverev, "Handbook of filter synthesis", John Wiley & Sons, 1967, ISBN 0 471 98680 1