CAS 2022 RF-Exercise

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Diplexer Design

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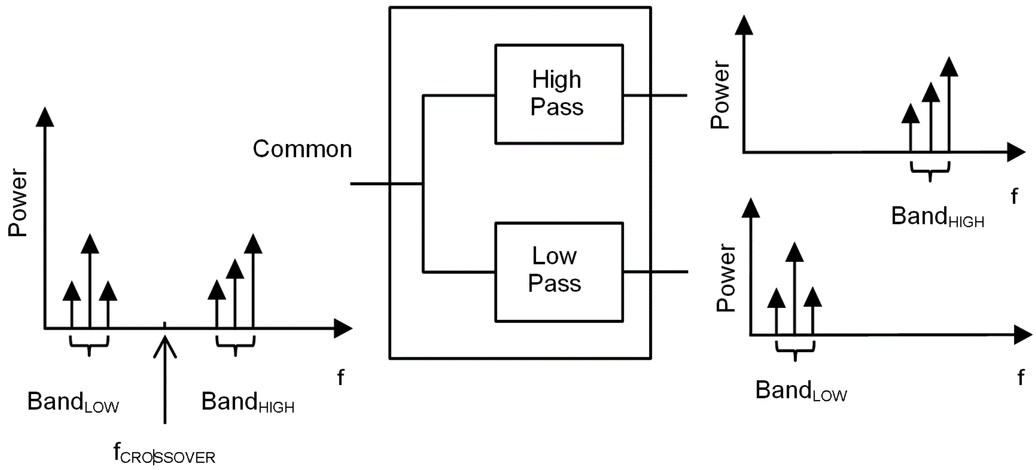
Outlook:

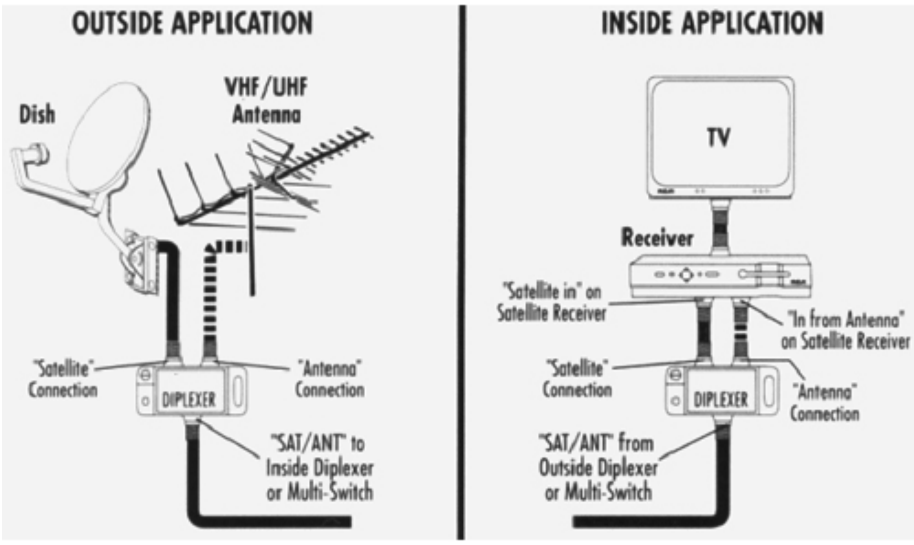
This exercise should help you to design, simulate and build your own diplexer. Finally you can measure our ready diplexer and compare with the theoretical values you obtained in your simulations.

1 Introduction

A **Diplexer** is a 3-port passive device that implements frequency multiplexing. Two ports, usually named L and H (L stands for *Low* band and H for *High* band respectively) are multiplexed onto third port named S (stands for *Sum*). The bandwidths of H and L are disjoint. The signals on L and H can coexist on port S without interfering with each other. In principle the diplexer consists of a low pass filter connecting ports L and S and high pass filter connecting ports H and S.



Diplexers are often used in the home to allow a direct broadcast satellite TV dish antenna and a terrestrial TV antenna (local broadcast channels) to share one coaxial cable. The dish antenna occupies the high frequency range (typically 950 to 1450 MHz), while the TV antenna uses lower television channel frequencies (typically 50 to 870 MHz). It is advantageous in the house that have already a TV installation made by means of a single coaxial cable: the distribution of the satellite and terrestrial TV signals does not require installation of the second cable.



In the world of accelerators, diplexers are used, e.g. if different particle species are accelerated in the same synchrotron, utilizing different RF frequencies. Similar to the example above, the related beam pickups deliver complex signals which may need to be separated in the frequency domain to provide a clean measurement for each type of particle.

An import feature of the diplexer lies in the characteristics of the **high-pass (H) and low-pass (L) sections**, which are not just simply joint, but also follow a **complementary frequency response**. As a consequence, a matching of the characteristic impedance at the diplexer input can be achieved over a broad frequency band. We will confirm this characteristic with a S11 measurements you will perform within this exercise.

The diplexer, being a passive device, is normally reciprocal: the device itself doesn't have a notion of input or output. However poorly designed diplexers may have differing impedance on various ports. You should not simply assume that such device is fully **reciprocal** unless you measure S21, S31, S12 and S13.

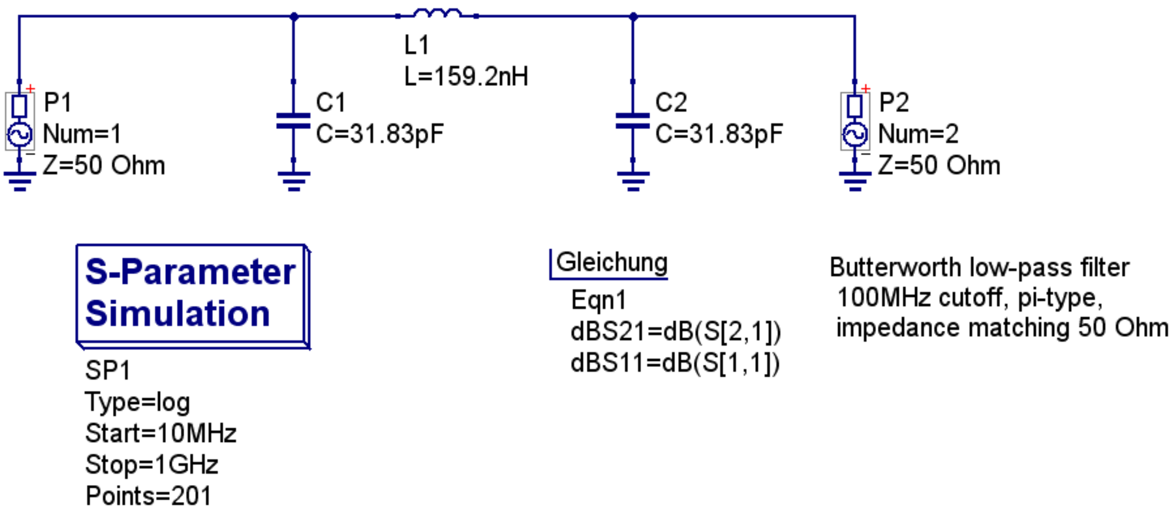
In the ideal case, the low-band frequency signal power on the common port L is transferred to the common port S, while all the high-band signal power on port H is transferred to the same port S, or in the other direction, a signal with a broad frequency spectrum at the common port S is divided by its frequency contents in low and high frequency bands at the L and H ports. However, in real life the frequency separation is not perfect, and a certain **cross-talk** between the channels has to be accepted. As a consequence, some power will be lost, and some signal power will leak into the wrong port. A typical diplexer may have around 30 dB isolation between its L and H ports, which is still sufficient for most applications.

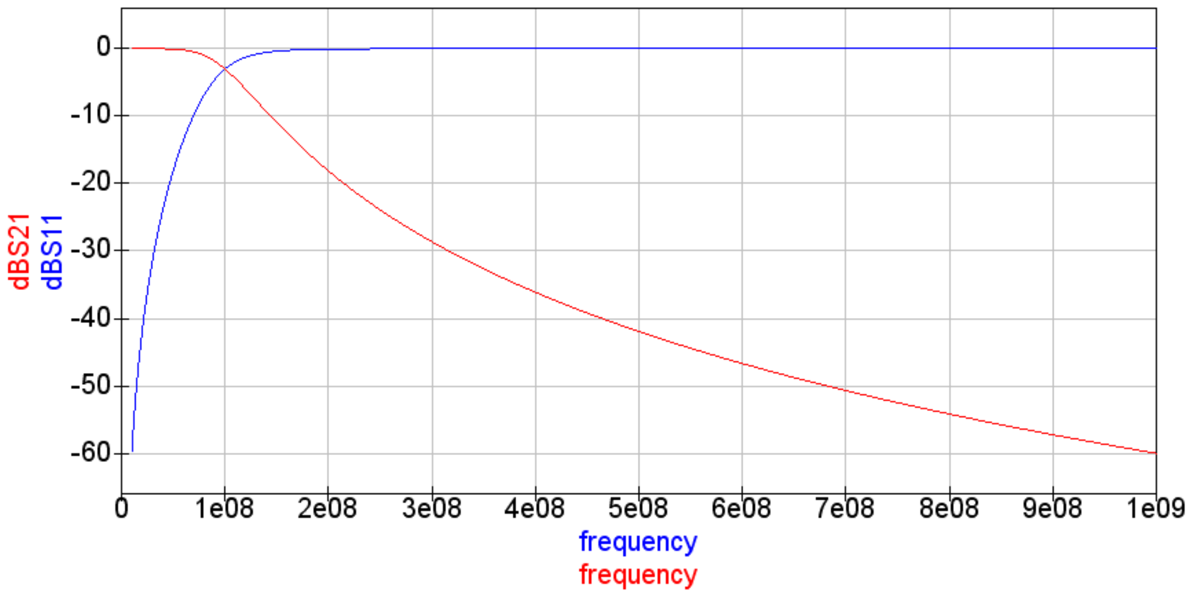
Please note: The diplexer is a different device than a passive splitter/combiner. The ports of a diplexer are frequency selective whereas the ports of a combiner are not! Moreover, a divider takes all the power delivered to the S port and equally divides it between the A and B ports. A diplexer distributes the power depending on the frequency band occupation.

2 Diplexer Design by means of QUCS Simulations

2.1 Low-pass Filter

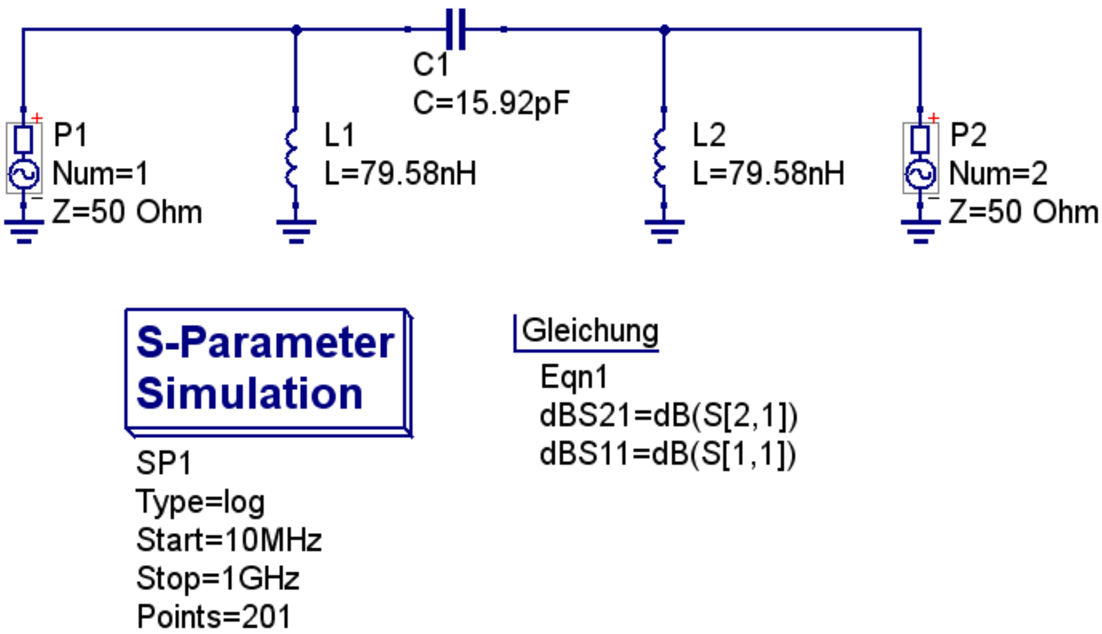
Let us start with a simulation of the Butterworth low-pass filter with cut-off frequency of 100 MHz. As this filter will be tested with network analyzer the characteristic impedance should be matched to 50 Ohm. Use an integrated in QUCS filter synthesis tool. Run simulation and plot the results.

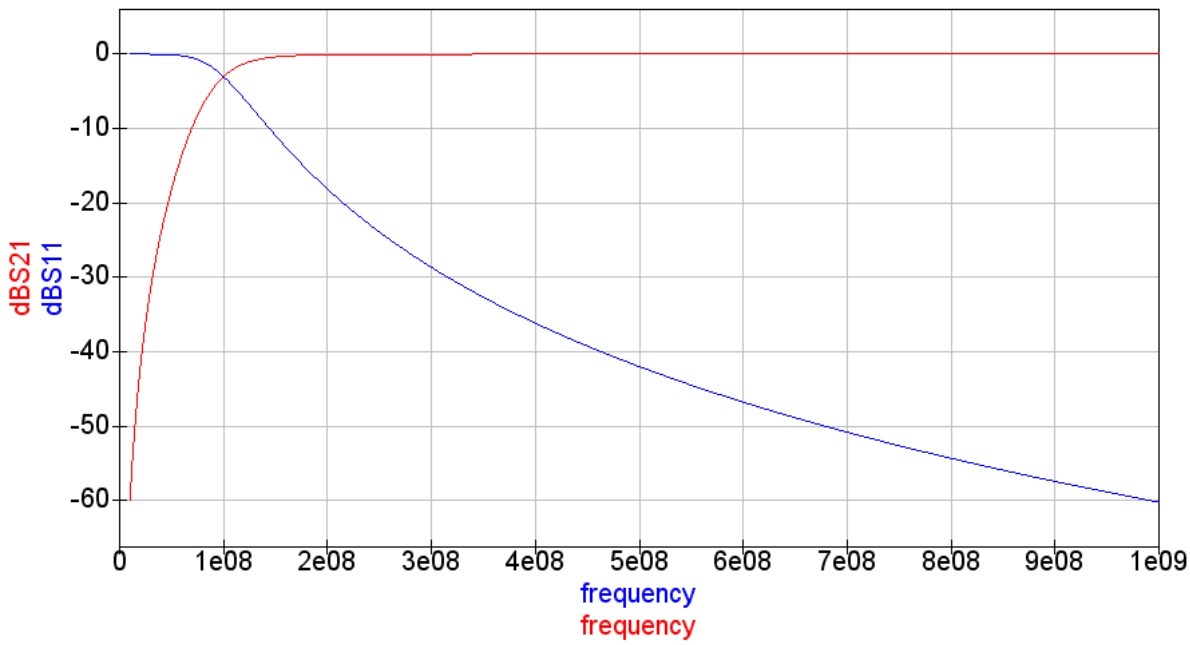




2.2 High-pass Filter

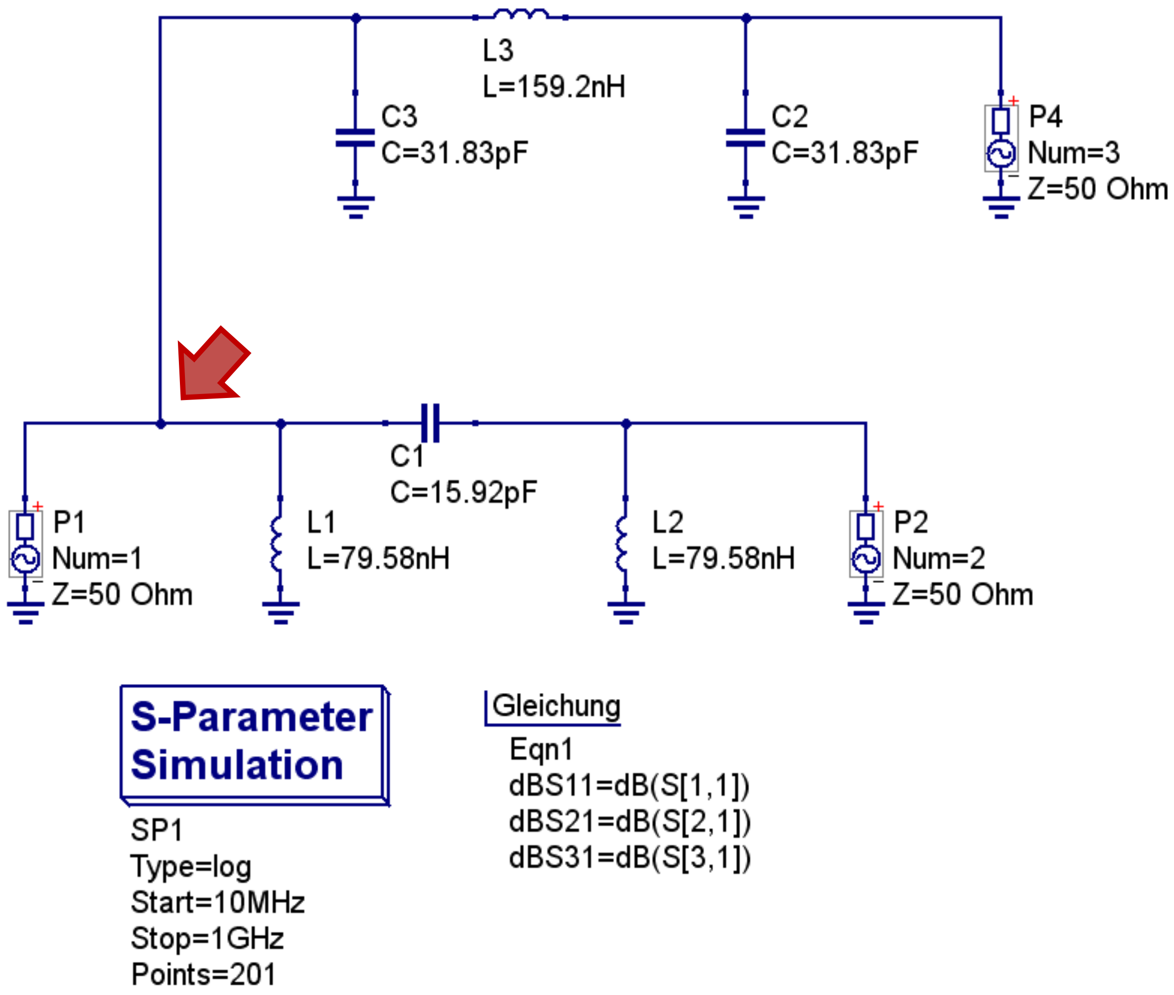
Now, simulate a Butterworth high-pass filter with same cut-off frequency as previous i.e. 100 MHz and characteristic impedance of 50 Ohm. Run simulation and plot the results.

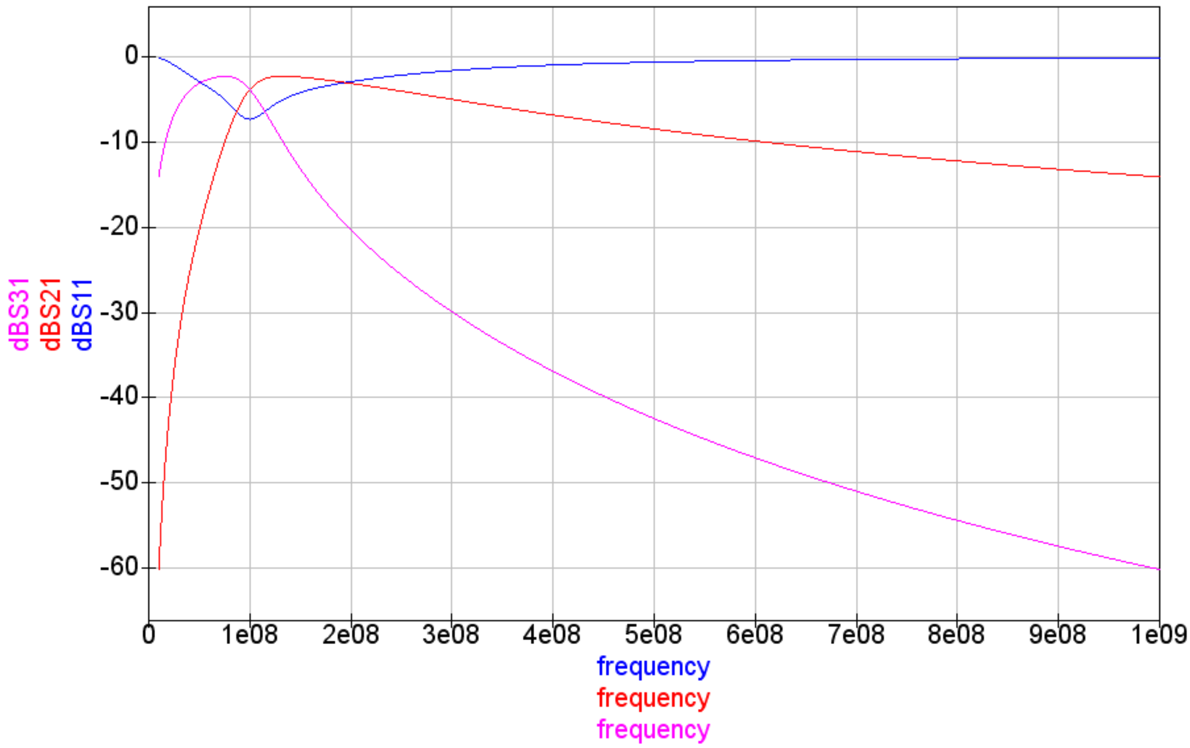


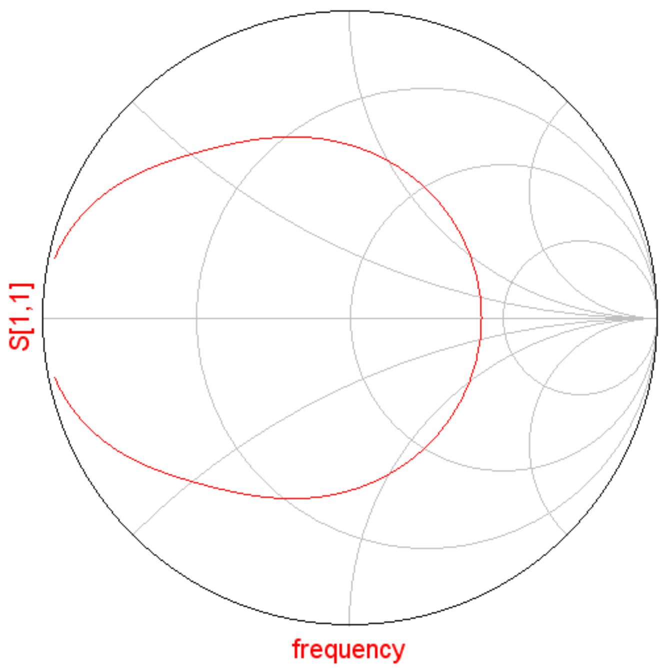


2.3 Diplexer: First Attempt

As a next step let's try to combine both high-pass and low-pass filters together to arrange a kind of diplexer. Why is the transmission (S21 and S31) so bad? Moreover, there is an impedance mismatch on input? Hint: discuss the impedance in the point marked by the red arrow in the schematics bellow.




0
-10
-20
-30
-40
-50
-60
dBS31
dBS21
dBS11
0
1e08
2e08
3e08
4e08
5e08
6e08
7e08
8e08
9e08
1e09
frequency
frequency
frequency

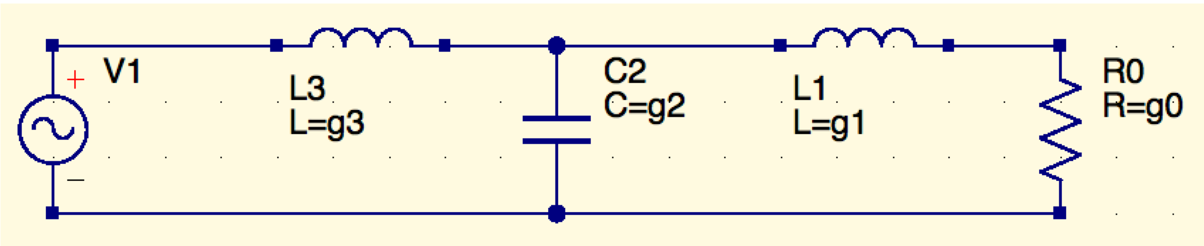

S[1,1]
frequency

2.4 Diplexer of an improved design

Let's now follow the idea of impedance matching the two diplexer sections a of the diplexer at the input port S. In that way, the reactance of the low-pass filter will compensate the reactance of the high pass filter. Here we will provide you a solution for the 6-order diplexer based on the two single-terminated Butterworth filters of 3[rd] order.

In the theory of simple ladder-type filter networks, a so-called "normalized low-pass" (NLP) prototype network, normalized to reference values $R = 1\Omega$, and $\Omega_{3dB} = 1\ s^{-1}$, is synthesized, which approximates the characteristics of a given transfer function, here a maximally flat (Butterworth) magnitude response

$|S21(\omega)| = \frac{1}{\sqrt{1+\Omega^{2n}}}$, with $\Omega = {}^{j\omega}/_{j\omega_{3dB}}$ and $n = 3$ filter elements:



and normalized element values of:

number	g0	g1	g2	g3
1	1	0.5	1.33	1.5

A frequency transformation has to be applied, to get the values of the circuit elements for the low-pass (LP) and high-pass (HP) sections, here we assume a reference (load) impedance of $R_r = 50\ \Omega$ and a reference (3 dB cut-off or corner) frequency $\omega_{3dB} = 2\pi f_{3dB}$ with $f_{3dB} = 100\ MHz$. We now define transformed reference capacitance and inductance values as:

$$C_r = \frac{1}{R_r 2\pi f_{3dB}};\ L_r = \frac{R_r}{2\pi f_{3dB}}$$

The value of the *n*-th element of the low-pass branch is given by:

$$X_n = X_r g_n$$

And similar, the value of the *n*-th element of the high-pass branch is given by:

$$X_n = \frac{X_r}{g_n},$$

where *X* stands for *C* or *L*

S-Parameter Simulation

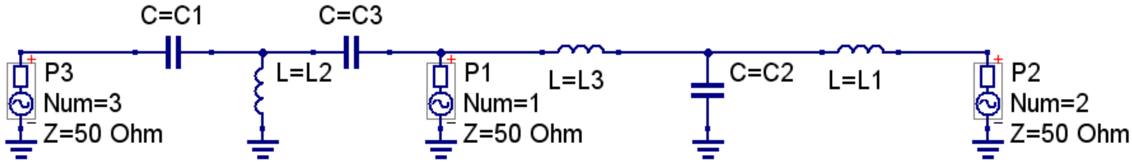
SP1
Type=lin
Start=10 MHz
Stop=500 MHz
Points=201

Gleichung
Eqn1
g0=1
g1=0.5
g2=1.3333
g3=1.5

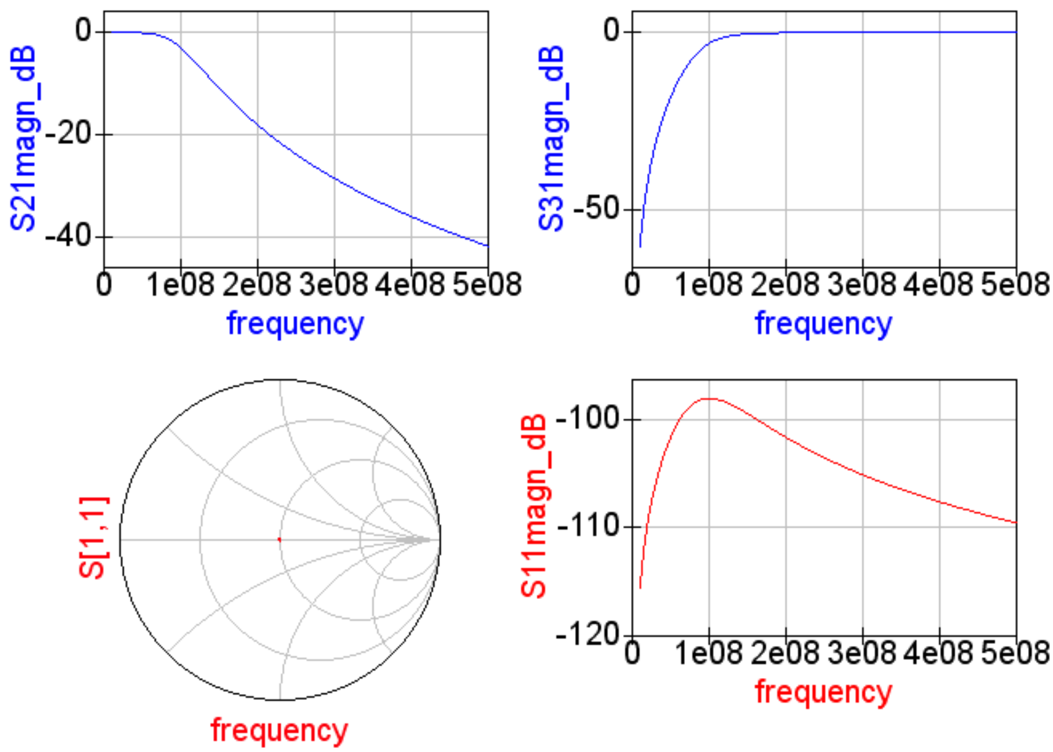
Gleichung
Eqn2
Rr=50
f3dB=100e6
Lr=Rr/(2*pi*f3dB)
Cr=1/(Rr*2*pi*f3dB)

Gleichung
Eqn3
L1=g1*Lr
C2=g2*Cr
L3=g3*Lr
C1=Cr/g1
L2=Lr/g2
C3=Cr/g3

Gleichung
Eqn4
S21magn_dB=dB(S[2,1])
S31magn_dB=dB(S[3,1])
S11magn_dB=dB(S[1,1])



number	C1	C2	C3	L1	L2	L3	f3dB
1	6.37e-11	4.24e-11	2.12e-11	3.98e-08	5.97e-08	1.19e-07	1e+08



3 Prototype: Soldering and Measurements

Please use provided PCBs and builds the filters diplexer. Use SMD components with values you obtained in simulations.