



FILTER TOPOLOGIES

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Field Application Engineer

WÜRTH ELEKTRONIK MORE THAN YOU EXPECT

- Filter basics
- Passive filters
- Practical filter topologies



FILTER BASICS

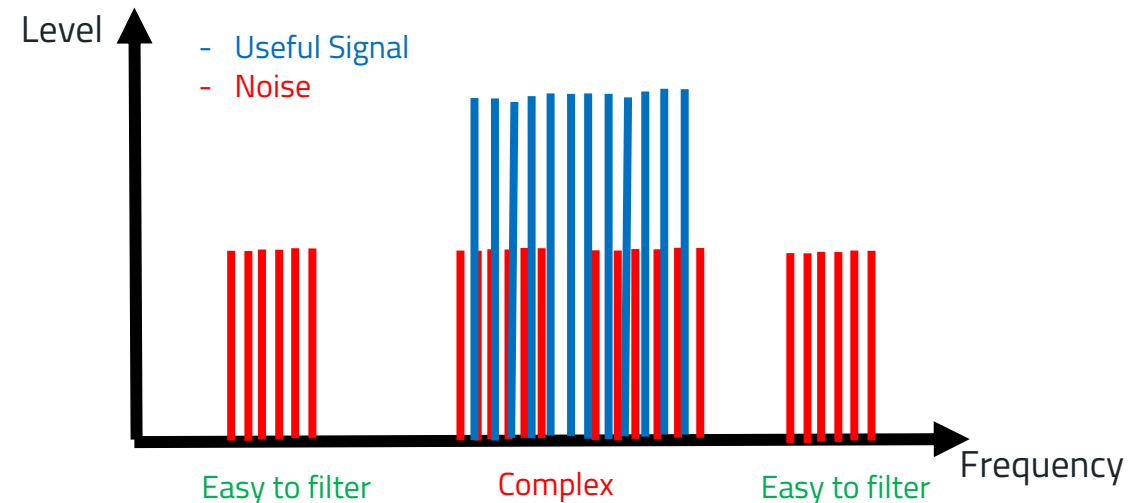


Filter – Function

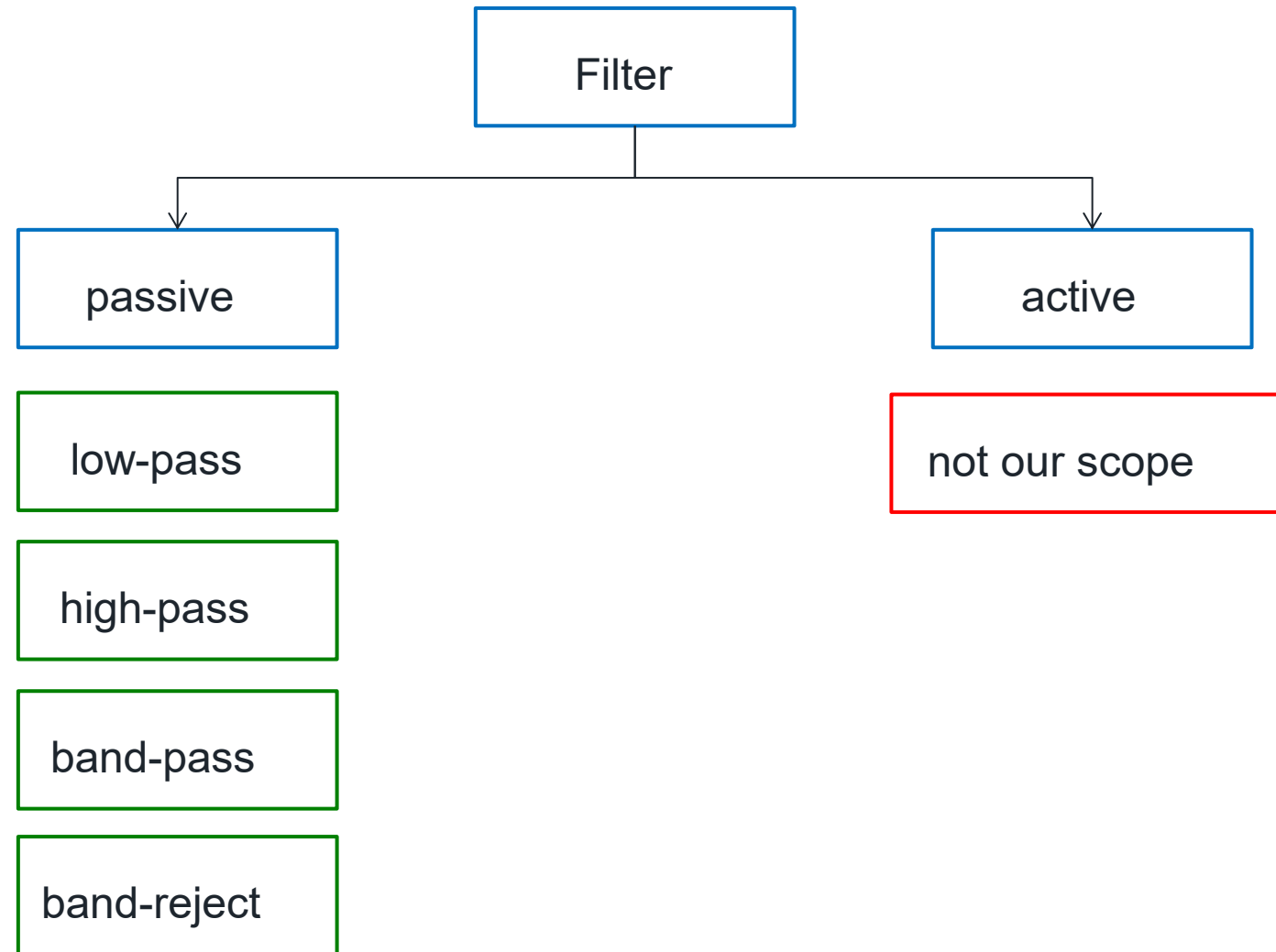
- **What is the function of a filter?**
- reduction of the coupling of interferences between two points
- lowering the emission of disturbances
- increasing the immunity against disturbances
- preferably no interaction with the wanted signal

Filter – Complexity

- How much effort does it take to design the proper filter?
- The filter design depends on the “spectral distance” between the disturbance and the wanted signal.
- So we look at the filter characteristics in spectral domain.
 - Filtering can be **complex** if the spectral distance is **short**.
 - If the spectral distance is **large** enough, the design of a filter becomes **simple**.

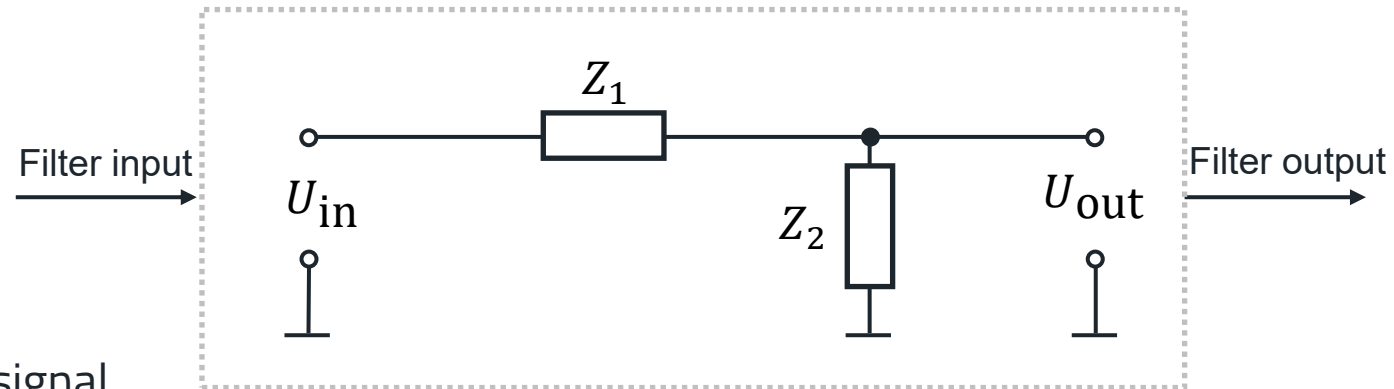


Basic types of filters



Filter – Principle

- A discrete filter consists of
 - ...at least two (discrete) components,
 - ...whereas at least one component must be frequency-selective.



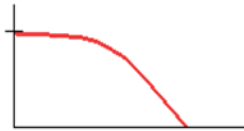
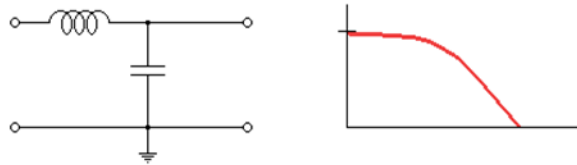
- match for the wanted signal
- mismatch for the disturbance signal

A filter is a frequency-dependent voltage divider.

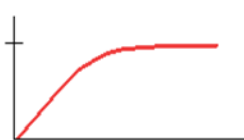
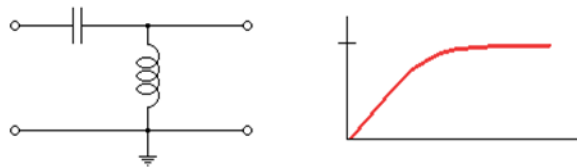
PASSIVE FILTERS



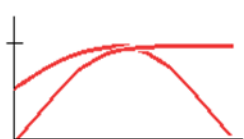
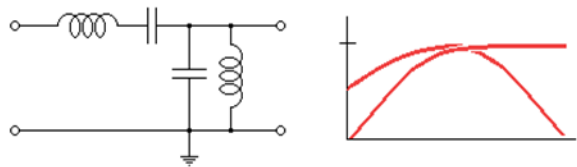
Passive filter topologies



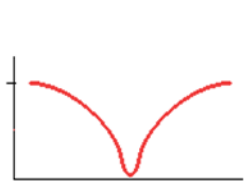
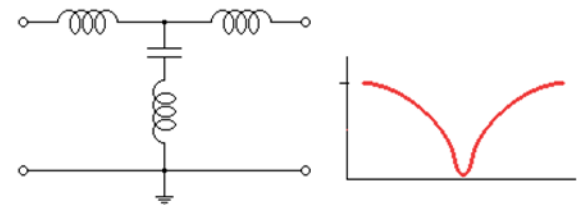
low-pass filter



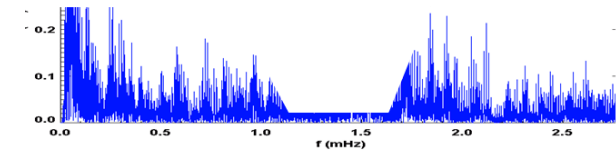
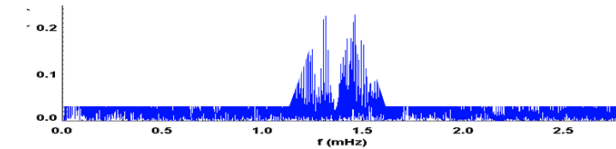
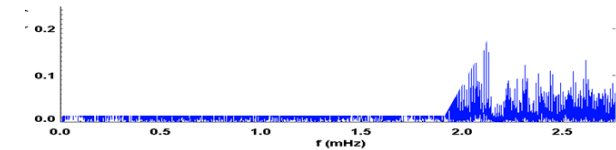
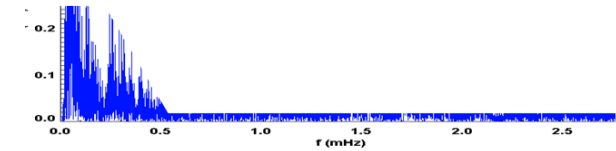
high-pass filter



band-pass filter



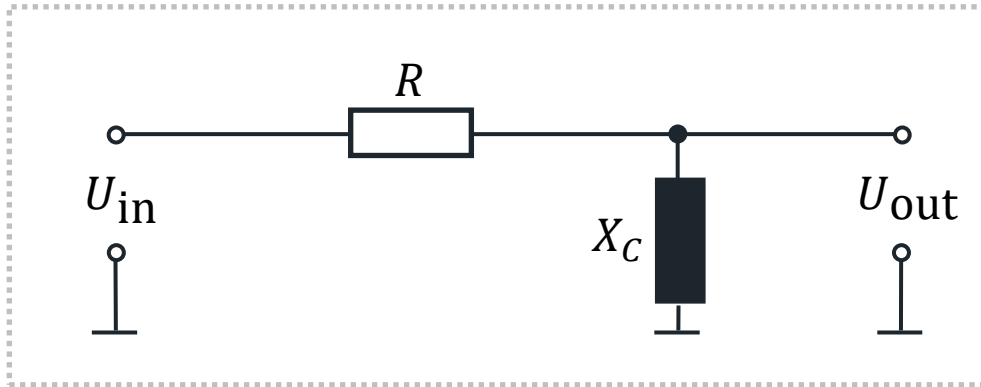
band-reject filter



Filter order

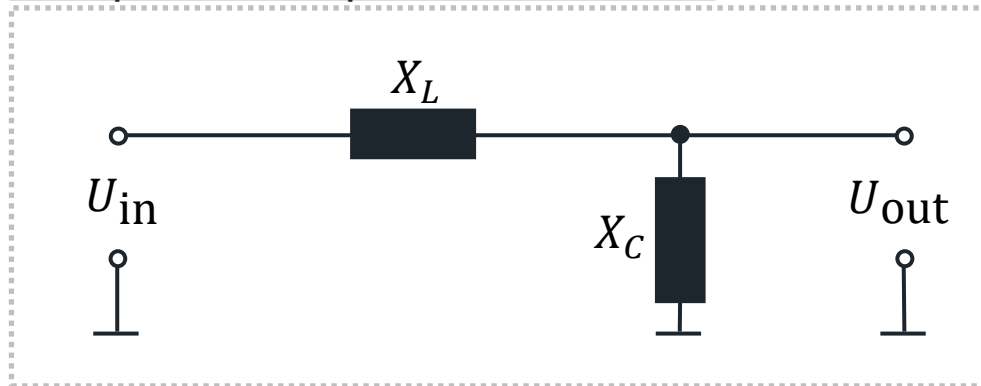
- The filter order is determined by the number of energy storage elements (L & C).

Low-pass example: first order



$$f \uparrow \rightsquigarrow X_C = -\frac{1}{\omega C} \downarrow$$

Low-pass example: second order

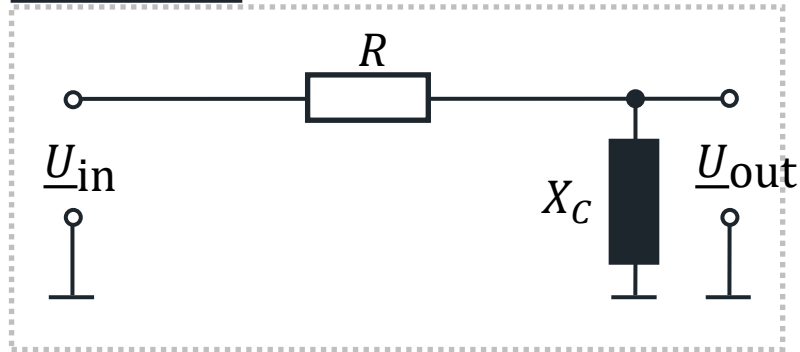


$$f \uparrow \rightsquigarrow X_L = \omega L \uparrow$$

$$f \uparrow \rightsquigarrow X_C = -\frac{1}{\omega C} \downarrow$$

Low-pass filter – Basics

First order:

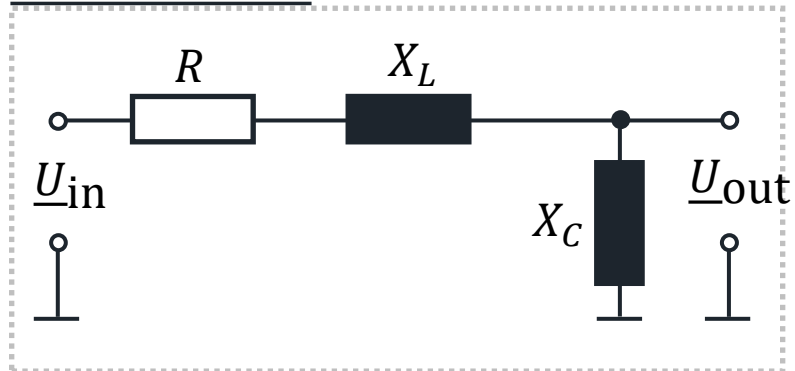


Transfer function and cutoff frequency:

$$\underline{H}(\omega) = \frac{\underline{U}_{out}}{\underline{U}_{in}} = \frac{1}{\sqrt{1 + (\omega \cdot R \cdot C)^2}} \cdot e^{-j \cdot \arctan(\omega \cdot R \cdot C)}$$

$$f_{c1} = \frac{1}{2\pi \cdot R \cdot C}$$

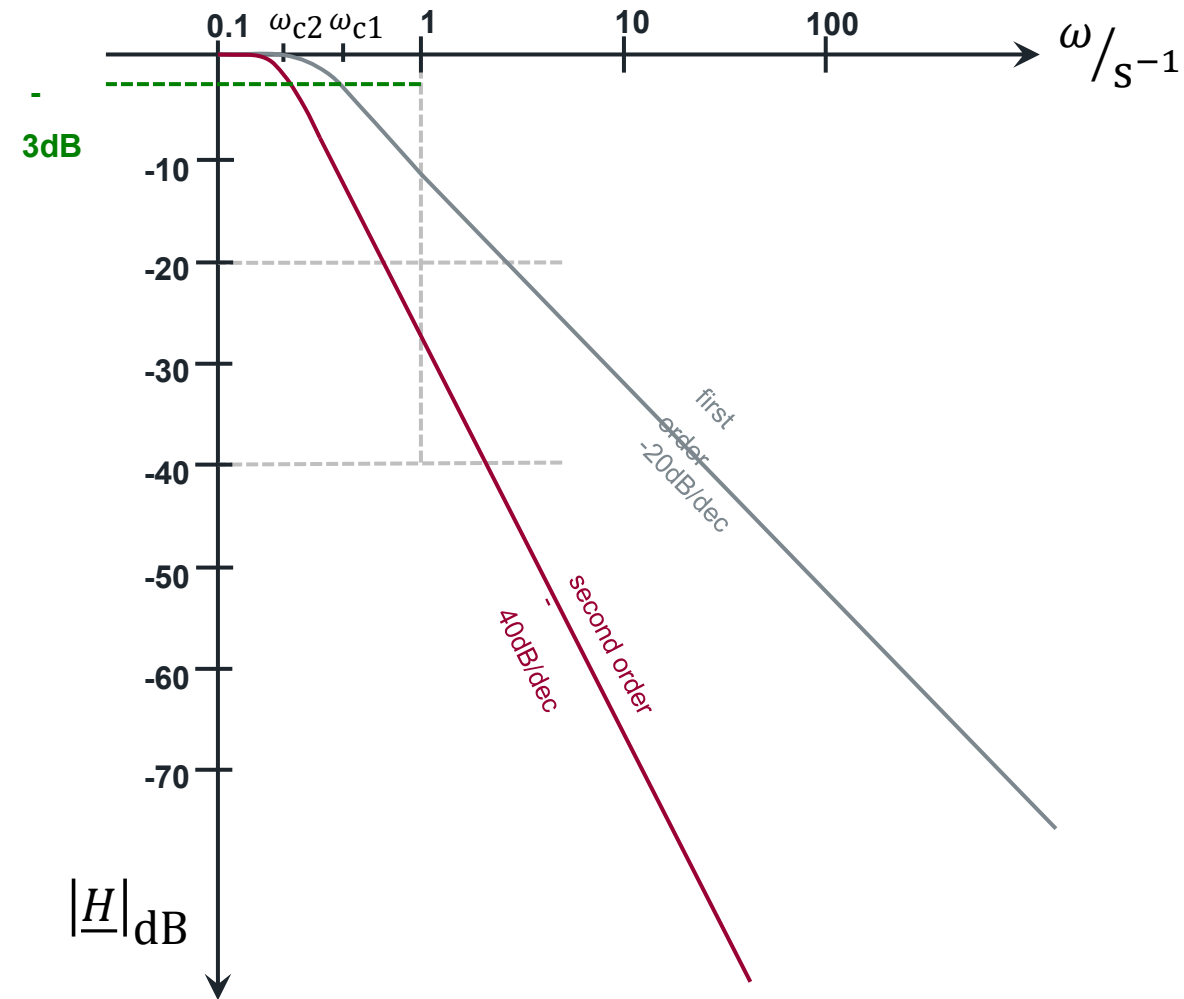
Second order:



$$\underline{H}(\omega) = \frac{|X_C|}{\sqrt{R^2 + (X_L + X_C)^2}} \cdot e^{-j \cdot \arctan\left(\frac{R}{X_L + X_C}\right)}$$

$$f_{c2} = \frac{1}{2\pi} \cdot \left(\sqrt{\frac{R^2}{4L^2} + \frac{1}{L \cdot C}} - \frac{R}{2L} \right)$$

Low-pass filter – Amplitude response



Low-pass filter – Effect on digital signals

Example:

$T=1.3\mu\text{s}$

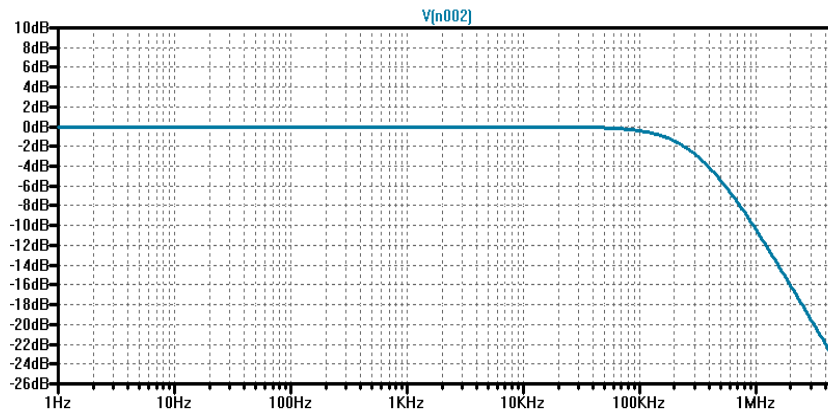
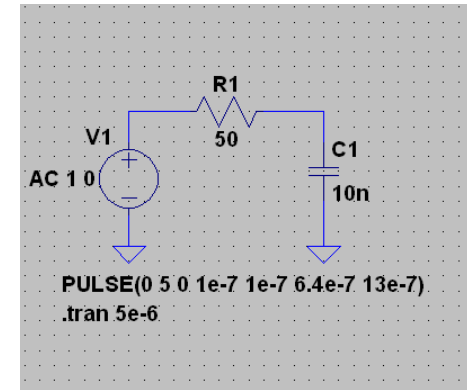
$t_{\text{rise}}=t_{\text{fall}}=100\text{ns}$

$U=5\text{V}$

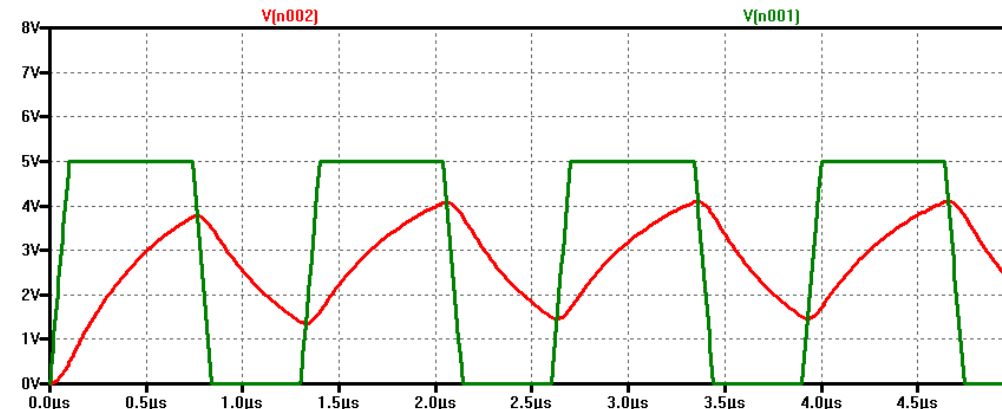
$R=50\Omega$

$C=10\text{nF}$

$$f_c = \frac{1}{2\pi \cdot R \cdot C} = 318.3\text{kHz}$$



Amplitude response



— Input — Output

The low-pass filter has an averaging effect on the input signal.

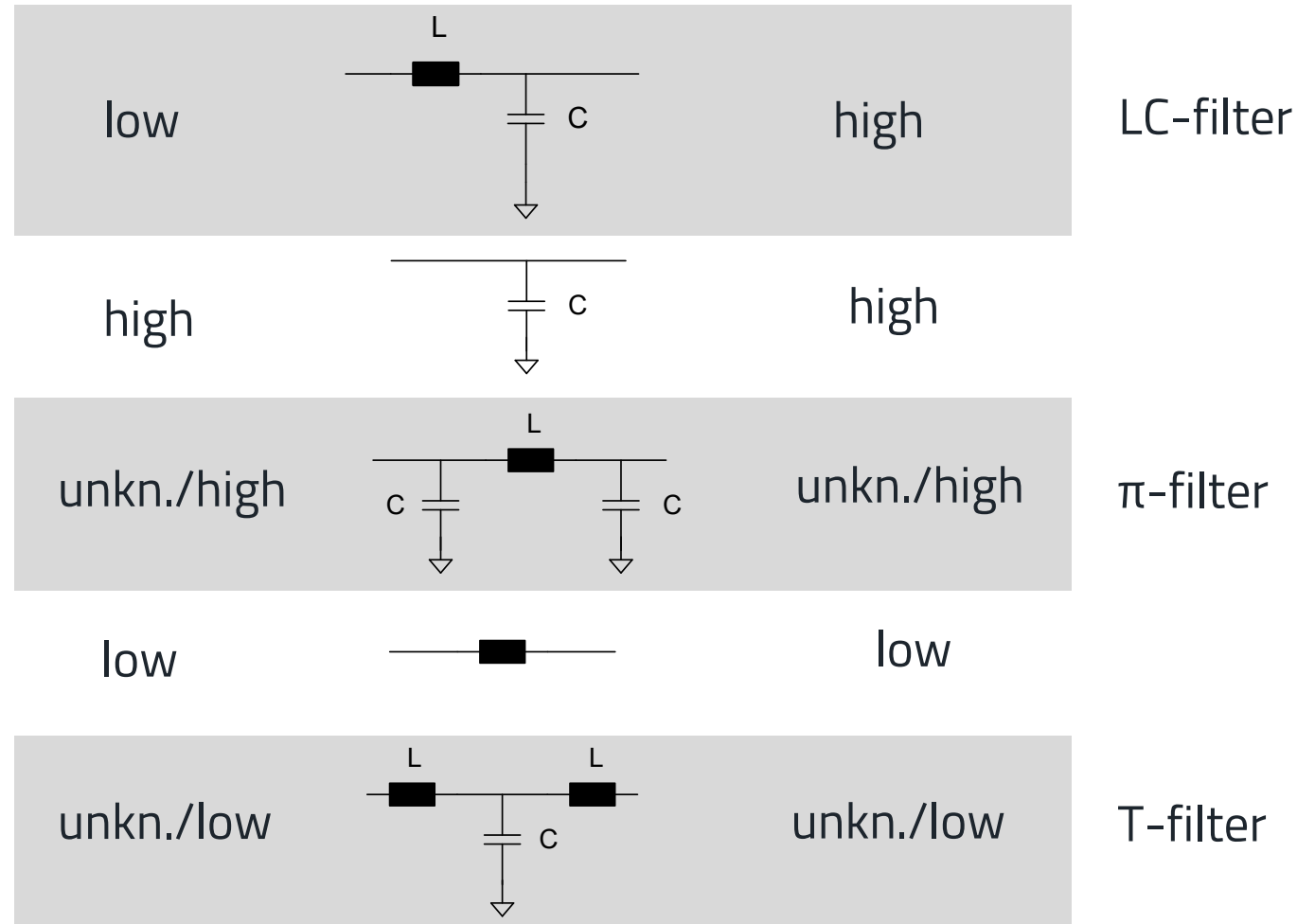
PRACTICAL FILTER TOPOLOGIES



Recommended filter topologies

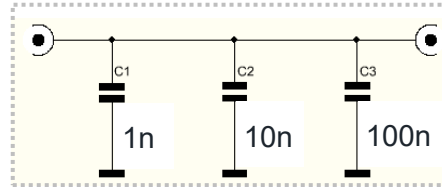
Source impedance

Load impedance

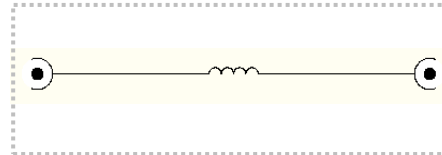


Filter topologies – Demoboard

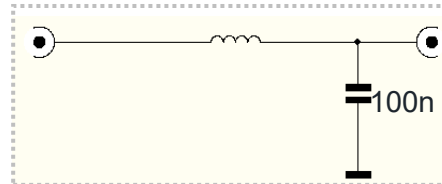
- Parallel-C-filter



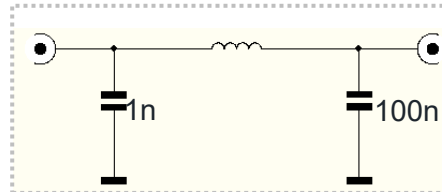
- L-filter



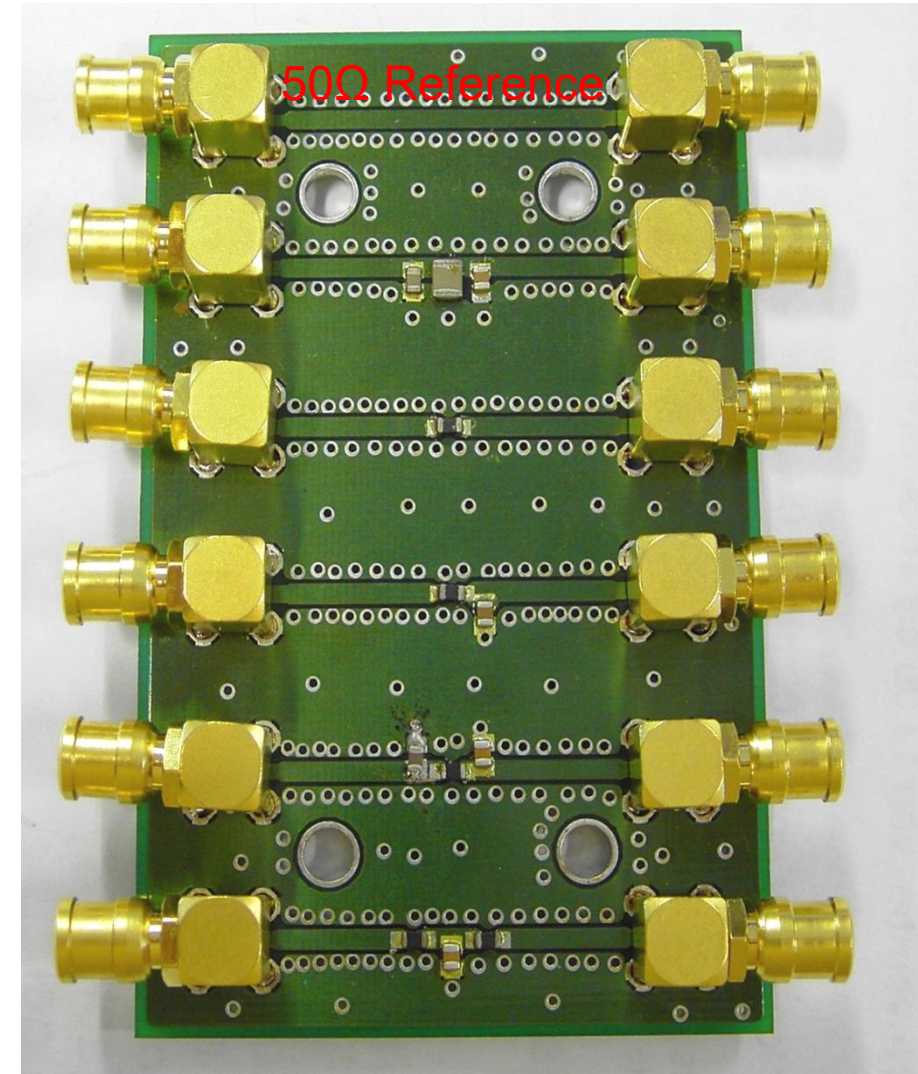
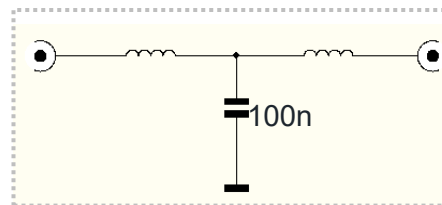
- LC-filter



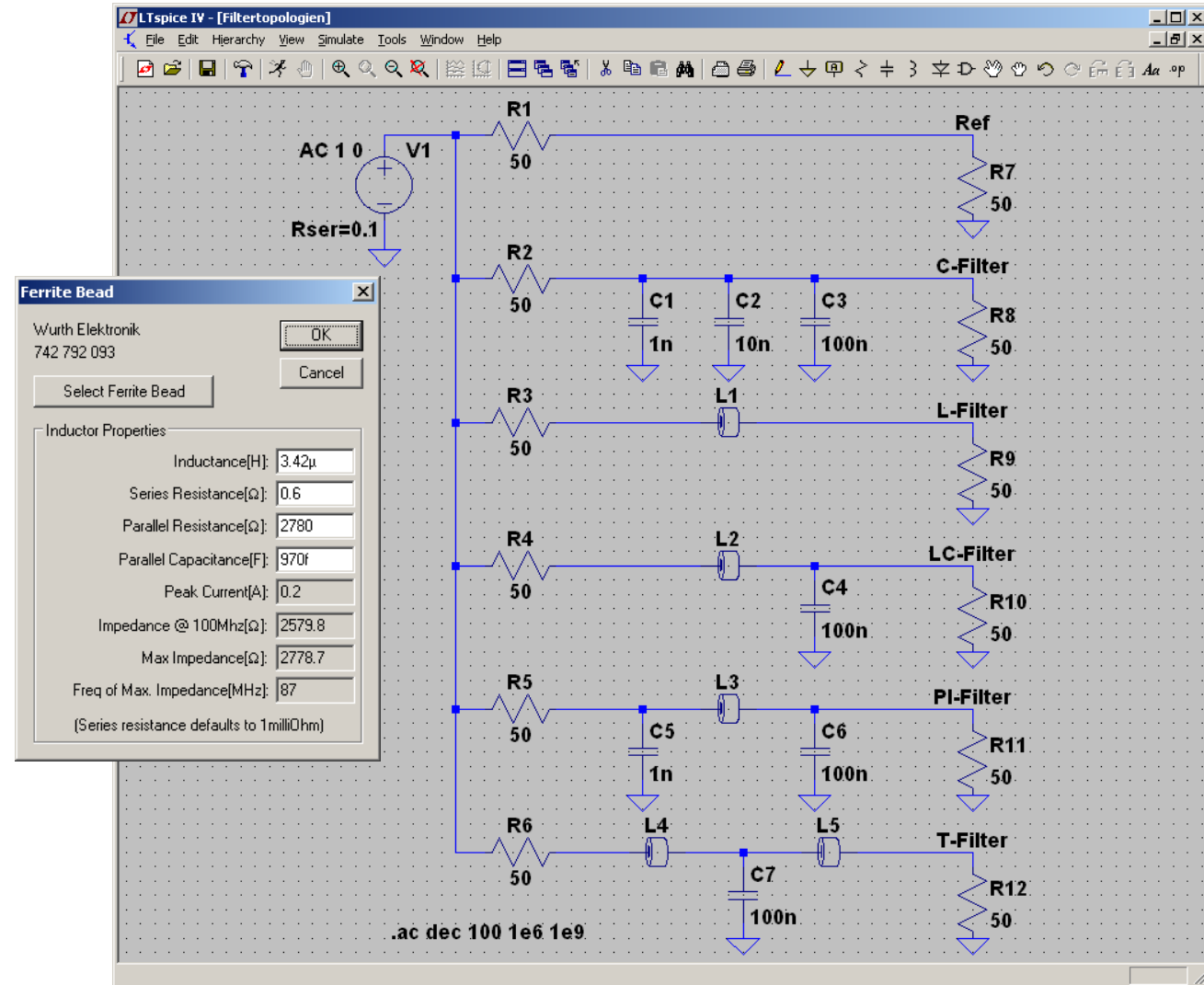
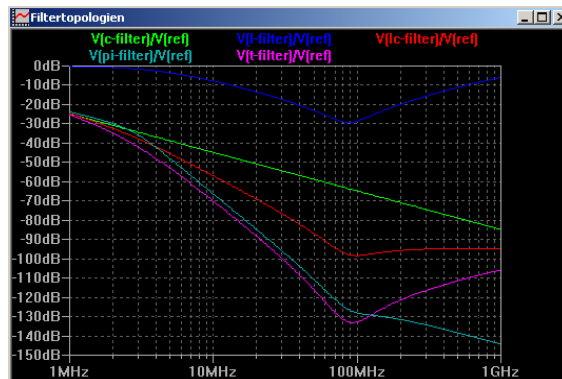
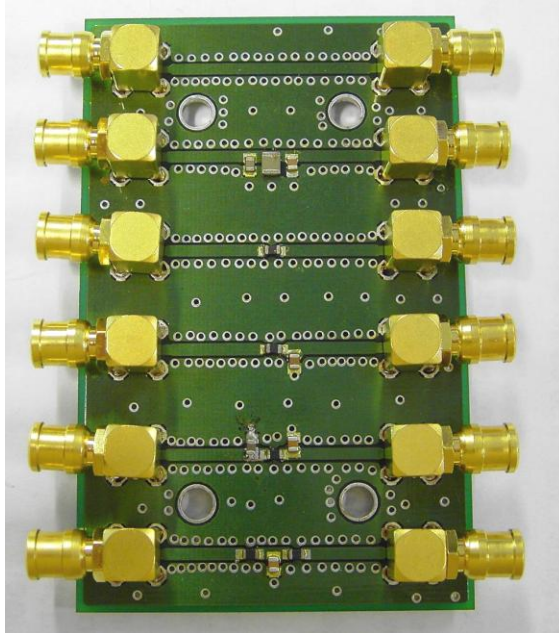
- Π -filter



- T-filter

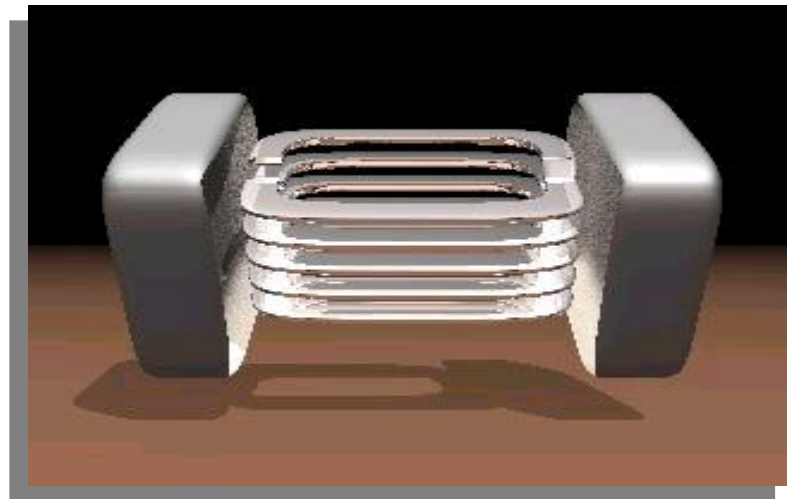
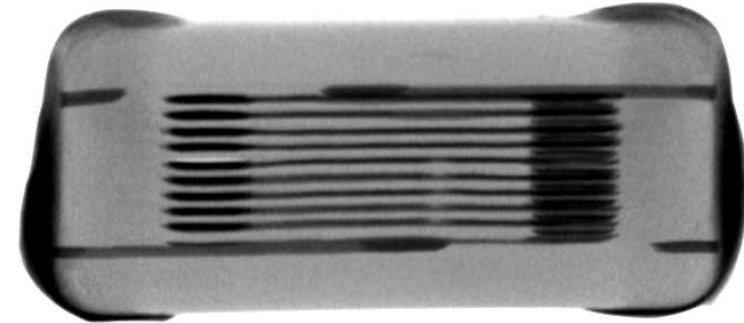
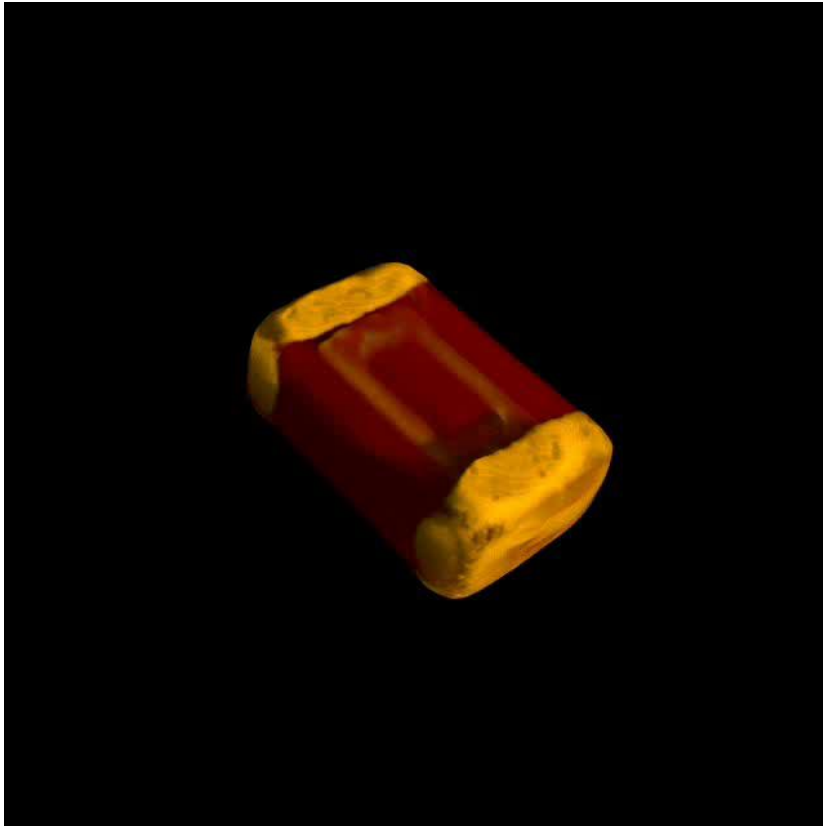


Filter topologies – LTspice simulation



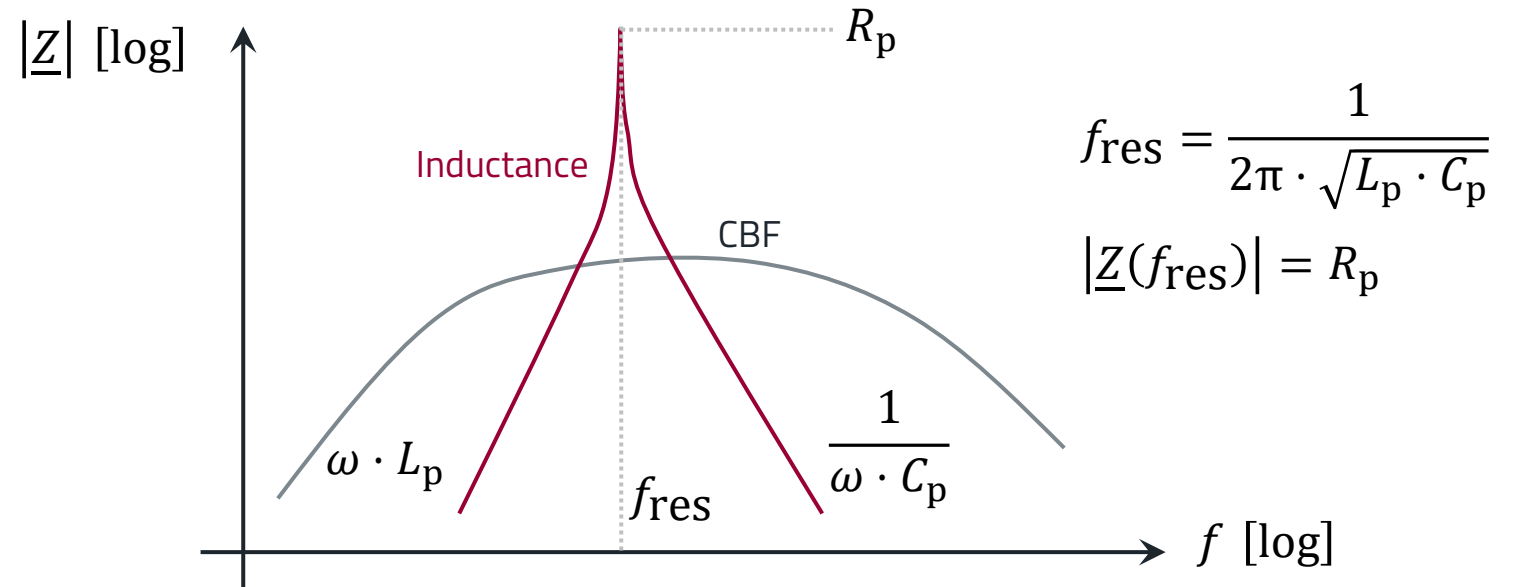
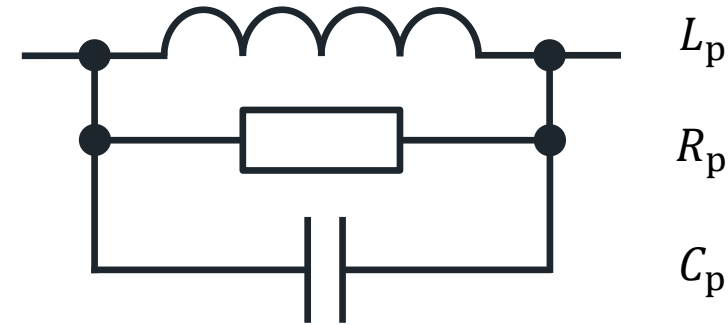
L-filter using WE-CBF

- The resistive losses $R(f)$ are used to convert differential-mode noise into heat.



Filter elements – Inductance / CBF

- Parasitic capacitances C_p :
 - Inductance: 10pF ... 500pF
 - Chip bead ferrite: 5fF ... 5pF
- Loss resistances R_p :
 - Inductance: < 30kΩ
 - Chip bead ferrite: 10Ω ... 3kΩ



Selection of CBF – REDEXPERT


**WÜRTH
ELEKTRONIK**

REDEXPERT® Ferrites for PCB Assembly

Filters: Series = WE-CBF HF, WE-CBF Size = 0603 Is selected

System


Pulse


Order Code	Series	Size	Spec	Type	I_R	Spec. Z	Z_{max}	L_p	C_p	R_p	L	W	H
742861118	WE-CBF HF	0603		Wide Band	700 mA	180 Ω	300 Ω @450 MHz	487 nH	0.315 pF	228 Ω	1.60 mm	0.800 mm	0.800 mm
742792621	WE-CBF	0603		High Speed	1.25 A	140 Ω	430 Ω @550 MHz	200 nH	0.585 pF	408 Ω	1.60 mm	0.800 mm	0.800 mm
742792622	WE-CBF	0603		Wide Band	1.50 A	180 Ω	290 Ω @380 MHz	434 nH	0.680 pF	277 Ω	1.60 mm	0.800 mm	0.800 mm

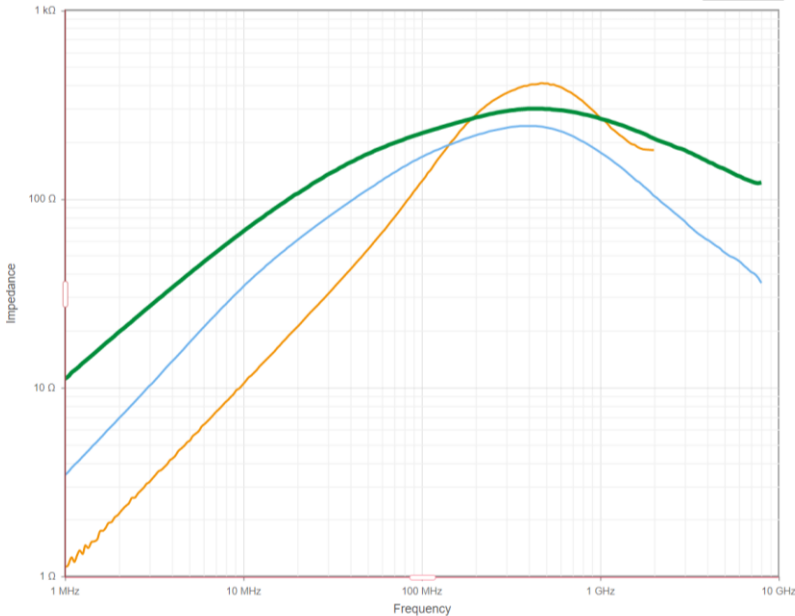
742861118 ×
 WE-CBF HF · 0603
 180 Ω

742792622 ×
 WE-CBF · 0603
 180 Ω

742792621 ×
 WE-CBF · 0603
 140 Ω

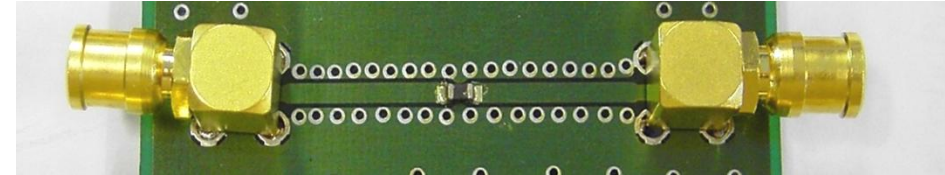
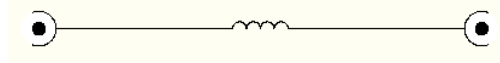
Impedance / Frequency

I = 0.00 A



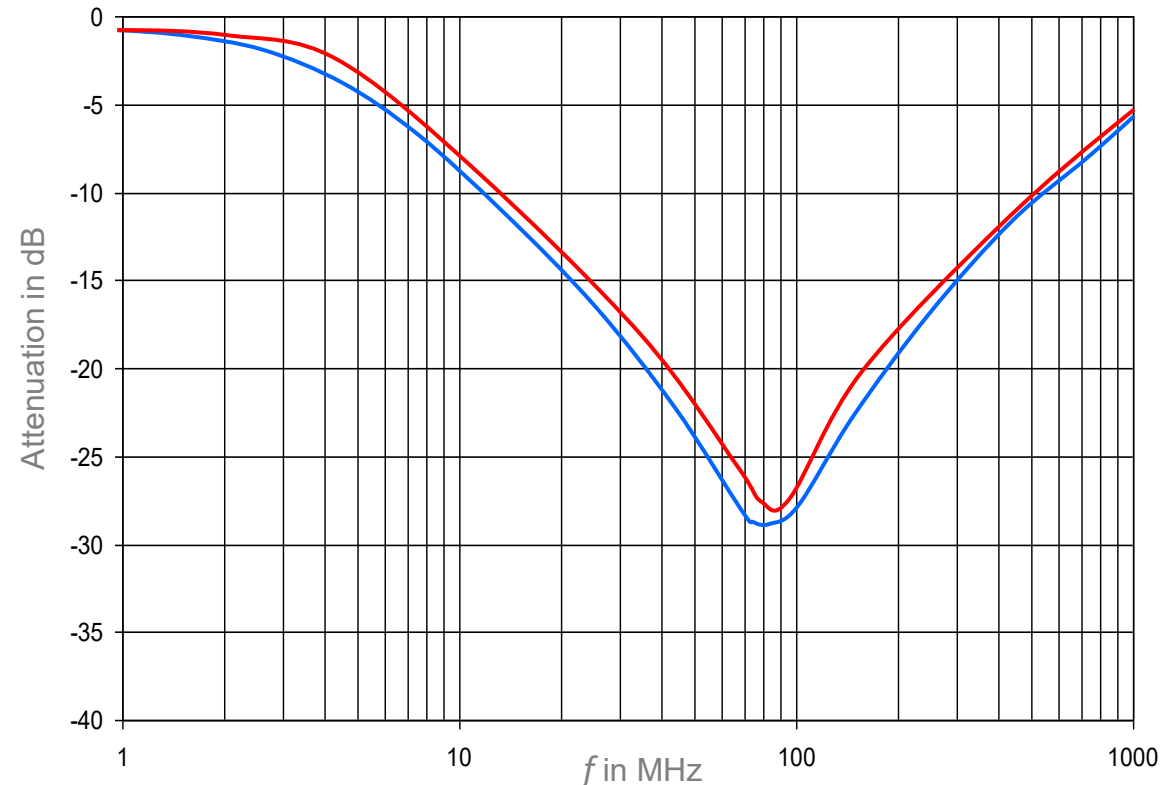
Filter topologies – L-filter

- L-filter

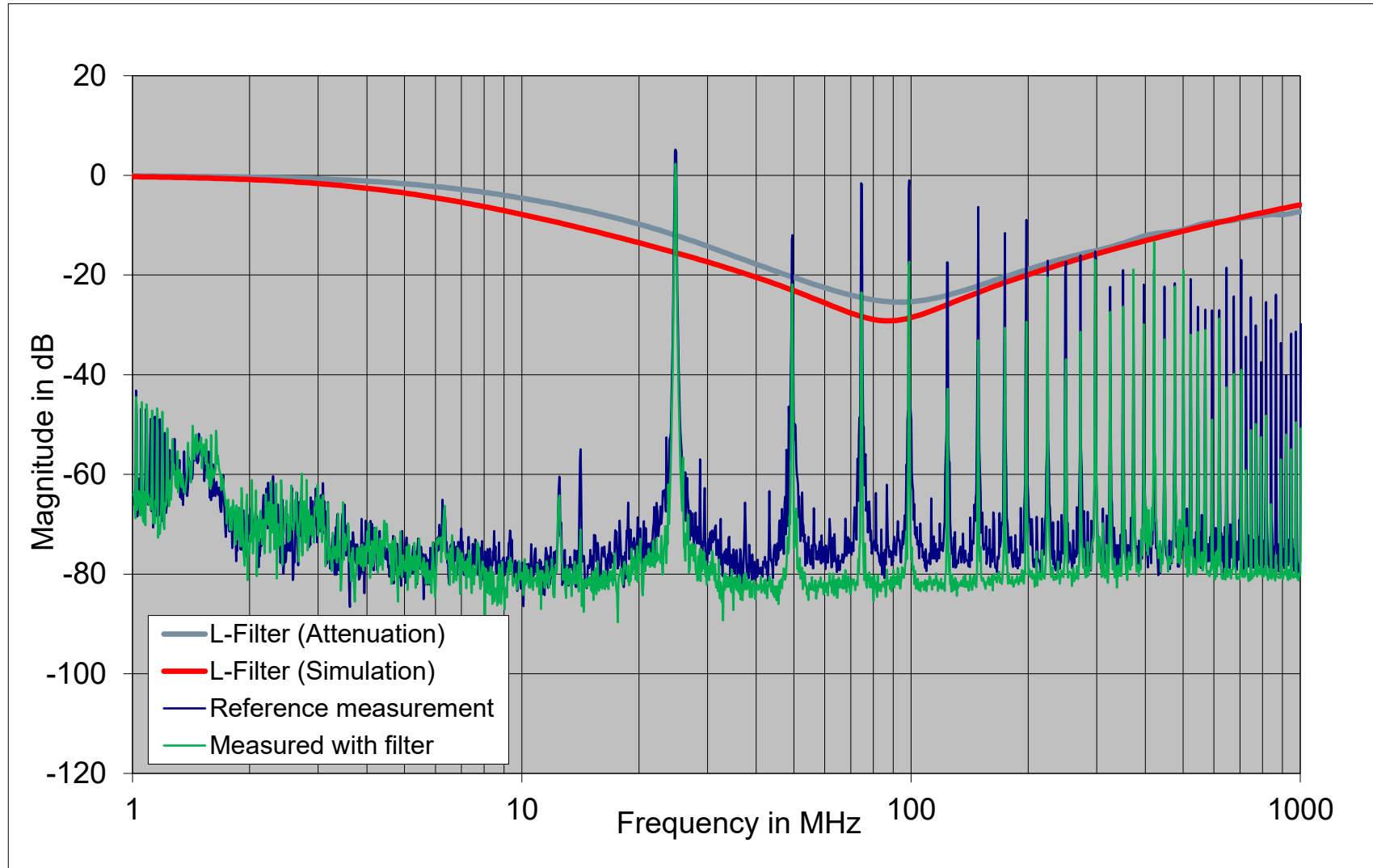


- A chip bead ferrite is used as an inductance.
- WE-CBF 742 792 093:
 - $Z_{\max} = 3000\Omega$ @ 80MHz
 - $A = -29\text{dB}$ @ 80MHz

Calculated
Measured

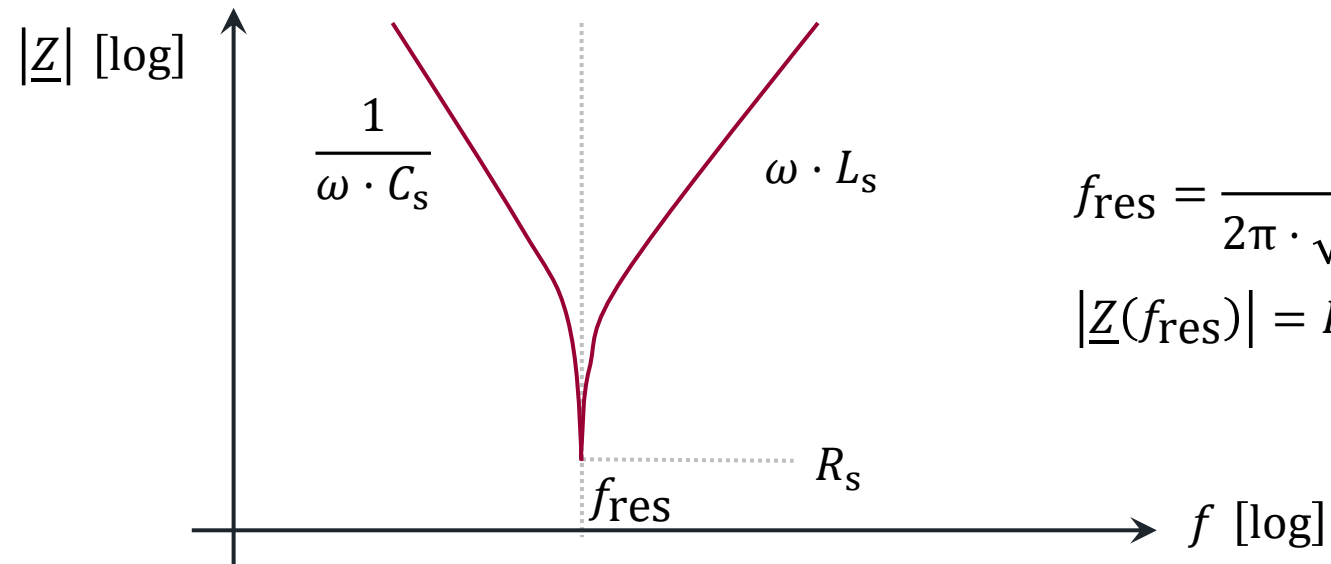


L-filter – Example measurement



Filter elements – Capacitance

- Extension of the L-filter with another frequency-dependent element:
 - Capacitor / capacitance
- Series inductance L_s :
 - SMD type: 1nH ... 5nH
- Series resistance R_s :
 - SMD type: 20mΩ ... 300mΩ (1Ω)

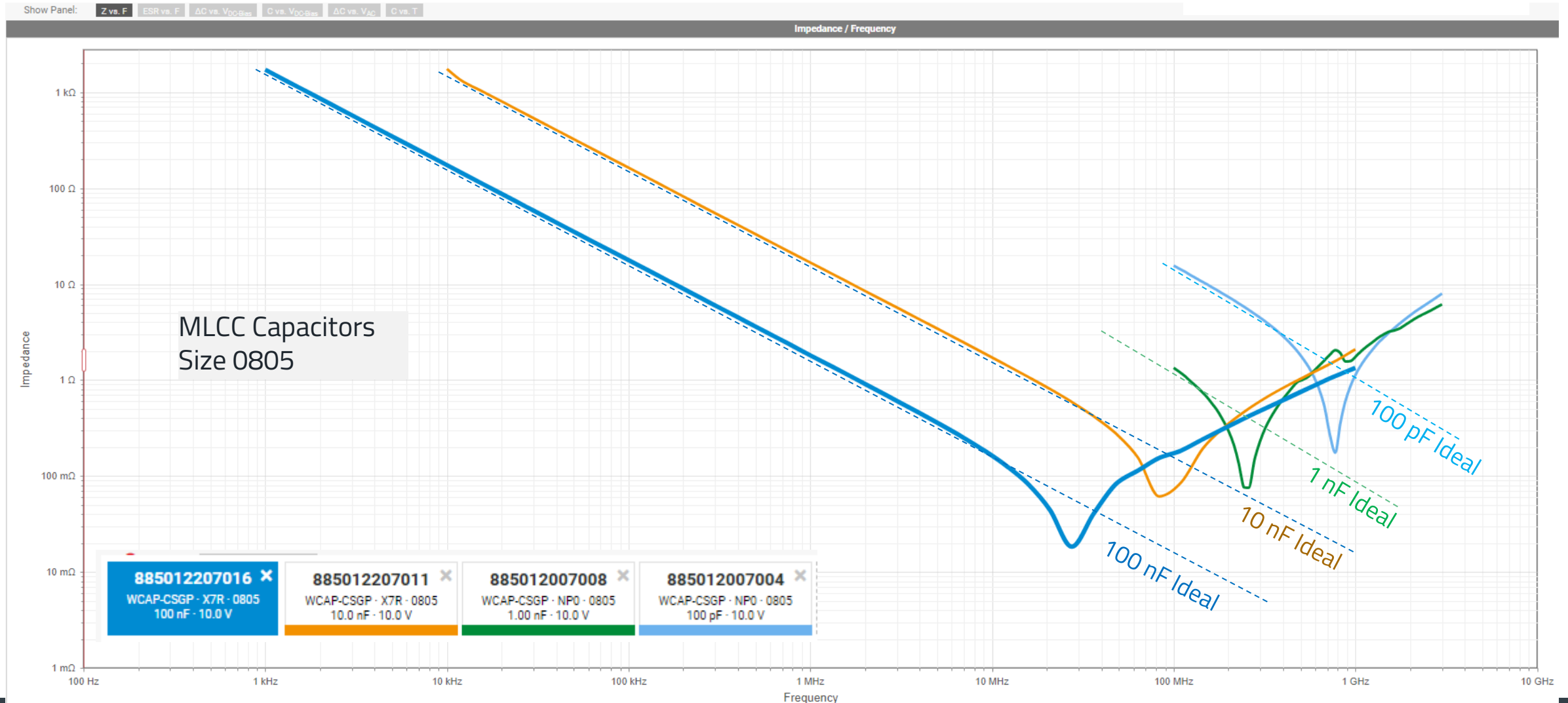


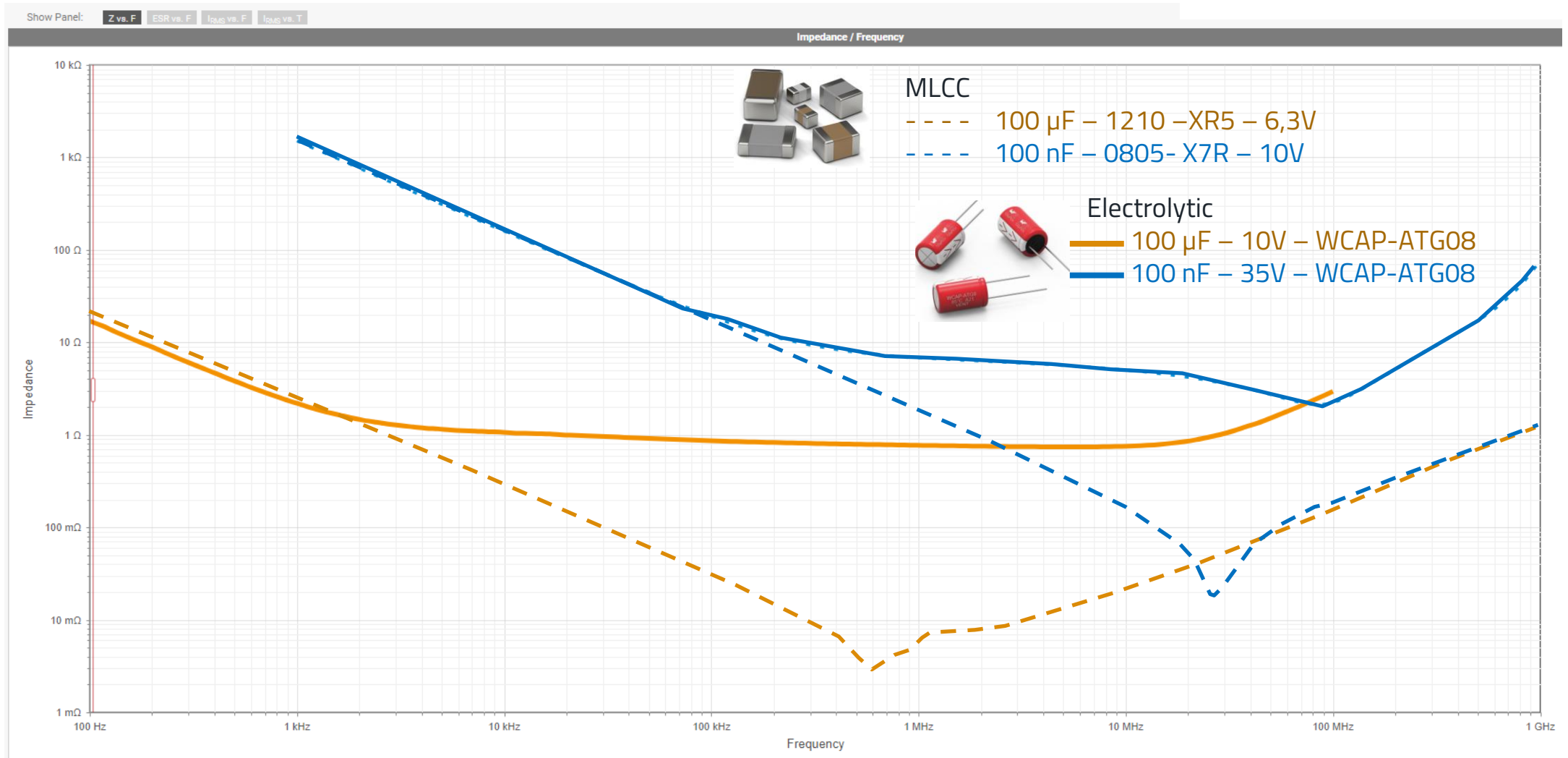
$$f_{res} = \frac{1}{2\pi \cdot \sqrt{L_s \cdot C_s}}$$
$$|Z(f_{res})| = R_s$$

Filter topologies – Capacitance

Real Vs ideal

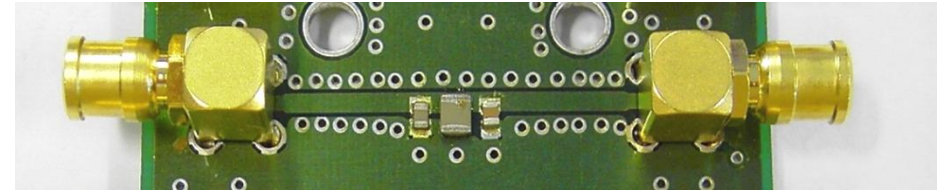
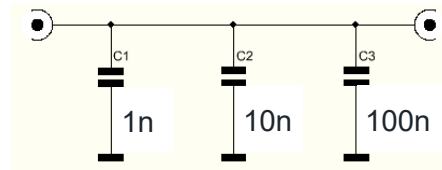
REDEXPERT®



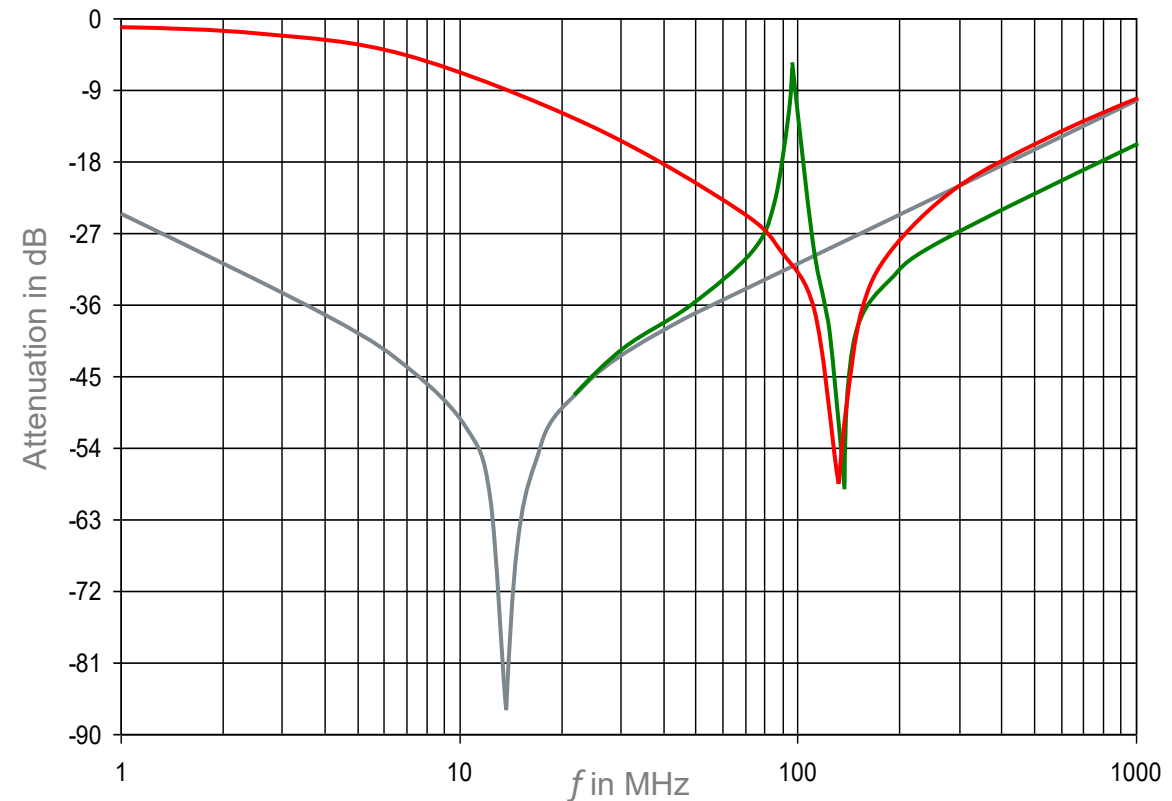
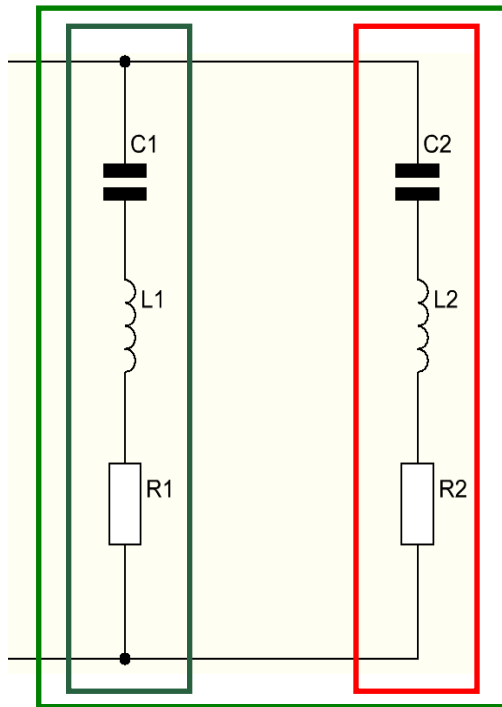


Filter topologies – Parallel-C-filter

- Parallel-C-filter



- Resonances:



Filter topologies – Parallel-C-filter

- Comparison of measurement and simulation

- $C_1 = 1\text{nF}$

- $C_2 = 10\text{nF}$

- $C_3 = 100\text{nF}$

$$f_{\text{res}} = \frac{1}{2\pi \cdot \sqrt{L_s \cdot C}}$$

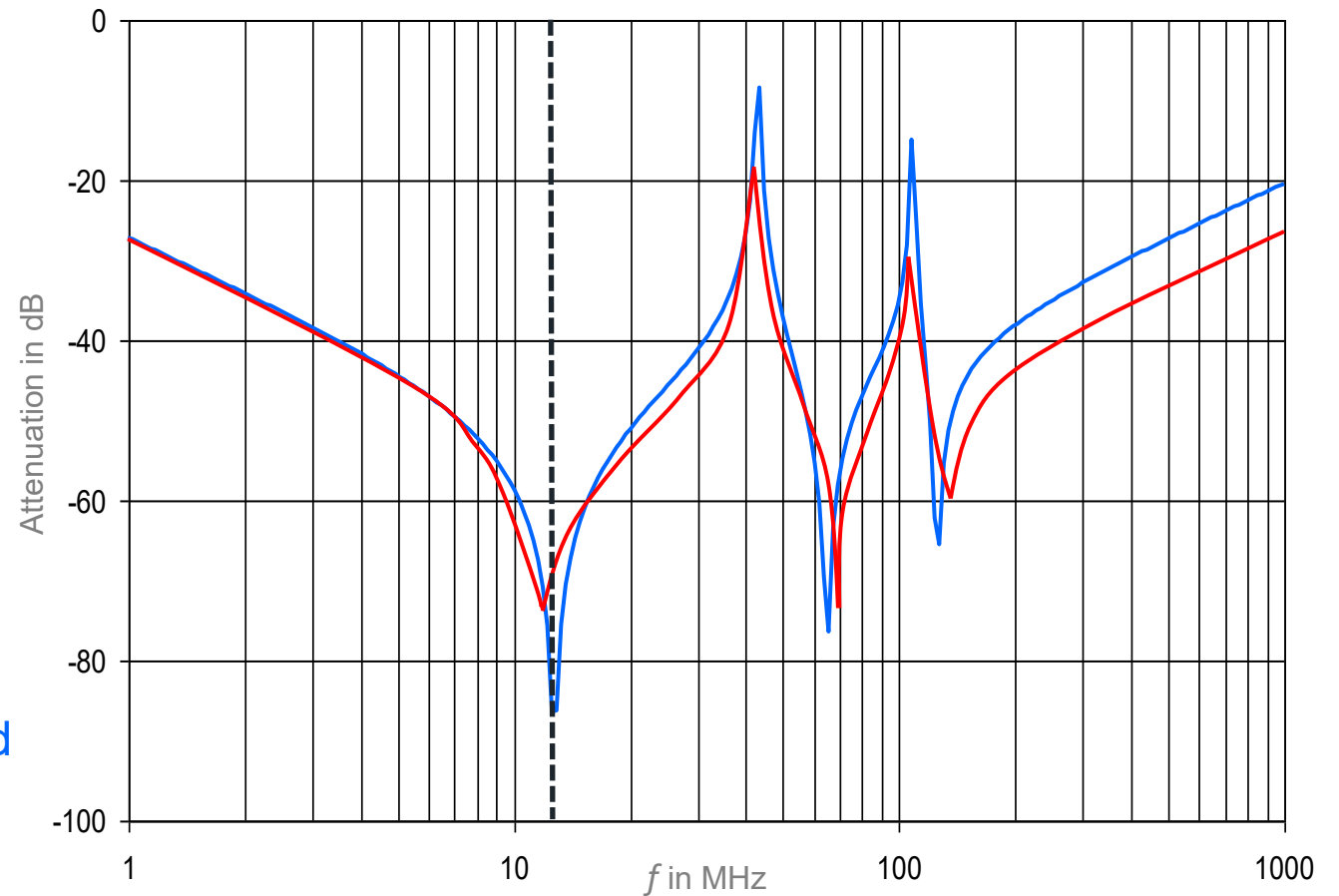
- Example:

$$L_s = 1\text{nH}$$

- $f_{\text{res,C3}} = 15.915\text{MHz}$

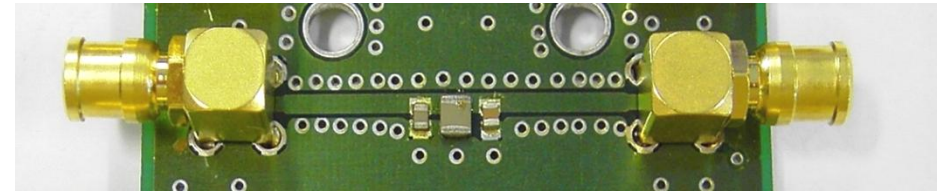
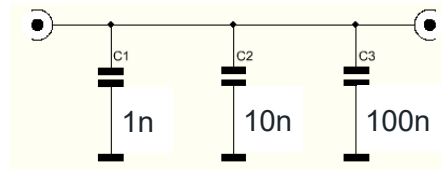
Calculated

Measured

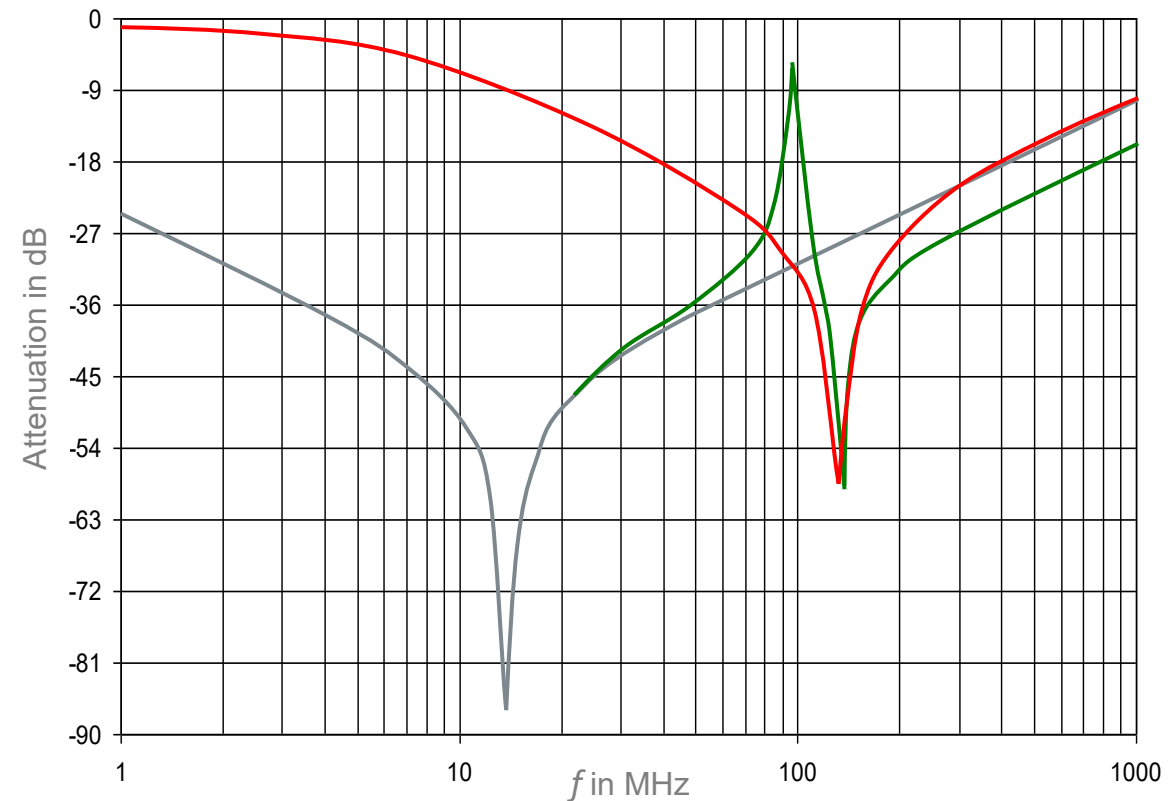
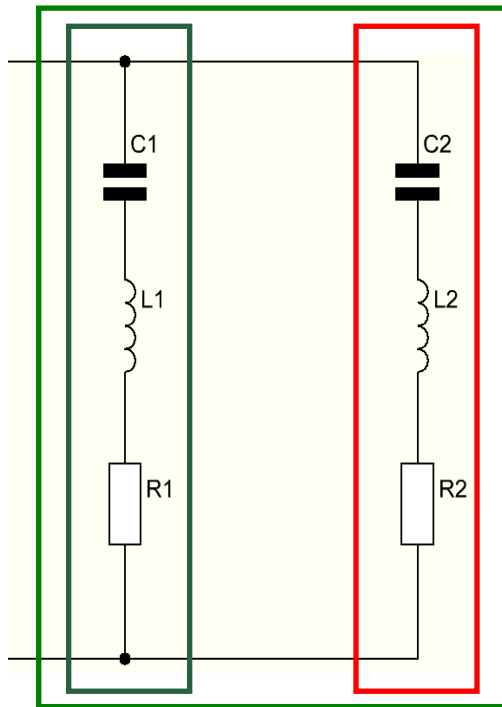


Filter topologies – Parallel-C-filter

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- Resonances:



Filter topologies – Parallel-C-filter

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$$C_1 = 1\text{nF}$$

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$$f_{\text{res}} = \frac{1}{2\pi \cdot \sqrt{L_s \cdot C}}$$

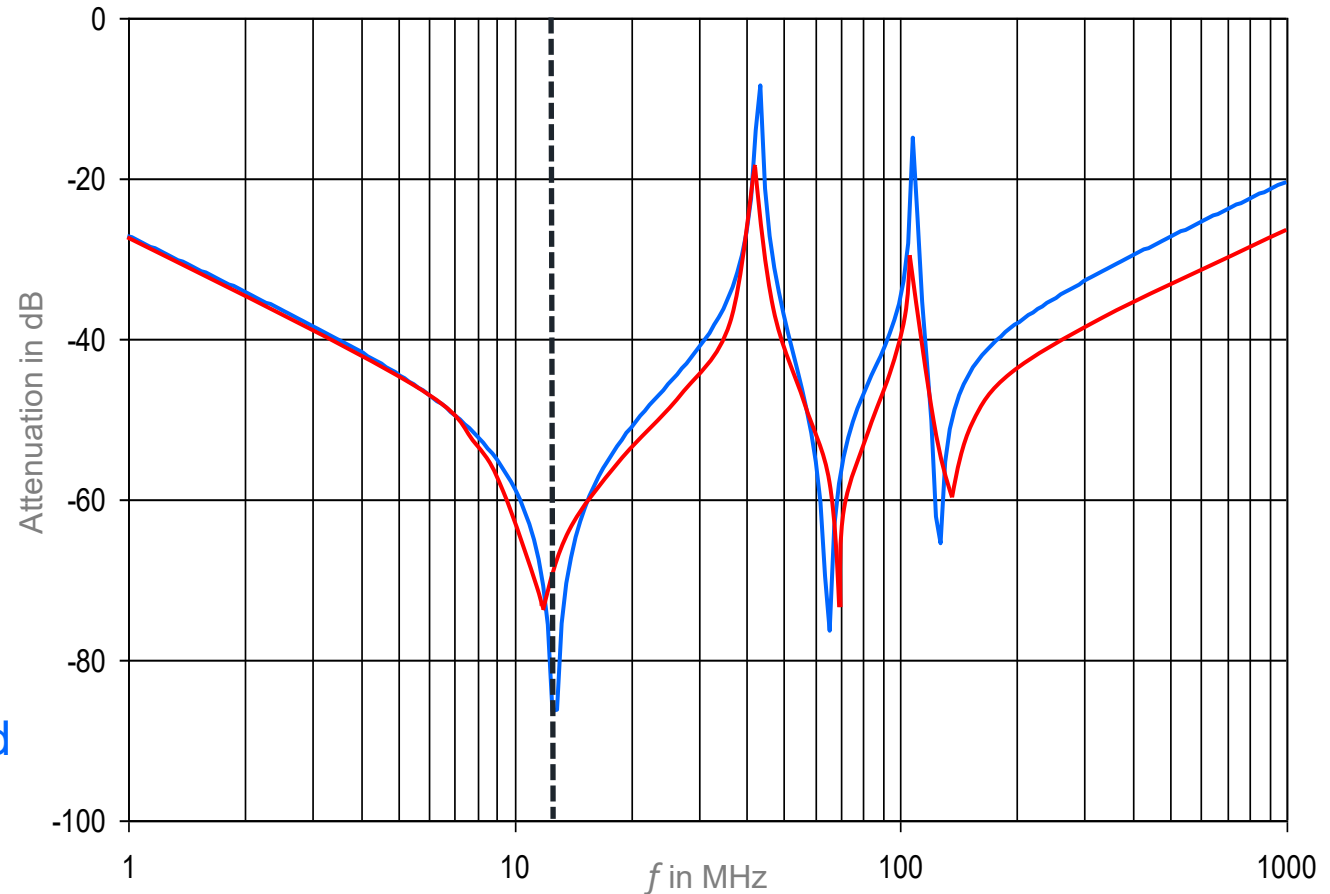
Example:

$$L_s = 1\text{nH}$$

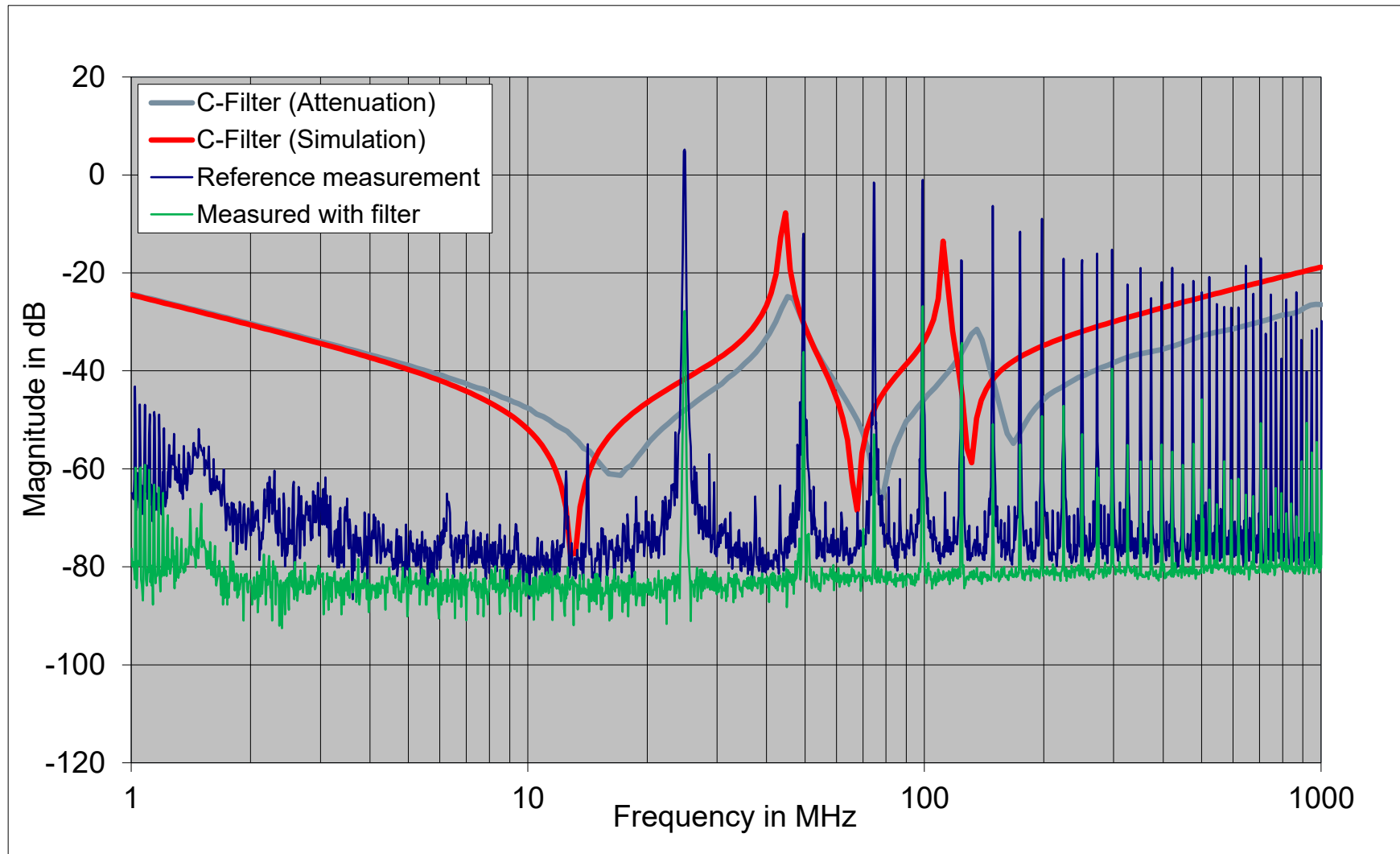
$$f_{\text{res},C3} = 15.915\text{MHz}$$

Calculated

Measured

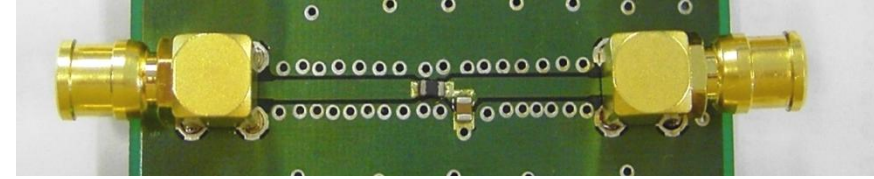
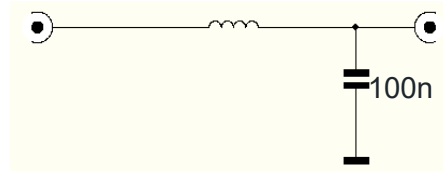


Parallel-C-filter – Example measurement



Filter topologies – Γ -filter

- Γ -filter

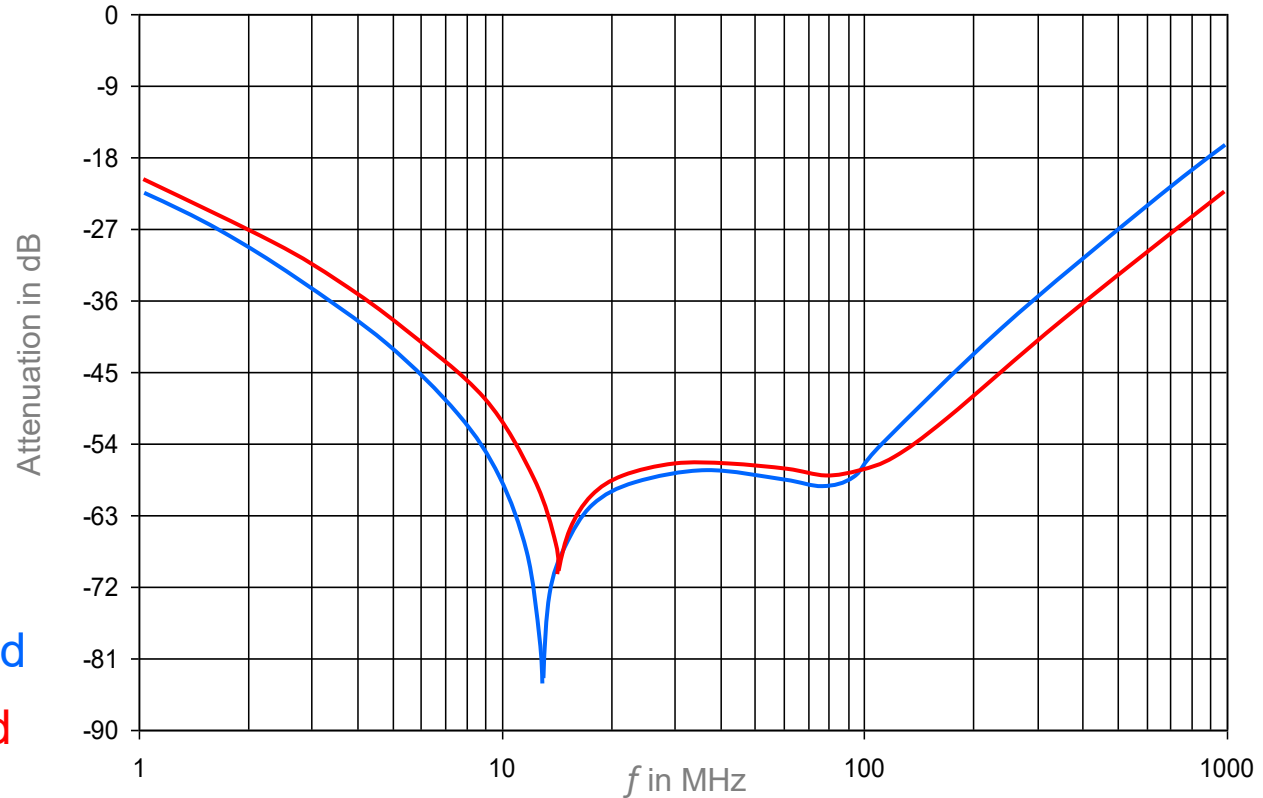


- Comparison of measurement and simulation

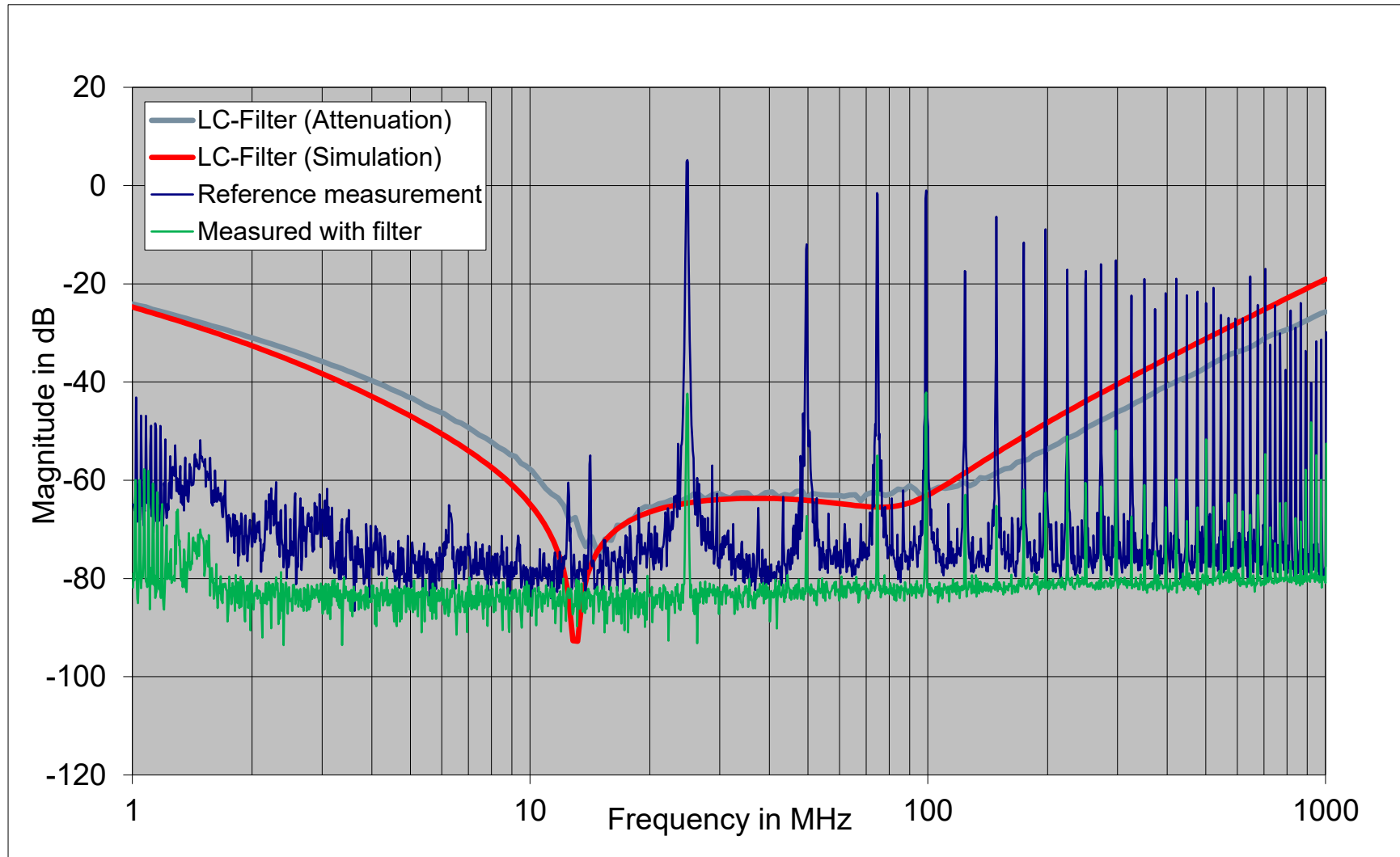
WE-CBF 742 792 093

$C = 100\text{nF}$

Calculated
Measured

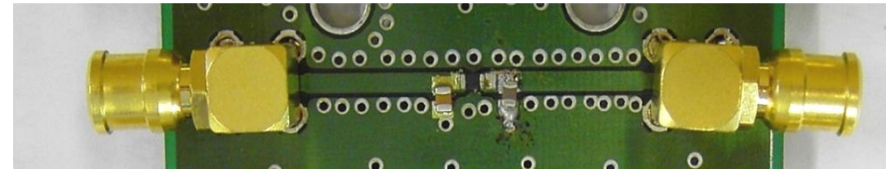
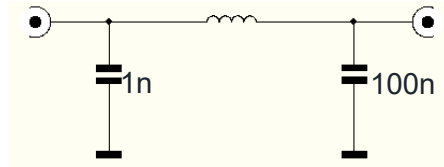


Γ -filter – Example measurement



Filter topologies – Π -filter

- Π -filter



- Comparison of measurement and simulation

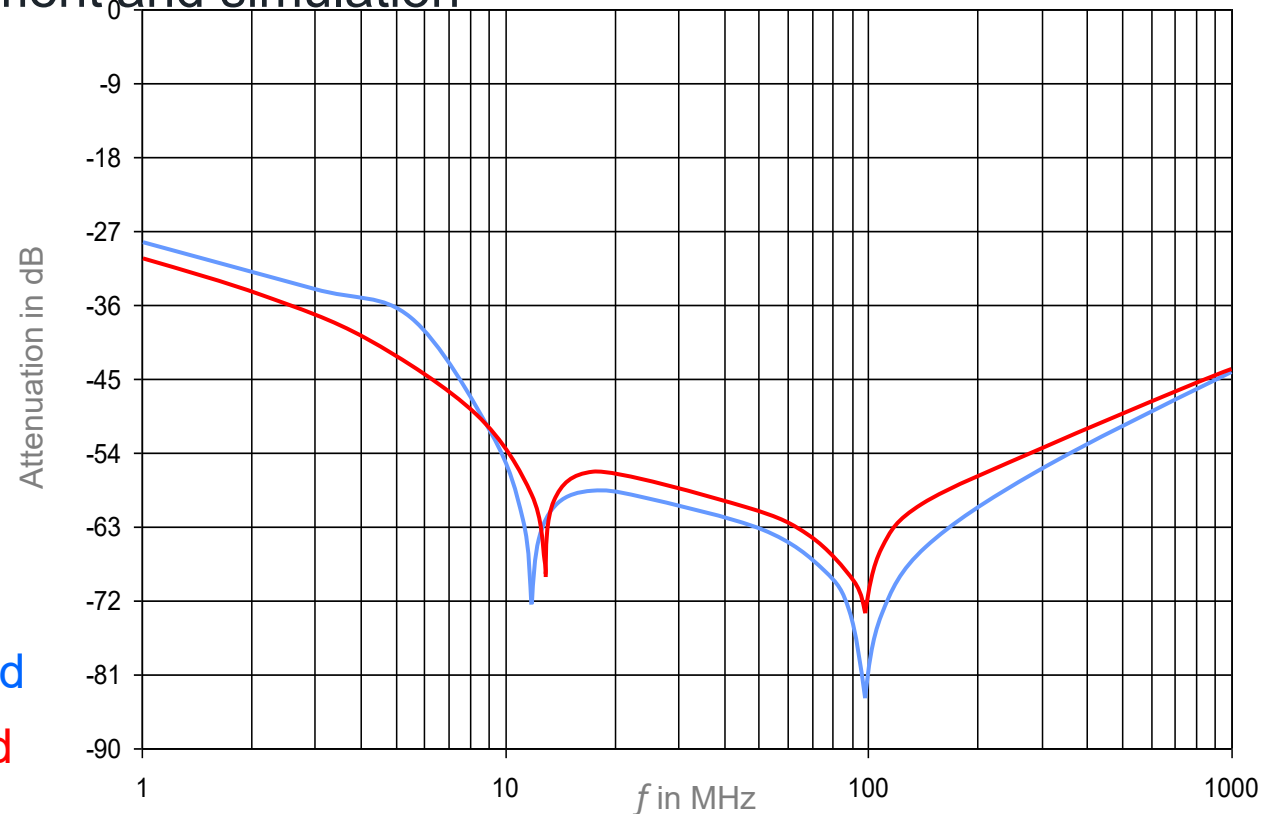
WE-CBF 742 792 093

$$C_1 = 1\text{nF}$$

$$C_2 = 100\text{nF}$$

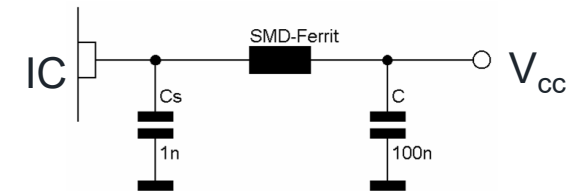
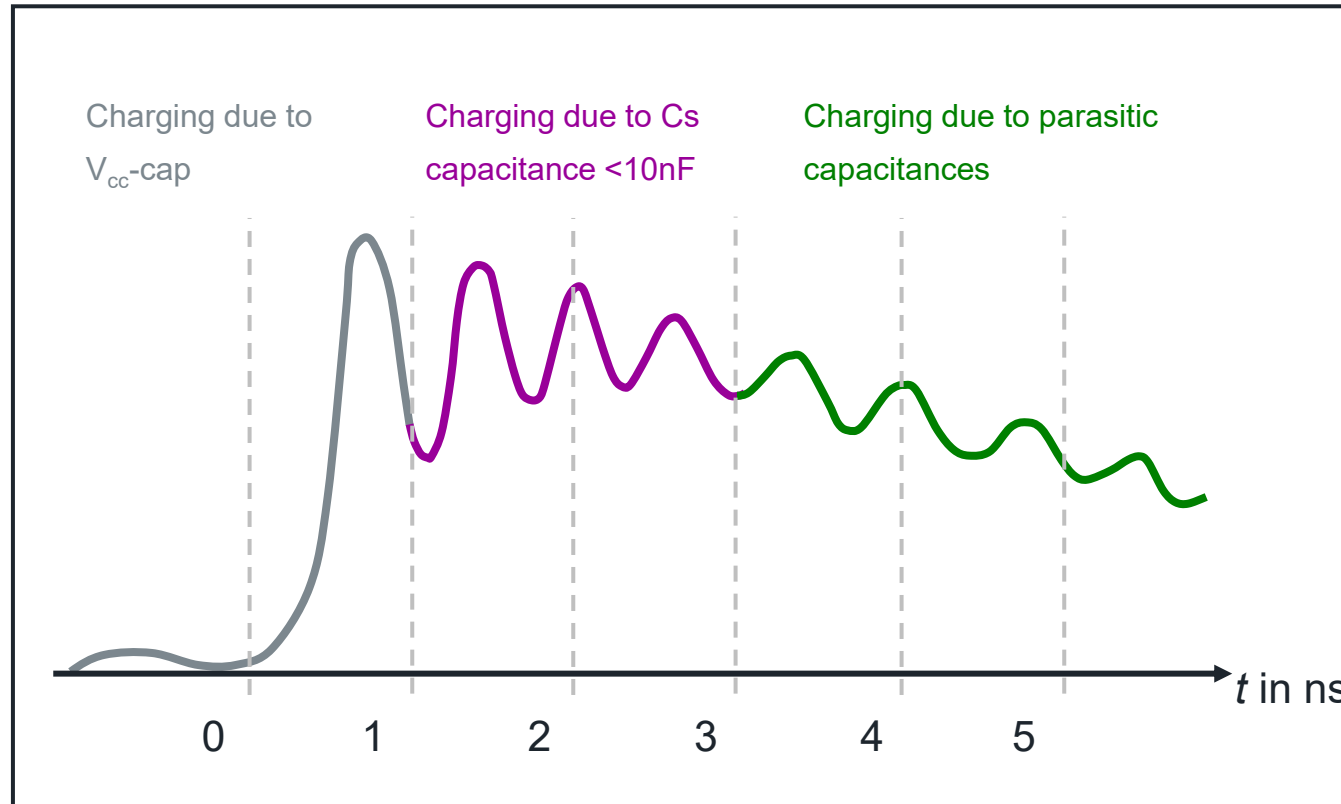
Calculated

Measured



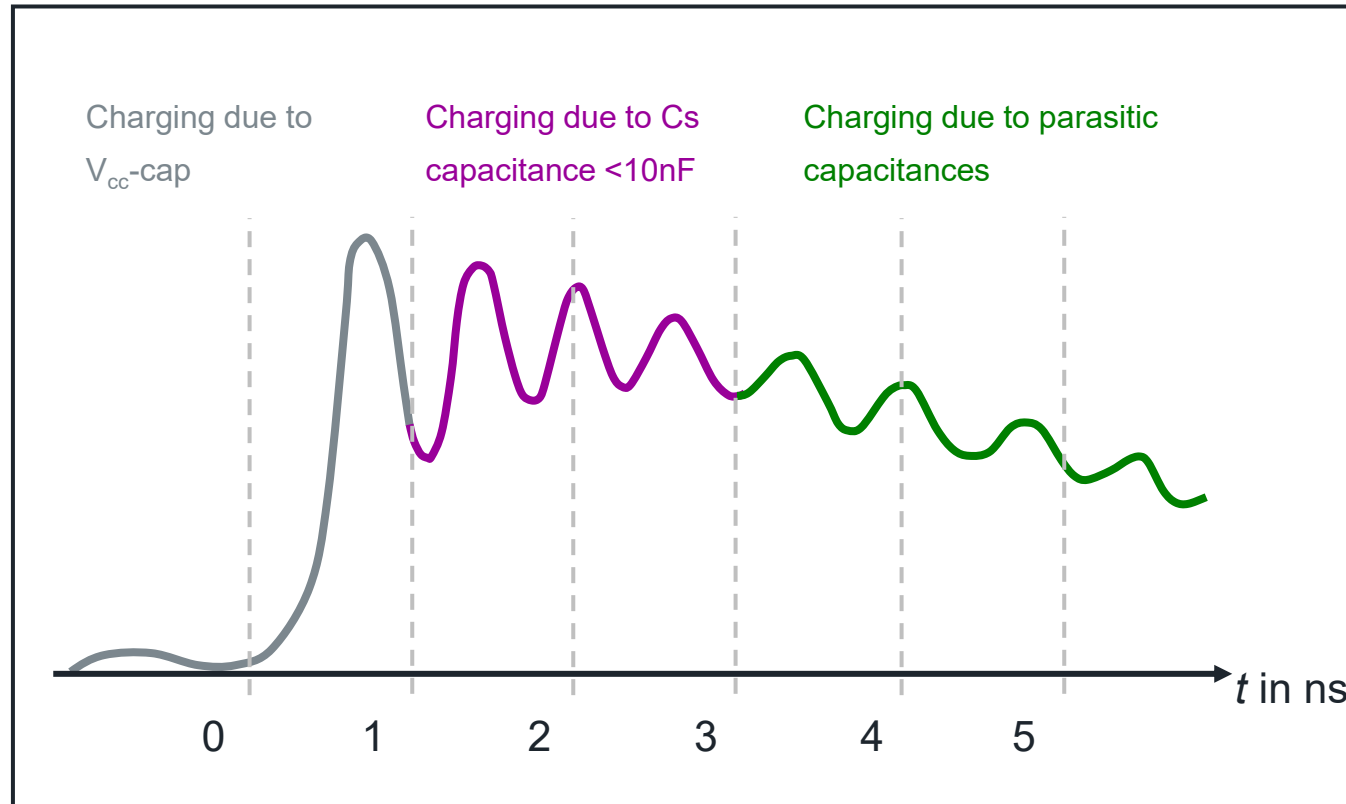
Filter topologies – Π -filter

- Lowering the noise current reflected from the IC input



Filter topologies – Π -filter

- Lowering the noise current reflected from the IC input



Example:

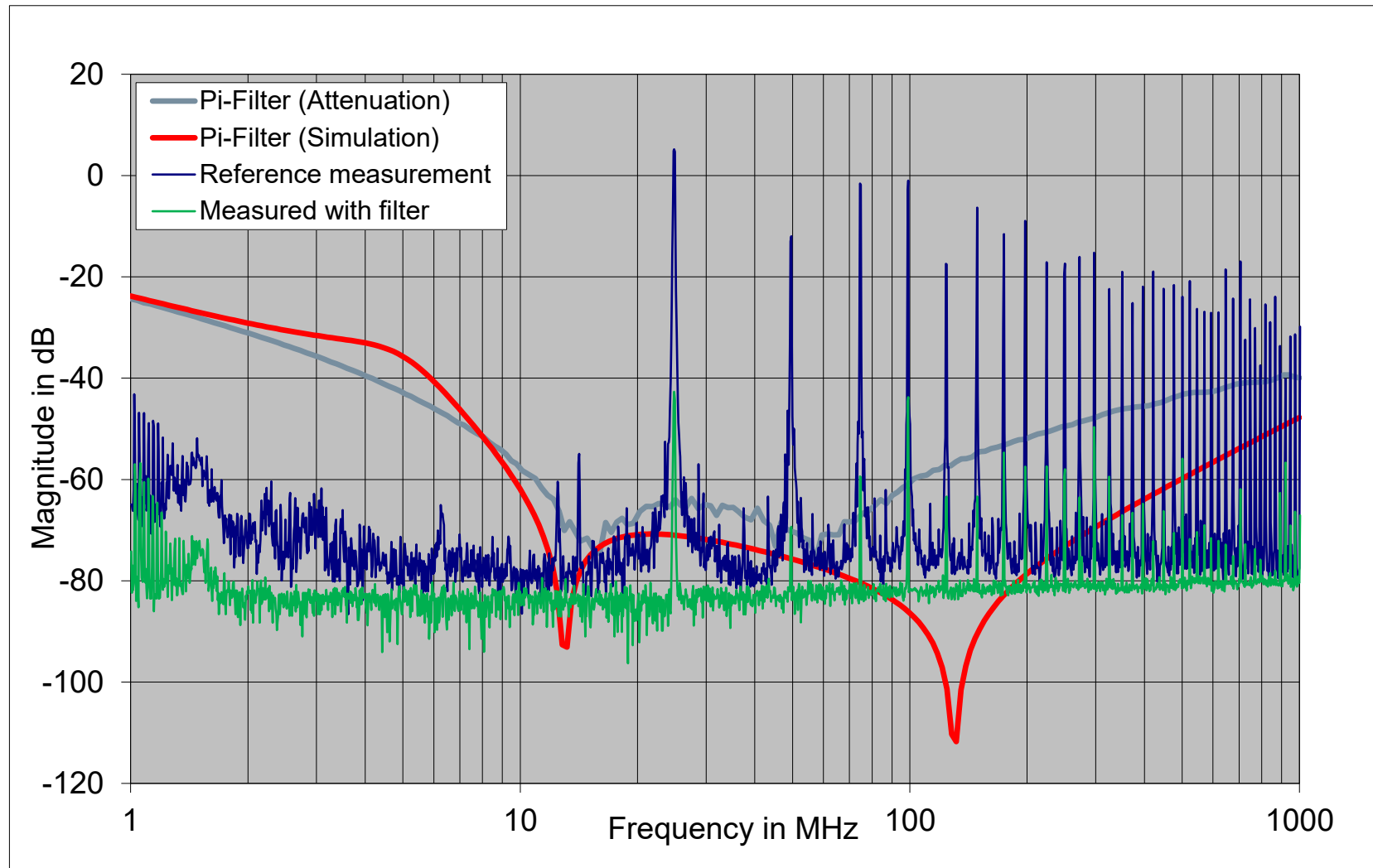
Tolerable voltage drop
of 200mV at a peak
current of
40mA @ $t = 5\text{ns}$:

$$C_s = I_{pk} \cdot \frac{\Delta t}{\Delta U}$$

$$C_s = 40\text{mA} \cdot \frac{5\text{ns}}{200\text{mV}}$$

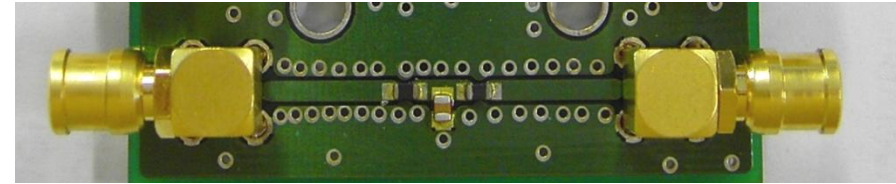
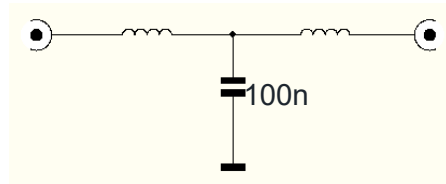
$$\underline{C_s = 1\text{nF}}$$

Π -filter – Example measurement



Filter topologies – T-filter

- T-filter



- Comparison of measurement and simulation

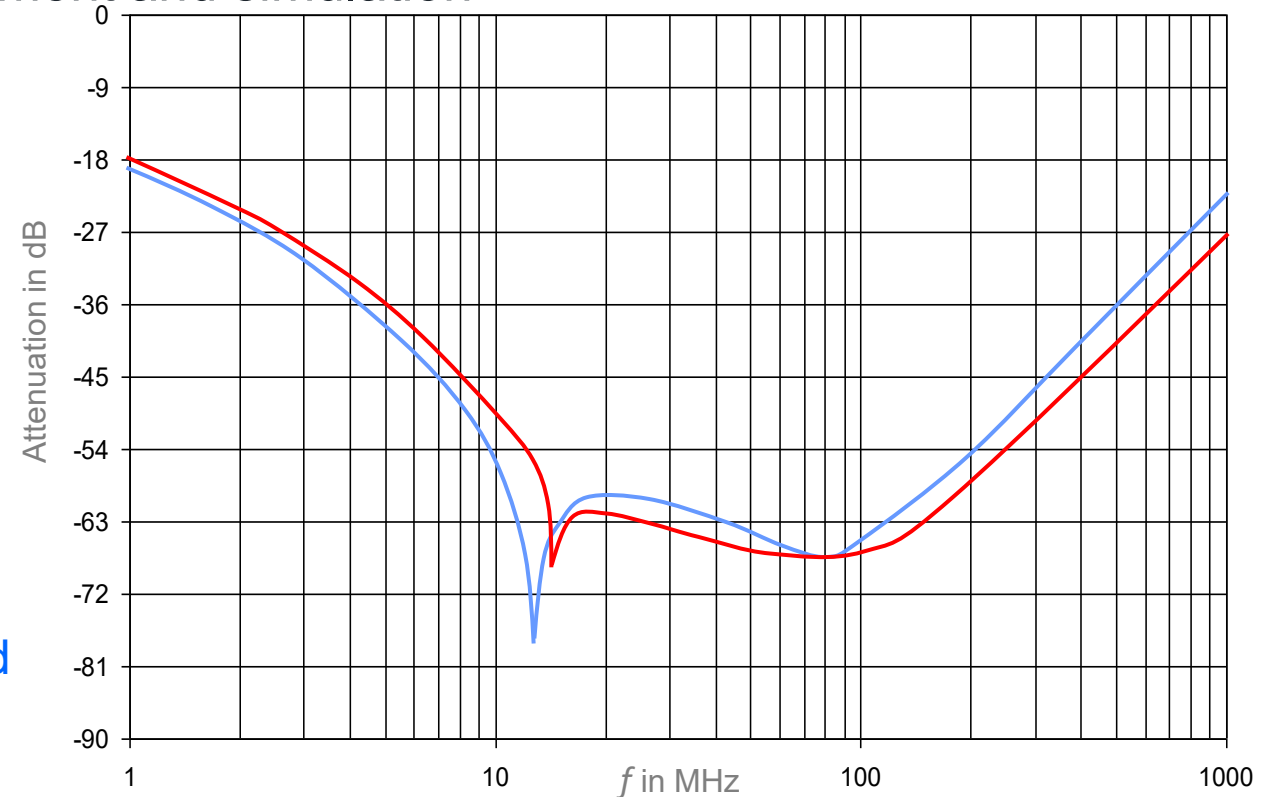
WE-CBF 742 792 040

WE-CBF 742 792 093

$C = 100\text{nF}$

Calculated

Measured



T-filter – Example measurement

