Analog filters

Introduction

Function

Here: selection in the frequency domain or correction of the response

Application

- Anti-aliasing filters and reconstruction filters
- Frequency selection in modulation and demodulation systems
- Equalization filters for correction of the frequency-domain response of a system
- Pulse-shaping filters (e.g. in class E and F amplifiers)
- Power supply filters

Performance measures

Function performance measure

- Pass-band frequency range
- Pass-band attenuation
- Pass-band ripple
- Stop-band frequency range
- Stop-band attenuation
- Stop-band ripple
- Phase characteristic
- Phase ripple
- ...

Other performance measures

- Noise performance
- Power dissipation
- Current / voltage handling capability
- Linearity
- Accuracy and temperature dependency
- ...

Filter Types

- Low-pass - Band-pass - All-pass
- High-pass - Band-stop

Filter Characteristics [Zverev]

Chebyshev filter family

Most effective for frequency-domain selection

- Butterworth filters (MFM)
- Chebyshev filters (ripple in pass-band magnitude characteristic)
- Chebyshev complete, elliptical filters or Cauer filters (ripple in pass band and in stop band)

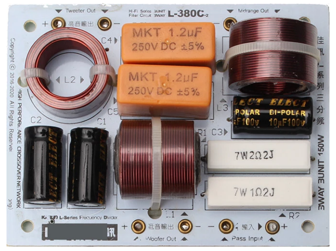
Gaussian filter family

Not very effective for frequency-domain selection but a relatively low pulse distortion

- Gaussian filter (Gaussion impulse response and magnitude characteristic)
- Transitional Gaussian filters (steeper rol-off)
- Bessel filter (maximally flat group delay, low pulse distortion)
- Equiripple linear phase (steeper roll-off comaperd with Bessel)
- Maximally flat delay with Chebyshev stop-band (improved frequency selection capability compared to Bessel)

Technology

- Passive (LRC) filters
- Active filters with discrete operational amplifiers
- Integrated circuit active filters with application-specific amplifiers
- Integrated circuit switched capacitor filters
- Integrated circuit CCD filters
- Crystal and ceramic resonator filters
- Surface Acoustic Wave (SAW) filters
- Transmission line and stripline filters
- Helical resonator filters
- Digital filters (IC, FPGA)



LC filters

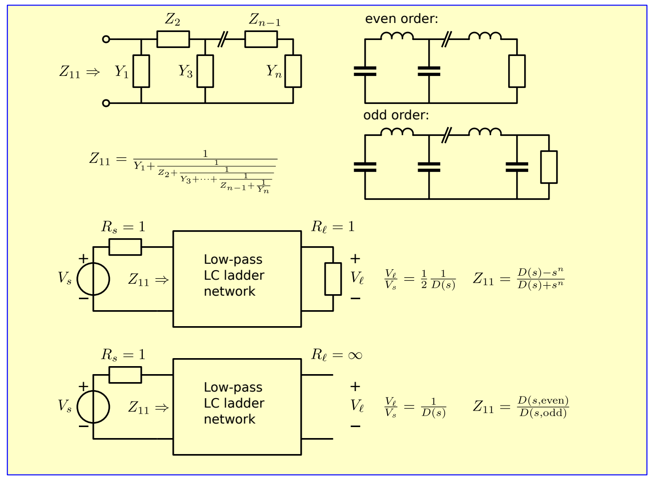
Design form normalized low-pass prototypes

Normalized drive and/or termination resistance (1 Ohm)
Normalized cut-off frequency (usually -3dB, 1 rad/s)

Design by equating coefficients:

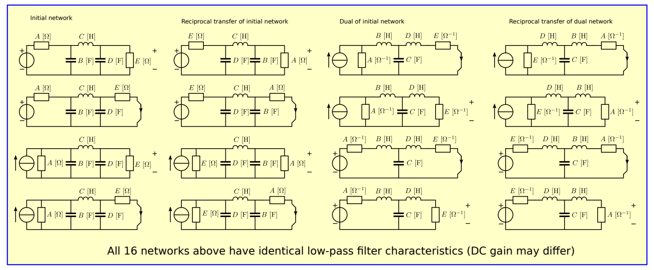
All-pole low-pass prototypes

All-pole low-pass filter prototypes can be synthesized by Expansion of Driving-Point Impedance



Use properties of networks to obtain alterative low-pass configurations:

Thevenin-Norton Duality Reciprocity

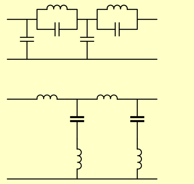


All 16 networks above have identical low-pass filter characteristics (DC gain may differ)

Low-pass elliptic filter prototypes

Elliptic filters (Cauer filters) have the steepest transition from the passband to the stopband compared with other types of filters of the same order.
Transmission zeros are realized with parallel resonant circuits in series with the signal path or series resonant circuits in parallel with the signal path.

Elliptic filters can be designed from their pole-zero pattern and polynomial expansion or from normalized prototypes (tables)



Design of LC low-pass filters from prototypes

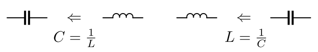
1. Obtain the desired normalized prototype either from the Expansion of Driving Point Impedance or from handbooks on filter design.
2. Denormalize the components:

$$R \Leftarrow \text{drive and/or termination resistance.} \qquad L \Leftarrow \frac{RL}{2\pi f} \quad C \Leftarrow \frac{1}{2\pi f R}$$

Design of LC high-pass filters from prototypes

The transfer function of a normalized high-pass filter can be obtained from that of a normalized low-pass filter by replacing s by 1/s in the transfer function of the low-pass prototype.

low-pass $s \Leftrightarrow \frac{1}{s}$ high-pass



1. Obtain the desired normalized prototype either from the Expansion of Driving Point Impedance or from handbooks on filter design.
2. Replace inductors with capacitors and vice versa
   - normalized capacitor values of the high-pass filter equal the reciprocal value of the corresponding normalized inductors of the low-pass prototype and vice versa
3. Denormalize the components as described above

Design of LC band-pass filters from prototypes

Approach for narrow-band band-pass filters:

The transfer function of a normalized band-pass filter can be obtained from that of a normalized low-pass filter by replacing s by (s+1/s)/B in the transfer function of the low-pass prototype.

low-pass $s \Leftrightarrow \frac{1}{2\pi B}\left(s+\frac{1}{s}\right)$ band-pass

1. Obtain the desired normalized prototype either from the Expansion of Driving Point Impedance or from handbooks on filter design.
2. Denormalize the low-pass filter as indicated below (B is the -3dB bandwidth of the band-pass filter) $B = f_{\max} - f_{\min} \qquad f_c = \sqrt{f_{\min} f_{\max}}$

$$R \Leftarrow \text{drive and/or termination resistance.} \qquad L \Leftarrow \frac{RL}{2\pi B} \quad C \Leftarrow \frac{1}{2\pi B R}$$

3. Replace the inductors with series resonance circuits and the capacitors with parallel resonance circuits as indicated below,

Design of LC band-stop filters from prototypes

Approach for narrow-band band-stop filters:

The transfer function of a normalized band-pass filter can be obtained from that of a normalized high-pass filter by replacing s by s-1/s in the transfer function of the high-pass prototype.

high-pass $s \Leftrightarrow s - \frac{1}{s}$ band-stop

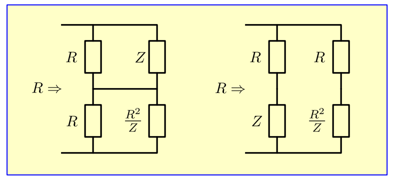
1. Obtain the desired normalized prototype either from the Expansion of Driving Point Impedance or from handbooks on filter design.
2. Conversion of high-pass to band-reject is similar to the conversion of low-pass to band-pass.

Tables for normalized element values can be found in books on filter design

Filter Data Electronic Filter Design Handbook 4-th ed.

Filter type	Data type	passband attenuation	stopband attenuation	group delay	impulse response	step response	pole locations	LC values prototype	RC values active sections
Butterworth		F 2-34	F 2-34	F 2-35	F 2-36	F 2-37	T 11-1	T 11-2	T 11-21
Butterworth, uniform dissipation								T 11-3 - T 11-11	
Butterworth, lossy L network								T 11-12 - T11-20	
Chebyshev 0.01 [dB]		F 2-41	F 2-41	F 2-46	F 2-49	F 2-50	T 11-22	T 11-27	T 11-36
Chebyshev 0.1 [dB]		F 2-42	F 2-42	F 2-47	F 2-51	F 2-52	T 11-23	T 11-28	T 11-37
Chebyshev 0.25 [dB]		F 2-43	F 2-43				T 11-24	T 11-29	T 11-38
Chebyshev 0.5 [dB]		F 2-44	F 2-44	F 2-48	F 2-53	F 2-54	T 11-25	T 11-30	T 11-39
Chebyshev 1 [dB]		F 2-45	F 2-45				T 11-26	T 11-31	T 11-40
Chebyshev 0.1 [dB], uniform dissipation								T 11-32	
Chebyshev 0.25 [dB], uniform dissipation								T 11-33	
Chebyshev 0.5 [dB], uniform dissipation								T 11-34	
Chebyshev 1 [dB], uniform dissipation								T 11-35	
Bessel		F 2-56	F 2-56	F 2-57	F 2-58	F 2-59	T 11-41	T 11-42	T 11-43
Linear phase, 0.05 degrees		F 2-61	F 2-61	F 2-63	F 2-65	F 2-66	T 11-44	T 11-46	T 11-48
Linear phase, 0.5 degrees		F 2-62	F 2-62	F 2-64	F 2-67	F 2-68	T 11-45	T 11-47	T 11-49
Transitional Gaussian to 6 [dB]		F 2-69	F 2-69	F 2-71	F 2-73	F 2-74	T 11-50	T 11-52	T 11-54
Transitional Gaussian to 12 [dB]		F 2-70	F 2-70	F 2-72	F 2-75	F 2-76	T 11-51	T 11-53	T 11-55
Synchronously tuned		F 2-77	F 2-77	F 2-78	F 2-79	F 2-80			
Elliptic (Cauer)				Use Filter Solutions Program					
Maximally flat delay with Chebyshev stopband								T 11-56	

Impedance correction

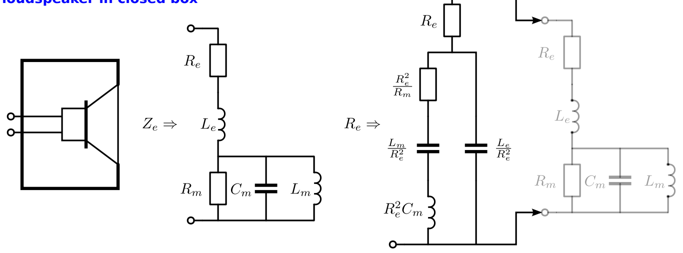


LC filters can be designed for resistive termination

Use Zobel impedance correction for non-resistive loads.

Correction requires dual network.

Example correction impedance loudspeaker in closed box



Loudspeaker in closed box

Electrical impedance model

Impedance correction network (dual network)

Active Filters

Cascade connection of first, second and thrid order structures

- Transfer functions of cascaded sections are sensitive for component tolerances.
- Signal levels can be designed per section

Filter types

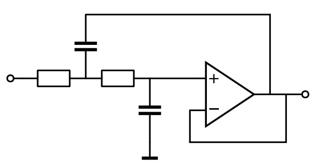
- Second and third order Sallen Key filters
  Design from tables (literature) or by equating coefficients
- Cascaded biquad sections
- Second order single OpAmp configurations
  Design equations found in literature
- Second order dual OpAmp configurations
  Design equations found in literature

Multiple feedback structures of arbitrary order

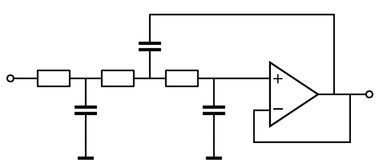
- Less sensitive to component tolerances
- Different signal levels at the various stages may seriously limit the dynamic range of the filter.

Filter types

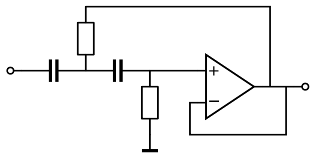
- Multiple-loop Sallen-Key filters
  Design from tables or by equating coefficients
- GIC filters
  Design from LC prototypes, convert R to C, L to R and C to D element.
- Gyrator filters
  Design from LC prototypes, replace inductors with gyrator and capacitor
- Direct implementations of the transfer function
  Structures of which the element values show a simple ralation to the coefficients of the transfer function



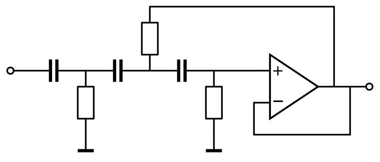
Second order low-pass Sallen Key filters



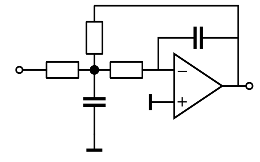
Third order low-pass Sallen Key filters



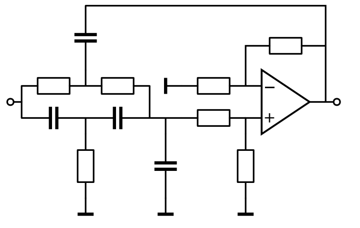
Second order high-pass Sallen Key filters



Third order high-pass Sallen Key filters

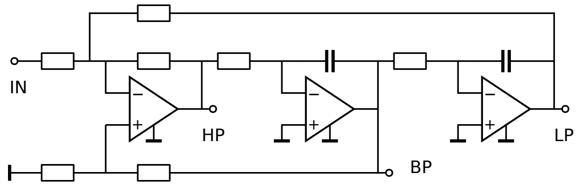


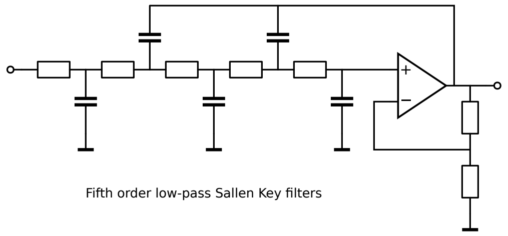
Second order low-pass filter with gain other than unity



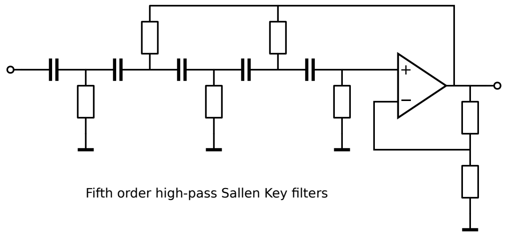
Second order elliptic filter

Two-integrator universal filter

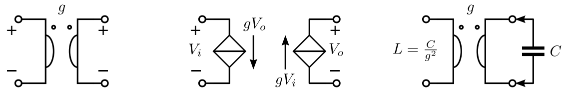




Fifth order low-pass Sallen Key filters

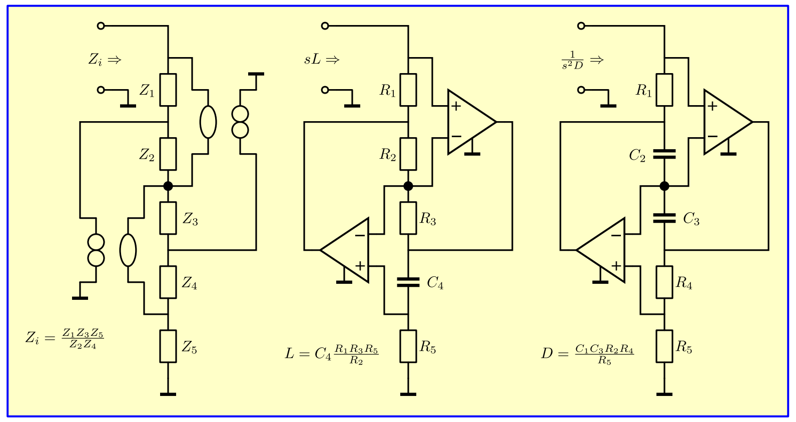


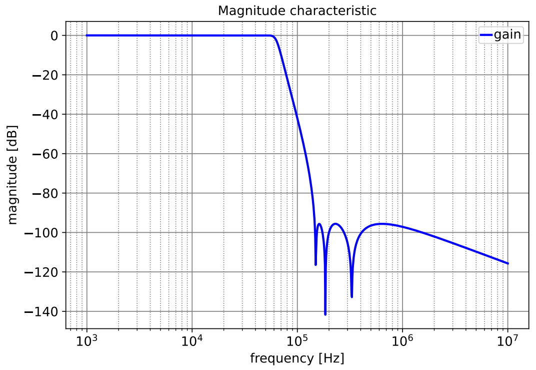
Fifth order high-pass Sallen Key filters



The gyrator can be used to replace inductors in LC filters with capacitors

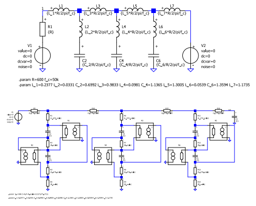
Generalized Impedance converter



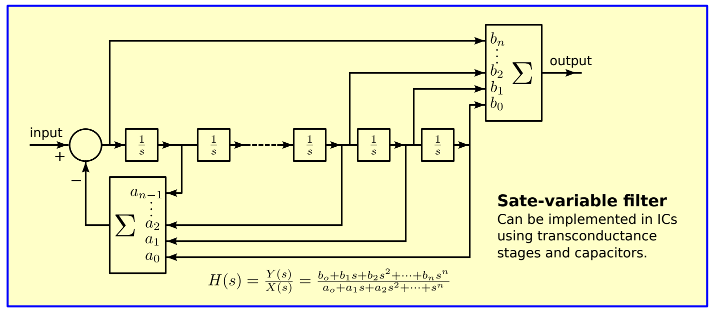


Elliptic filter with D elements.
Designed from reciprocal transfer of LC prototype [Zverev]
Cauer n=7, rho=1%, K=inf.
p. 259 no. 20.

SLiCAP example
50kHx -96dB
anti-aliasing filter.

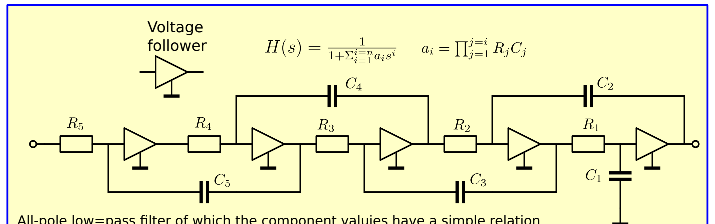


Synthesis from the transfer function



Sate-variable filter
Can be implemented in ICs using transconductance stages and capacitors.

$$H(s) = \frac{Y(s)}{X(s)} = \frac{b_o+b_1 s+b_2 s^2+\cdots+b_n s^n}{a_o+a_1 s+a_2 s^2+\cdots+s^n}$$



$$H(s) = \frac{1}{1+\Sigma_{i=1}^{i=n} a_i s^i} \qquad a_i = \prod_{j=1}^{j=i} R_j C_j$$

All-pole low=pass filter of which the component valuies have a simple relation with the coefficients of the transfer function.

Zeros can be added by creating paths from the output of the buffers (voltage followers) to the output.

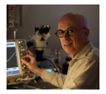
Other Filters

Switched Capacitor Filters

Surface Acoustic Wave filters

Crystal filters

Delay line filters



anton@montagne.nl
https://www.analog-electronics.eu