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Active filters

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Active filters

Electronic filters are circuits with signal processing functions,

they remove unwanted frequency to enhance wanted ones.

Electronic filters can be:

- passive or active (LC (SAW -Surface Acoustic Wave) OR with active elements e.g. Op-Amp)
- analogue or digital (Digital Signal Processing) or switched capacitor

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Active filters realization

Active filters can be realized as:

- continuous time filters – analogue filters
- switched capacitor filters

Active filters

Frequency specification:

- high-pass,
- low-pass,
- band-pass,
- band-stop (band-rejection; notch),
- all-pass (usually specific phase transmission)

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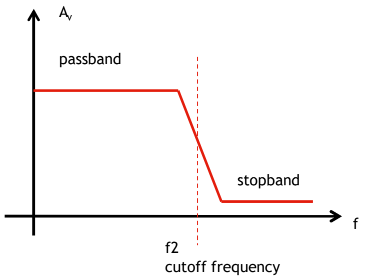
Low-Pass filter



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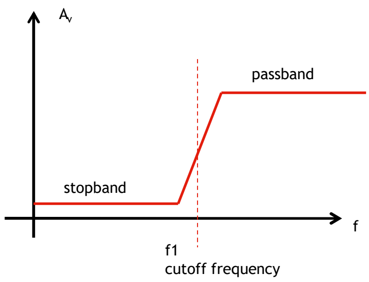
High-Pass filter



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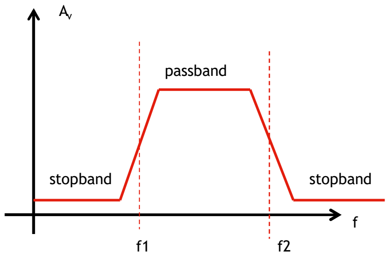
Band-Pass filter



cutoff frequencies
f2-f1 = bandwith

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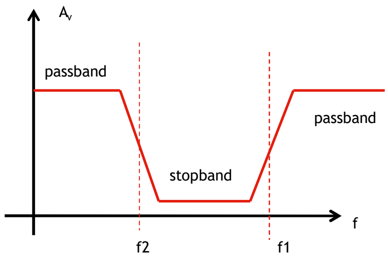
Band-Stop filter



cutoff frequencies
f1-f2 = stop-bandwith

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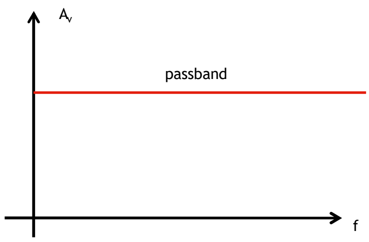
All-Pass filter (phase depends on frequency)



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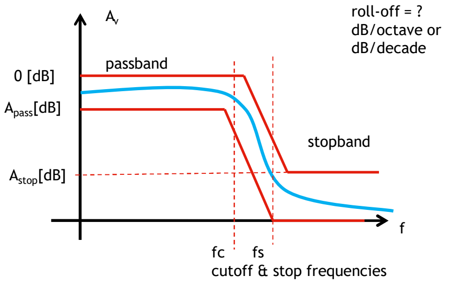
Passband and Stopband attenuation



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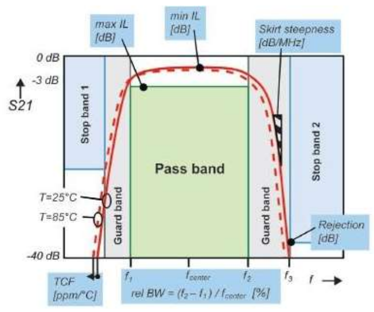

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Active filters - shape of transfer function

- Chebyshev (I i II kind (inverse))
- Eliptic (Cauer)
- Bessel (Thompson)
- Butterworth - Thompson

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Order of a filter

$$H(s)=\frac{U_{out}(s)}{U_{in}(s)}=\frac{a_m s^m + a_{m-1}s^{m-1}+\ldots+a_0}{b_n s^n + b_{n-1}s^{n-1}+\ldots+b_0}=\frac{a_m}{b_n}\frac{\prod_i (s-z_i)}{\prod_j (s-p_j)}$$

n = number of capacitors and inductances (LC - filter)
n = number of capacitors (RC - filters)

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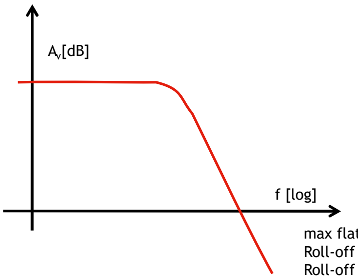
Butterworth approximation pass-band max flatness



max flatness of pass-band
Roll-off = 20*n dB/decade
Roll-off = 6*n dB/octave
-for low & high -pass
-½ for stop & pass -band
Phase/impule response = acceptable

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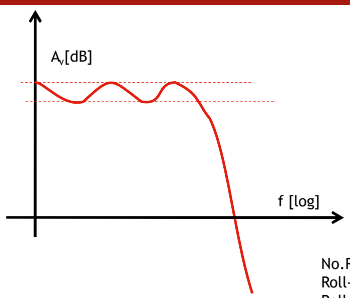
Chebyshev (I) approximation pass-band rippels



No.Rippels = n/2
Roll-off > 20n dB/decade
Roll-off > 6n dB/octave
Phase/impulse response = bad

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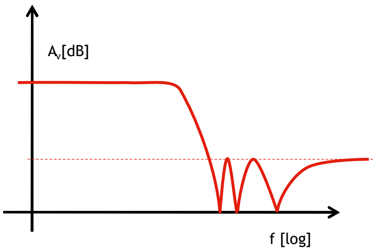
Invers Chebyshev (II) approximation stpop-band rippels



No.Rippels = n/2
Roll-off > 20n dB/decade
Roll-off > 6n dB/octave
Phase/impulse response = bad

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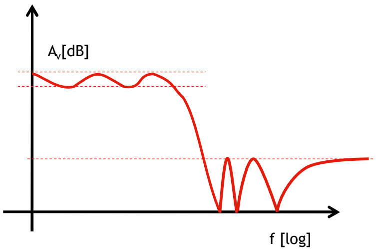
Eliptic (Cauer) approximation stpop & pass -band rippels



Roll-off > 20n dB/decade
Roll-off > 6n dB/octave
Phase/impulse response = bad

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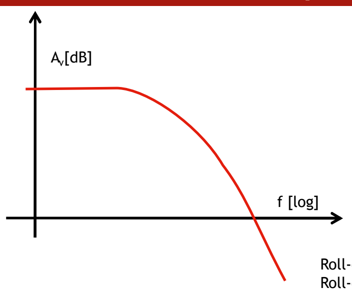
Bessel approximation ---linera phase



Roll-off < 20n dB/decade
Roll-off < 6n dB/octave
Phase/impulse response = v.good
Time delay = flat v. frequency

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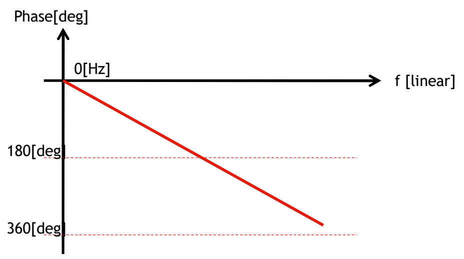
Bessel approximation ---linera phase



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6th order filter attenuation

octave

Type	f2 [dB]	2*f2 [dB]
Bessel	3	14
Butteworth	3	36
Chebyshev	3	63
Invers Chebyshev (II)	3	63
elliptic	3	93

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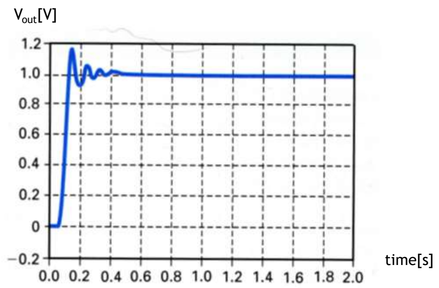
Step response Buttewoth, Chebyshev (I)



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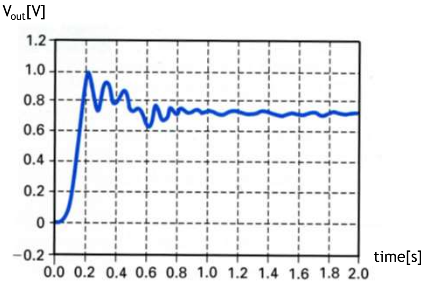
Step response invers Chebyshev (II), elliptic



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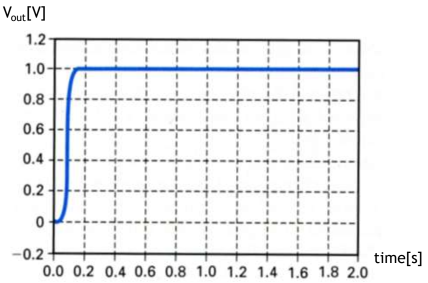
Step response Bessel



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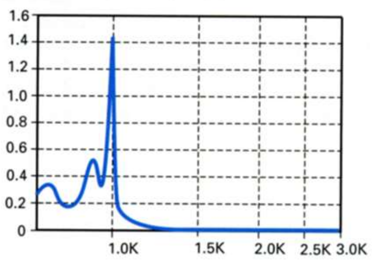
Time delay elliptic



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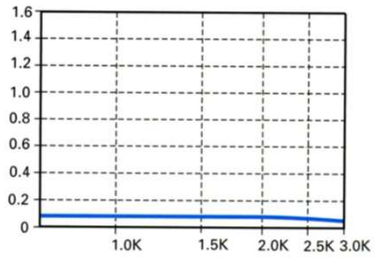
Time delay Bessel



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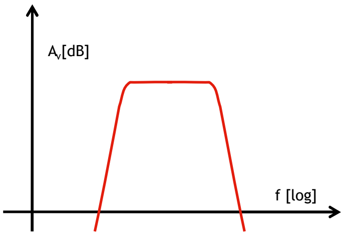
band- pass Butteworth



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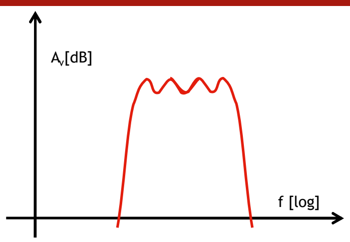
band- pass Chebyshev



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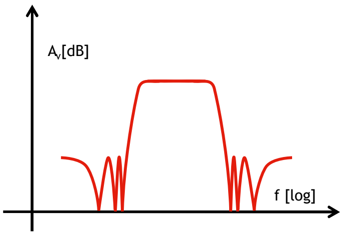
band- pass inver Chebyshev (II) (invers Chebyshev filter)



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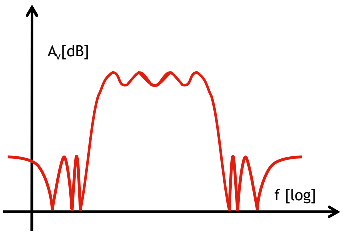
band- pass elliptic



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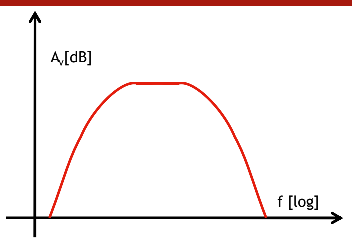
band- pass Bessel



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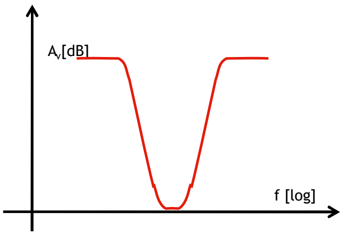
band- stop Butteworth



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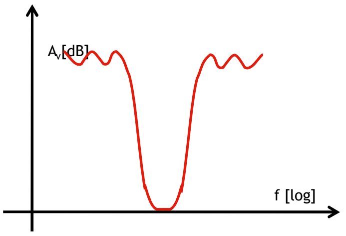
band- pass Chebyshev



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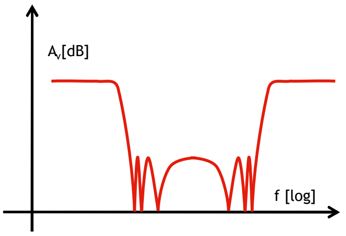
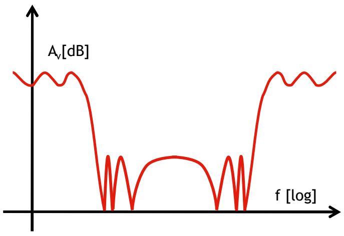
band- stop inver Chebyshev (II)



band- stop elliptic



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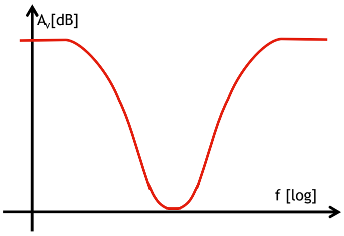
band- stop Bessel



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Filter approximation general features

Type	passband	stopband	Roll-off	Step response
Bessel	flat	monotonic	poor	best
Butterworth	flat	monotonic	good	good
Chebyshev	rippled	monotonic	v. good	poor
In.Chebyshev (II)	flat	rippled	best	poor
Elliptic (Cauer)	rippled	rippled	best	v.poor

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Active filter implementation

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Active filters - introduction

Transmittance:

$$H(s)=\frac{U_{out}(s)}{U_{in}(s)}=\frac{a_m s^m + a_{m-1}s^{m-1}+\dots+a_0}{b_n s^n + b_{n-1}s^{n-1}+\dots+b_0}=\frac{a_m}{b_n}\frac{\prod_i (s-z_i)}{\prod_j (s-p_j)}$$

a_i, b_j - real numbers

z_i, p_j - zeros and poles of transmittance

$$H(s)=|H(\omega)|\exp[j\varphi(\omega)]$$

|H(s)| - amplitude transmittance

φ(s) - phase transmittance

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Active filters - introduction c.d.

Transmittance factorization:

$$H(s)=\frac{N(s)}{D(s)}=\prod_k H_k(s)=\prod_k \frac{N_k(s)}{M_k(s)}$$

Degree of $N_k(s)$ ≤ degree of $M_k(s)$ ≤ 2

For $M_k(s)$ = 2 biquadratic section:

$$H_k(s)=\frac{a_2 s^2 + a_1 s + a_0}{s^2 + b_1 s + b_0}=\frac{N_k(s)}{s^2 + b_1 s + b_0}$$

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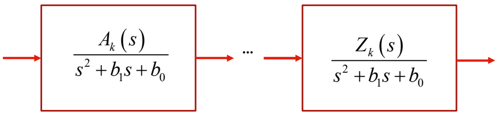
Cascade of biquadratic filters



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Active filters - intro

Biquadratic section can be expressed as:

$$H_k(s)=\frac{N_k(s)}{s^2+\frac{\omega_0}{Q}s+\omega_0^2}=\frac{N_k(s)}{(s-p_1)(s-p_2)}$$

where: p_1,p_2 - poles of the transmittance

For quality Q>1/2 poles are complex numbers

$$p_{1,2}=-\frac{\omega_0}{2Q}+j\frac{\omega_0}{2Q}\sqrt{4Q^2-1}=\sigma_p\pm j\omega_p$$

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Active filters - intro

Real and imaginary parts are:

$$\sigma_p=-\frac{\omega_0}{2Q} \qquad \omega_p=\omega_0\sqrt{1-\frac{1}{4Q^2}}$$

Specific frequency and quality are

$$\omega_0=\sqrt{\sigma_p^2+\omega_p^2} \qquad Q=\frac{\sqrt{\sigma_p^2+\omega_p^2}}{2|\sigma_p|}=\frac{\omega_0}{2|\sigma_p|}$$

Dumping factor:

$$\alpha=\frac{1}{2Q}$$

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Active filters - intro

When denominator is writen in he form:

$$s^2 + b_1 s + b_0 = s^2 + \frac{\omega_0}{Q} s + \omega_0$$

Parameters Q (quality) and ω_0 (characteristic frequency)

$$Q = \frac{\sqrt{b_0}}{b_1}$$

$$\omega_0 = \sqrt{b_0}$$

b_0, b_1 - real coefficients

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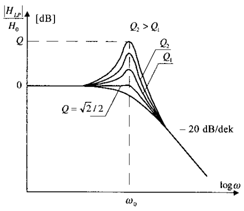
Interpretation of Q and ω_0



$$H_{LP}(s) = H_0 \frac{\omega_0^2}{s^2 + \frac{\omega_0}{Q} s + \omega_0^2}$$

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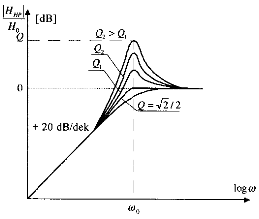
Interpretation of Q and ω_0



$$H_{HP}(s) = H_0 \frac{s^2}{s^2 + \frac{\omega_0}{Q} s + \omega_0^2}$$

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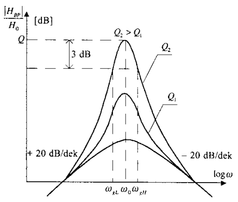
Interpretation of Q and ω_0



$$H_{BP}(s) = H_0 \frac{\omega_0 s}{s^2 + \frac{\omega_0}{Q}s + \omega_0^2}$$

$$Q = \frac{\omega_0}{\Delta\omega} = \frac{\omega_0}{\omega_{gH} - \omega_{gL}}$$

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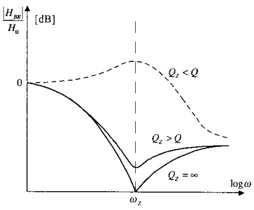
Interpretation of Q and ω_0



$$H_{BR}(s) = H_0 \frac{s^2 + \frac{\omega_z}{Q_z}s + \omega_z^2}{s^2 + \frac{\omega_0}{Q}s + \omega_0^2}$$

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Filtry aktywne - wprowadzenie

$Q_z = \infty$ - eliptic filter with transfer function:

$$H_{BR}(s) = H_0 \frac{\omega_z^2}{\omega_0^2} \frac{\frac{s^2}{\omega_z^2} + 1}{\frac{s^2}{\omega_0^2} + \frac{s}{Q\omega_0} + 1}$$

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Active filters - factorization of LP - prototype filter

Transmittance factorization:

$$H(s)=\frac{A}{D(s)}=\prod_k H_k(s)=\prod_k \frac{A_k}{M_k(s)}$$

order of $N_k(s)$ ≤ order of $M_k(s)$ ≤ 2

For order $M_k(s)$ = 2 biquadratic section, or =1 first order section:

$$H_i(s)=\frac{A_i}{a_i s^2+b_i s+1} \qquad \text{OR} \qquad H_j(s)=\frac{A_j}{a_j s\ +1}$$

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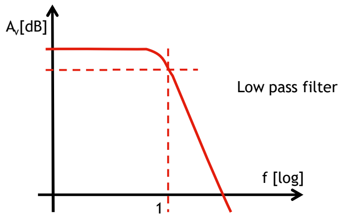
Filters transformation

$$S=\frac{s}{\omega_0} \qquad H_i(S)=\frac{Ku}{A_i S^2+B_i S+1}$$



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Bessel, Butterworth, Chebyshev(I) Chebyshev(II), Elliptic (Cauer)

N	i	a_i	b_i	f_{ci}/f_c	Q_i
1	1	1.0000	0.0000	1.000	–
2	1	1.3614	1.3827	1.000	0.86
3	1	1.8636	0.0000	0.537	–
	2	0.6402	1.1931	1.335	1.71
4	1	2.6282	3.4341	0.538	0.71
	2	0.3648	1.1509	1.419	2.94
5	1	2.9235	0.0000	0.342	–
	2	1.3025	2.3534	0.881	1.18
	3	0.2290	1.0833	1.480	4.54
6	1	3.8645	6.9797	0.366	0.68
	2	0.7528	1.8573	1.078	1.81
	3	0.1589	1.0711	1.495	6.51
7	1	4.0211	0.0000	0.249	–
	2	1.8729	4.1795	0.645	1.09
	3	0.4861	1.5676	1.208	2.58
	4	0.1156	1.0443	1.517	8.84
8	1	5.1117	11.9607	0.276	0.68
	2	1.0639	2.9365	0.844	1.61
	3	0.3439	1.4206	1.284	3.47
	4	0.0885	1.0407	1.521	11.53
9	1	5.1318	0.0000	0.195	–
	2	2.4283	6.6307	0.506	1.06
	3	0.6839	2.2908	0.989	2.21
	4	0.2559	1.3133	1.344	4.48
	5	0.0695	1.0272	1.532	14.58
10	1	6.3648	18.3695	0.222	0.67
	2	1.3582	4.3453	0.689	1.53
	3	0.4822	1.9440	1.091	2.89
	4	0.1994	1.2520	1.381	5.61
	5	0.0563	1.0263	1.533	17.99

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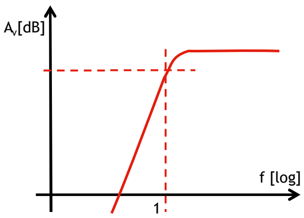
LOW → HIGH pass

$$S \to \frac{1}{S}$$

High pass filter



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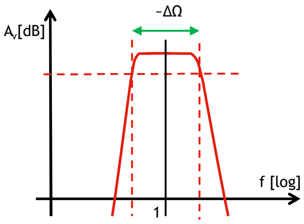
LOW → BAND PASS

$$S \to \frac{1}{\Delta\Omega}\left(S + \frac{1}{S}\right)$$

Band pass filter



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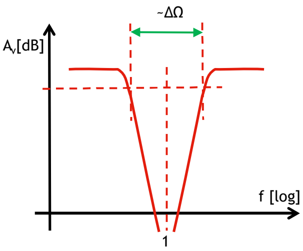
LOW → BAND STOP

$$S \to \frac{\Delta\Omega}{\left(S + \frac{1}{S}\right)}$$



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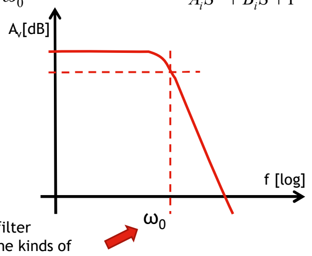
Filters transformation

$$S = \frac{s}{\omega_0} \qquad H_i(S) = \frac{Ku}{A_i S^2 + B_i S + 1}$$



Low pass filter
And all othe kinds of
filters

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Cascade of biquadratic filters

$$\rightarrow \boxed{\frac{A_k(s)}{s^2 + b_1 s + b_0}} \rightarrow \cdots \rightarrow \boxed{\frac{Z_k(s)}{s^2 + b_1 s + b_0}} \rightarrow$$

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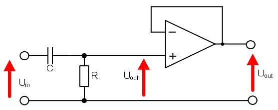
LP, BP, HP sections

$$\frac{A_i}{a_i s^2 + b_i s + 1} \qquad \frac{1}{a_i s + 1}$$

$$\frac{A_i s}{a_i s^2 + b_i s + 1}$$

$$\frac{A_i s^2}{a_i s^2 + b_i s + 1} \qquad \frac{s}{a_i s + 1}$$

1st order high pass filer



$$A_V = \frac{U_{out}}{U_{in}} = \frac{R}{R + \frac{1}{sC}} = \frac{sCR}{sCR+1} =$$

$$= \frac{R}{R + \frac{1}{j\omega C}} = \frac{1}{1 + \frac{1}{j\omega CR}} = \frac{1}{1 + \frac{1/RC}{j\omega}} = \frac{1}{1 + \frac{\omega_1}{j\omega}} = \frac{1}{1 + \frac{f_1}{jf}}$$

$$f_1 = \frac{1}{2\pi RC}$$

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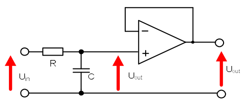
1st order low pass filer



$$A_V = \frac{U_{out}}{U_{in}} = \frac{\frac{1}{sC}}{R + \frac{1}{sC}} = \frac{1}{1 + jsCR} =$$

$$= \frac{1}{1 + j\omega \frac{1}{1/RC}} = \frac{1}{1 + \frac{j\omega}{\omega_2}} = \frac{1}{1 + j\frac{f}{f_2}} =$$

$$f_2 = \frac{1}{2\pi RC}$$

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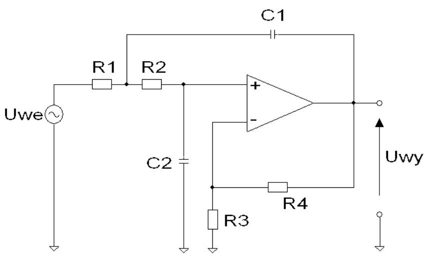
Active filters
Sallen - Key low pass implementation



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Sallen - Key low pass implementation

Transmittance:

$$H_{LP}(s)=\frac{U_{wy}(s)}{U_{we}(s)}=\frac{\dfrac{1+R_4/R_3}{R_1R_2C_1C_2}}{s^2+\left(\dfrac{1}{R_1C_1}+\dfrac{1}{R_2C_1}+\dfrac{R_4/R_3}{R_2C_2}\right)s+\dfrac{1}{R_1R_2C_1C_2}}$$

where:

$$\omega_0=\frac{1}{\sqrt{R_1R_2C_1C_2}}\qquad Q=\frac{\dfrac{1}{\sqrt{R_1R_2C_1C_2}}}{\left(\dfrac{1}{R_1C_1}+\dfrac{1}{R_2C_1}+\dfrac{R_4/R_3}{R_2C_2}\right)}$$

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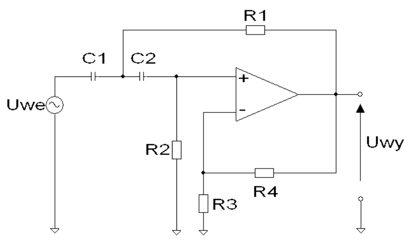
Sallen - Key high pass implementation



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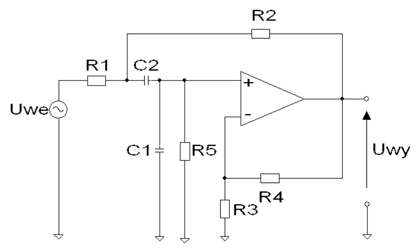
Sallen - Key high pass implementation

$$H_{HP}(s)=\frac{U_{out}(s)}{U_{in}(s)}=\frac{(1+R_4/R_3)s^2}{s^2+\left(\dfrac{1}{R_2C_1}+\dfrac{1}{R_2C_2}+\dfrac{R_4/R_3}{R_1C_1}\right)s+\dfrac{1}{R_1R_2C_1C_2}}$$

Sallen - Key band pass implementation

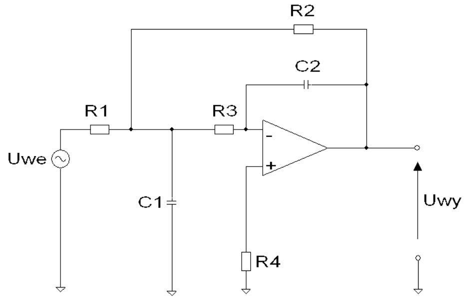


Sallen - Key band pass implementation

$$H_{BP}(s)=\frac{U_{out}(s)}{U_{in}(s)}=\frac{\frac{1+R_4/R_3}{R_1C_1}s}{s^2+\left(\frac{1}{R_1C_1}+\frac{1}{R_3C_2}+\frac{1}{R_3C_1}+\frac{R_4/R_3}{R_2C_1}\right)s+\frac{R_1+R_2}{R_1R_2R_3C_1C_2}}$$

$$\omega_0=\sqrt{\frac{R_1+R_2}{R_1R_2R_3C_1C_2}} \qquad Q=\frac{\sqrt{\frac{R_1+R_2}{R_1R_2R_3C_1C_2}}}{\left(\frac{1}{R_1C_1}+\frac{1}{R_3C_2}+\frac{1}{R_3C_1}+\frac{R_4/R_3}{R_2C_1}\right)}$$

LOW PASS multiple negative feedback



LOW PASS multiple negative feedback

$$H_{LP}(s)=\frac{U_{wy}(s)}{U_{we}(s)}=\frac{-\dfrac{R_2/R_1}{R_2R_3C_1C_2}}{s^2+\dfrac{s}{C_1}\left(\dfrac{1}{R_1}+\dfrac{1}{R_2}+\dfrac{1}{R_3}\right)+\dfrac{1}{R_2R_3C_1C_2}}$$

$$\omega_0=\frac{1}{\sqrt{R_2R_3C_1C_2}}\qquad Q=\left[\sqrt{\frac{C_2}{C_1}}\left(\sqrt{\frac{R_3}{R_2}}+\sqrt{\frac{R_2}{R_3}}+\frac{\sqrt{R_2R_3}}{R_1}\right)\right]^{-1}$$

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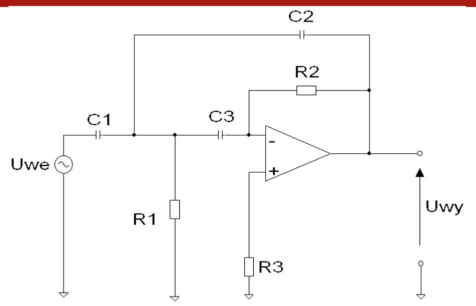
HIGH PASS multiple negative feedback



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HIGH PASS multiple negative feedback

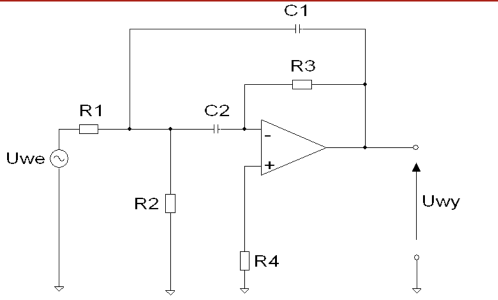
Transfer function:

$$H_{HP}(s)=\frac{U_{out}(s)}{U_{in}(s)}=\frac{-C_1/C_2\,s^2}{s^2+\dfrac{s}{R_2}\left(\dfrac{C_1}{C_2C_3}+\dfrac{1}{C_2}+\dfrac{1}{C_3}\right)+\dfrac{1}{R_1R_2C_2C_3}}$$

where:

$$\omega_0=\frac{1}{\sqrt{R_1R_2C_2C_3}}\qquad Q=\left[\sqrt{\frac{R_1}{R_2}}\left(\frac{C_1}{\sqrt{C_2C_3}}+\sqrt{\frac{C_3}{C_2}}+\sqrt{\frac{C_2}{C_3}}\right)\right]^{-1}$$

BAND PASS
multiple negative feedback



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BAND PASS
multiple negative feedback

$$H_{BP}(s)=\frac{U_{out}(s)}{U_{in}(s)}=\frac{-\frac{s}{R_1C_1}}{s^2+s\left(\frac{1}{R_3C_1}+\frac{1}{R_3C_2}\right)+\frac{R_1+R_2}{R_1R_2R_3C_1C_2}}$$

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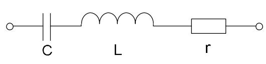
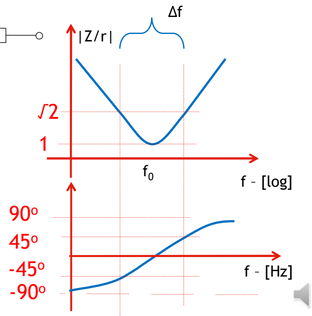
LC
resonant circuit (serial)



$$f_0=\frac{1}{2\pi\sqrt{LC}}$$

$$Q=\frac{f_0}{\Delta f}=\frac{\omega_0 L}{r}$$



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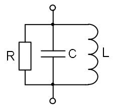
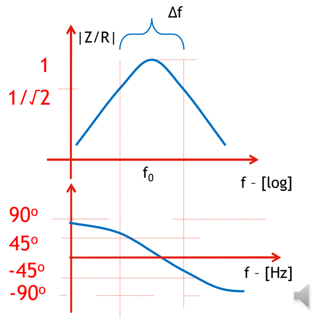
LC resonant circuit (paralel)



$$f_0 = \frac{1}{2\pi\sqrt{LC}}$$

$$Q = \frac{f_0}{\Delta f} = \frac{R}{1/\omega_0 C}$$



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Q-factor definition

$$Q = \frac{f_0}{\Delta f} = \frac{\omega_0}{\omega_{gH} - \omega_{gL}}$$

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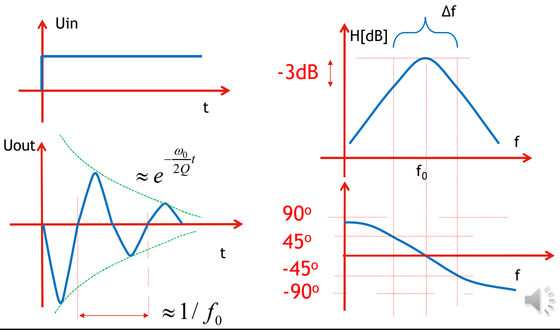
Band pass



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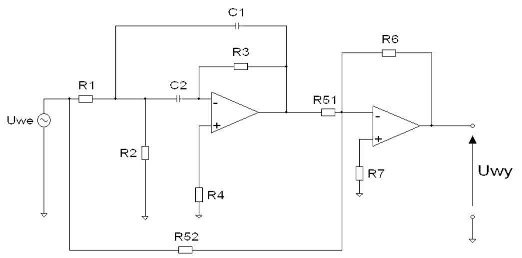
BAND STOP



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Active filters-multiple negative feedback

Transmitancja filtru:

$$H_{BR}(s) = -\left(\frac{R_6}{R_{51}} H_{BP}(s) + \frac{R_6}{R_{52}}\right)$$

Przy częstotliwości środkowej $\omega = \omega_0$

$$\left.\begin{aligned} |H_{BP}(\omega = \omega_0)| &= 1\frac{V}{V} \\ \varphi(\omega = \omega_0) &= \pi \end{aligned}\right\} H_{BP} = -1\frac{V}{V}$$

Dla: $R_{51} = R_{52} = R$

$$H_{BR}(\omega = \omega_0) = 0$$

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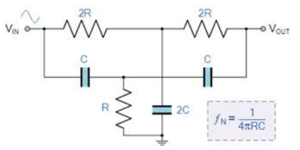
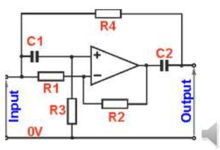
BAND STOP (NOTCH FILTER)



$C1 = C2 = C$
$R4 = R3 = R$
$R2 = R1 = R'$
$f_0 = 1/2\pi RC$



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ALL PASS FILTER

$$H(s)=\frac{N(s)}{D(s)}=\prod_k H_k(s)$$

$$H_k(s)=\frac{s^2-b_1s+b_0}{s^2+b_1s+b_0}$$

$$\left|H_k(s)\right|=1$$

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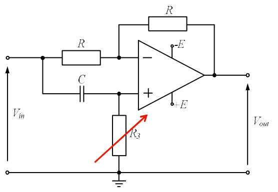
phase shifter (all pass filter of 1st order)



$$\frac{V_{out}}{V_{in}}=-\frac{1-sCR_3}{1+sCR_3}$$

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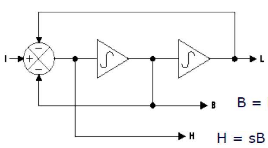
state variable filter

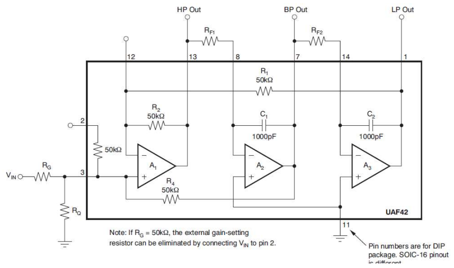


H = I - B - L

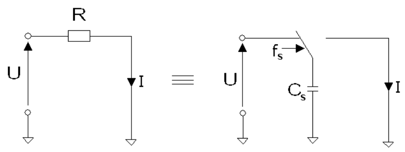
S^2L = I - sL - L

$$\frac{L}{I}=\frac{1}{s^2+s+1} \qquad \frac{B}{I}=\frac{s}{s^2+s+1} \qquad \frac{H}{I}=\frac{s^2}{s^2+s+1}$$

Biquadrqtic monolithic universal filter UF42 by TI (state variable filter)



Switched capacitor filter

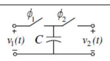
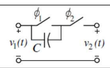
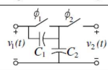
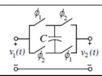


$$I = \frac{U}{R}$$

$$I = \frac{dQ}{dt} = \frac{d(UC_S)}{dt} = \frac{UC_S}{T_S} = UC_S f_S$$

$$R = \frac{1}{C_S f_S}$$

Switched capacitor circuits

Switched Capacitor Resistor Emulation Circuit	Schematic	Equivalent Resistance
Parallel		$\frac{T}{C}$
Series		$\frac{T}{C}$
Series-Parallel		$\frac{T}{C_1 + C_2}$
Bilinear		$\frac{T}{4C}$

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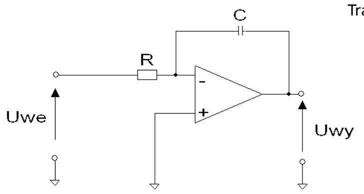
C switched filter



Transfer function

$$\frac{U_{wy}}{U_{wy}} = -\frac{1}{\tau s}$$

Where: $\tau = RC$

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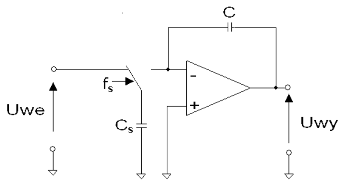
C switched filters



$$\frac{U_{wy}}{U_{wy}} = -\frac{1}{\tau s}$$

$$\tau = CR_{ZAST} = \frac{C}{f_S C_S} = \frac{\eta}{2\pi f_S}$$

$$\frac{\eta}{2\pi} = \frac{C}{C_S}$$

$$\eta = (50 \div 200)$$

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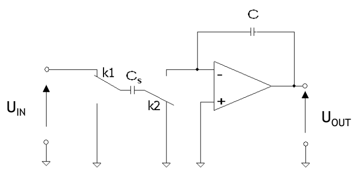
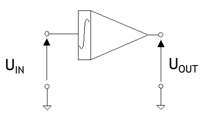
C switched integrator





C switched integrator

$$\frac{U_{wy}}{U_{we}} = \frac{f_S C_S}{sC} = \frac{1}{\tau s}$$

$$\tau = CR_{ZAST} = \frac{C}{f_S C_S} = \frac{\eta}{2\pi f_S}$$

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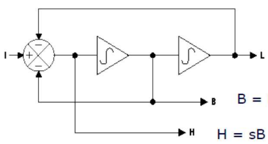
state variable filter



L = B/s

B = H/s   B = sL

H = sB = s²L

H = I - B - L   S²L = I - sL - L

$$\frac{L}{I} = \frac{1}{s^2+s+1} \qquad \frac{B}{I} = \frac{s}{s^2+s+1} \qquad \frac{H}{I} = \frac{s^2}{s^2+s+1}$$

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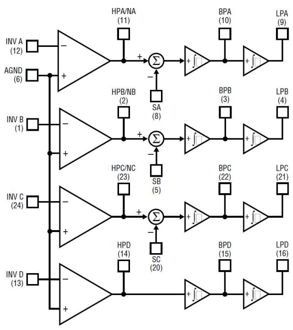
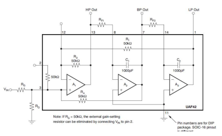
4 biquadratic filters with switched capacitors in LTC1064 by LT





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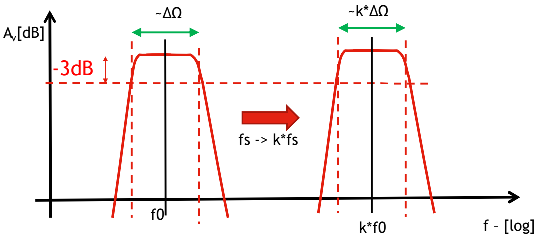
Switched capacitors filter fs -> k*fs



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Application note of LT(now AD) switched capacitor filters

Worth to be read:

https://www.analog.com/media/en/technical-documentation/application-notes/an40f.pdf

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Problems

1. Q-factor of a bandpass filter ?
2. Types of filters (band stop, b. pass etc.)
3. Types of frequency response of filters (Bessel, Butterworth, Chebyshev, Eliptic (Cauer)),
4. Biquadratic filter (biquadratic section)
5. General idea of C-switching filters