Op-Amp Circuits: Part 3

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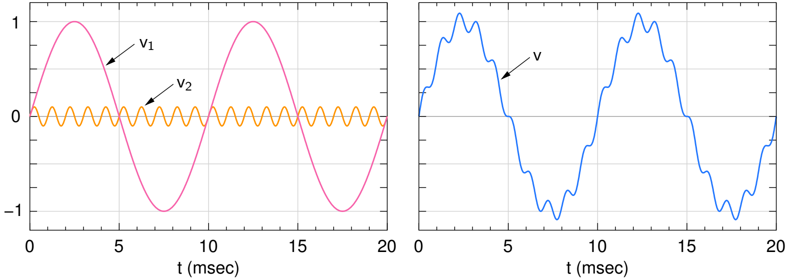
Consider $v(t) = v_1(t) + v_2(t) = V_{m1} \sin \omega_1 t + V_{m2} \sin \omega_2 t$.



Introduction to filters

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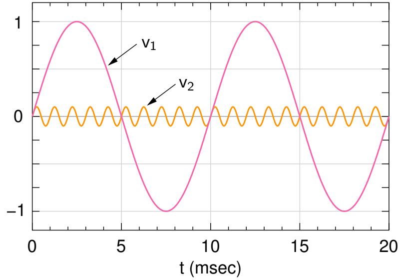

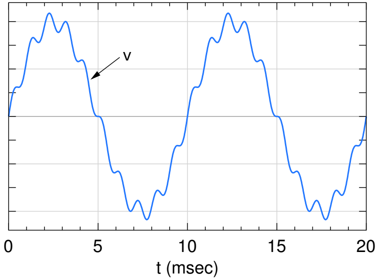

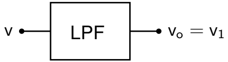

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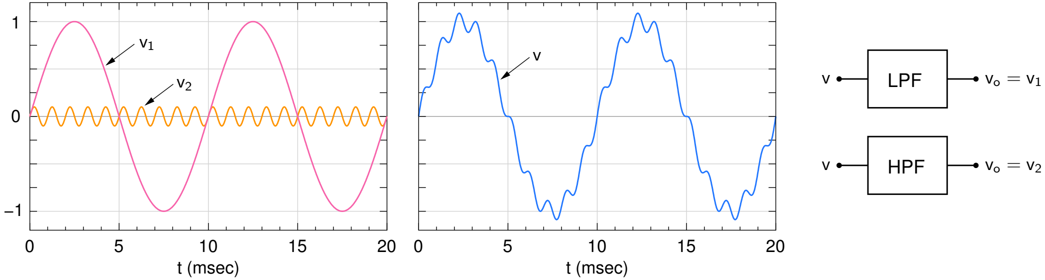

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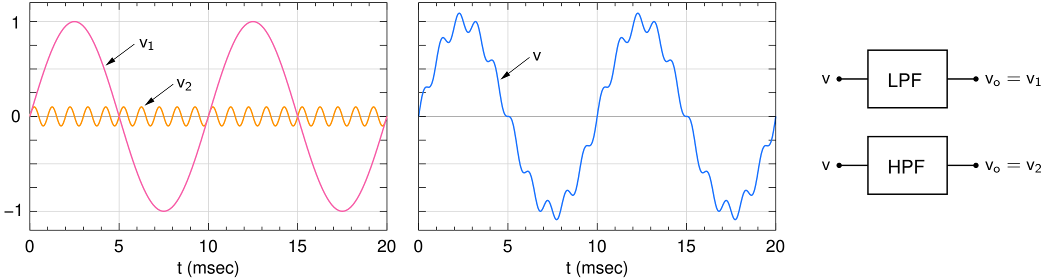

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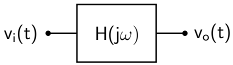
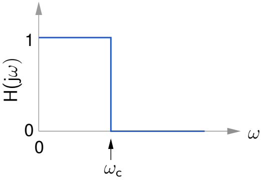
A high-pass filter with a cut-off frequency $\omega_1 < \omega_c < \omega_2$ will pass the high-frequency component $v_2(t)$ and remove the low-frequency component $v_1(t)$.

There are some other types of filters, as we will see.

Ideal low-pass filter





$$V_o(j\omega) = H(j\omega)\, V_i(j\omega)\,.$$

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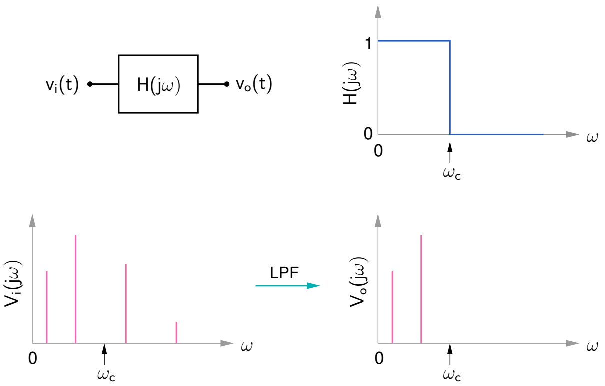

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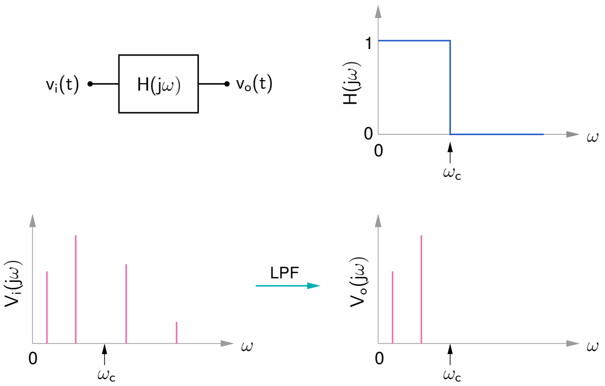


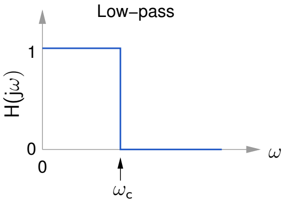
$V_o(j\omega) = H(j\omega)\, V_i(j\omega)$.

All components with $\omega < \omega_c$ appear at the output without attenuation.

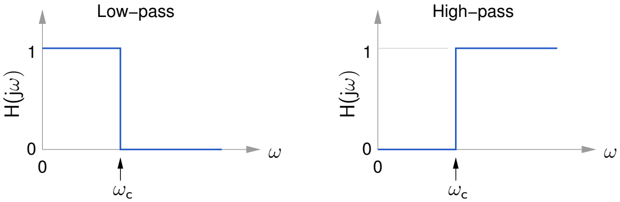
All components with $\omega > \omega_c$ get eliminated.

(Note that the ideal low-pass filter has $\angle H(j\omega) = 1$, i.e., $H(j\omega) = 1 + j0$.)

Ideal filters



Ideal filters



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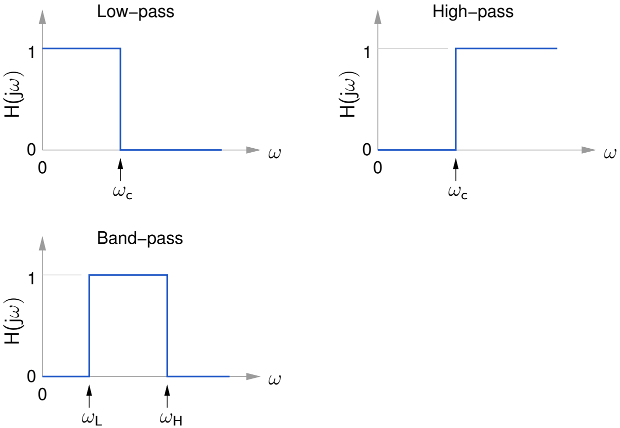
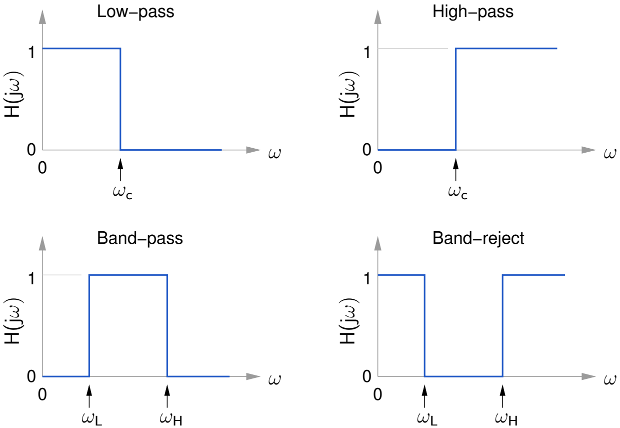
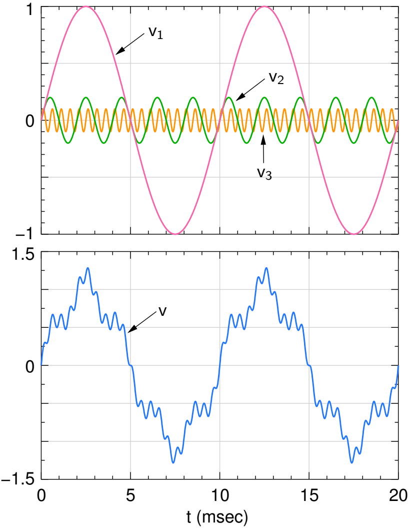
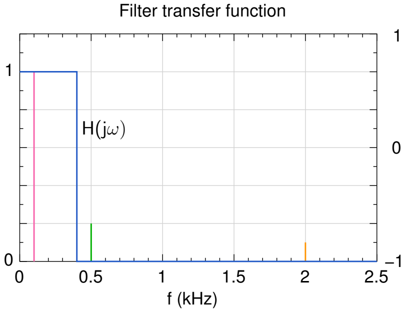
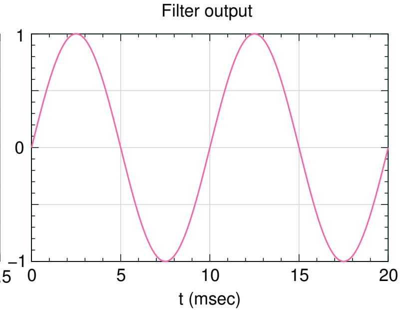



Low−pass
H(jω)
1
0
0
ω
ωc
High−pass
H(jω)
1
0
0
ω
ωc
Band−pass
H(jω)
1
0
0
ω
ωL
ωH
Band−reject
H(jω)
1
0
0
ω
ωL
ωH

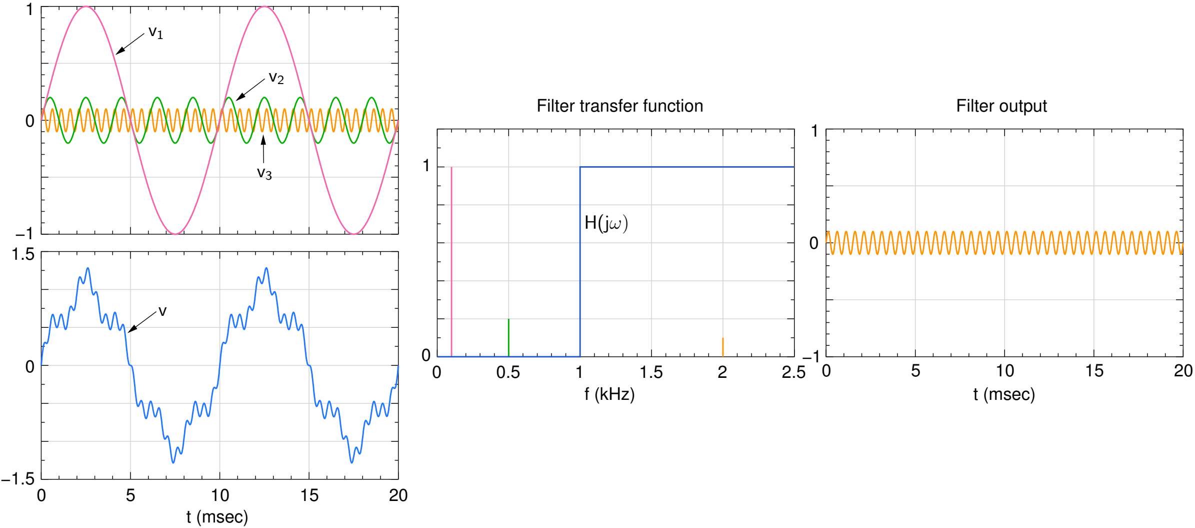
Ideal low-pass filter: example

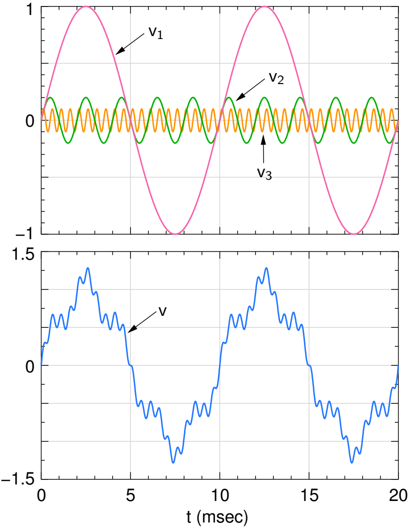


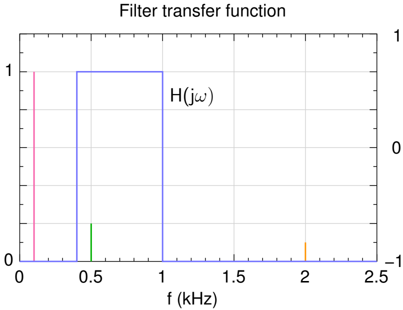


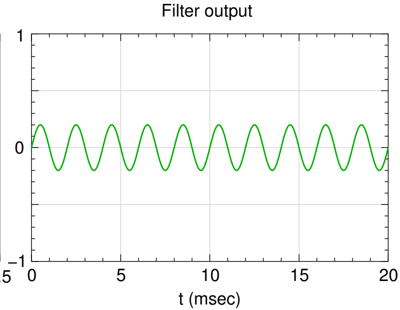


Ideal high-pass filter: example

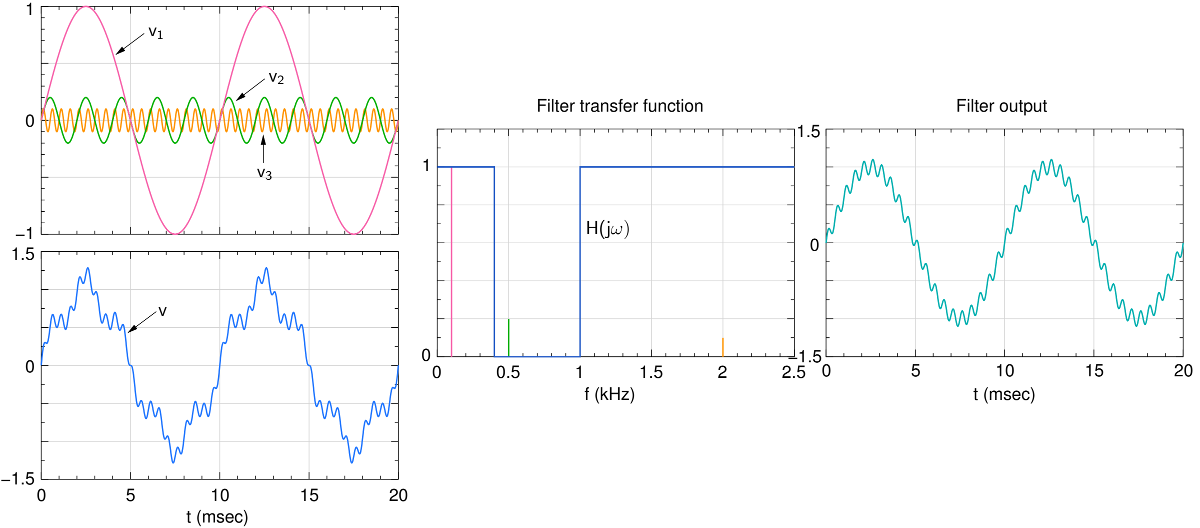



1
0
−1
v_1
v_2
v_3
1.5
0
−1.5
v
0
5
10
15
20
t (msec)


Filter transfer function
1
0
H(jω)
0
0.5
1
1.5
2
2.5
f (kHz)


Filter output
1
0
−1
0
5
10
15
20
t (msec)

Ideal band-reject filter: example



* In practical filter circuits, the ideal filter response is approximated with a suitable $H(j\omega)$ that can be obtained with circuit elements. For example,

$$H(s) = \frac{1}{a_5 s^5 + a_4 s^4 + a_3 s^3 + a_2 s^2 + a_1 s + a_0}$$

represents a 5^{th}-order low-pass filter.

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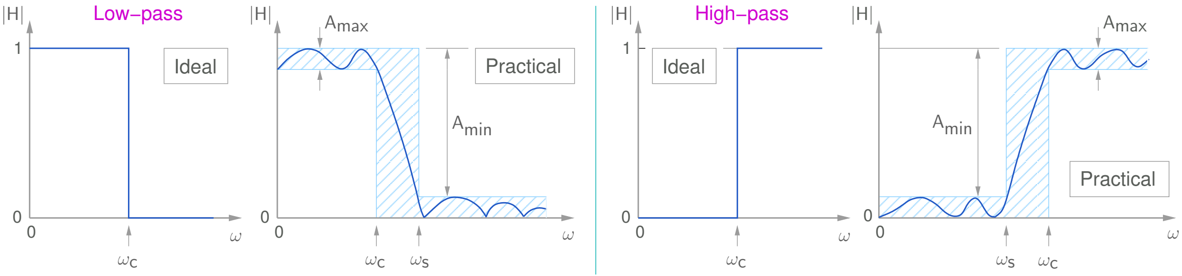
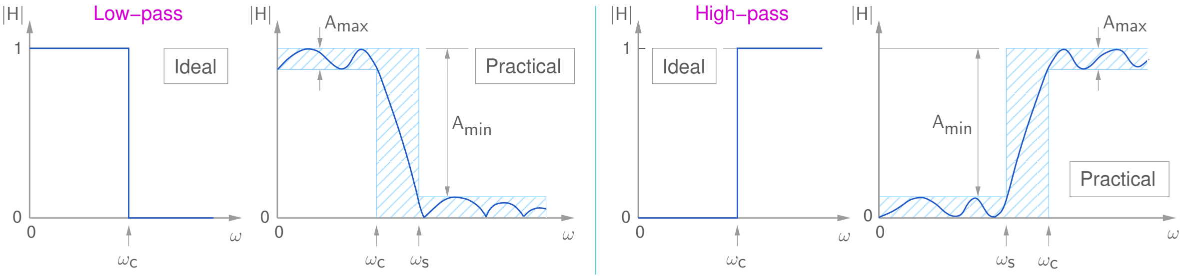
* Coefficients for these filters are listed in filter handbooks. Also, programs for filter design are available on the internet.


|H|
Low−pass
1
0
0
Ideal
ω
ω_c
|H|
A_{max}
0
0
Practical
A_{min}
ω
ω_c
ω_s
|H|
High−pass
1
0
0
Ideal
ω
ω_c
|H|
A_{max}
A_{min}
Practical
0
0
ω
ω_s
ω_c



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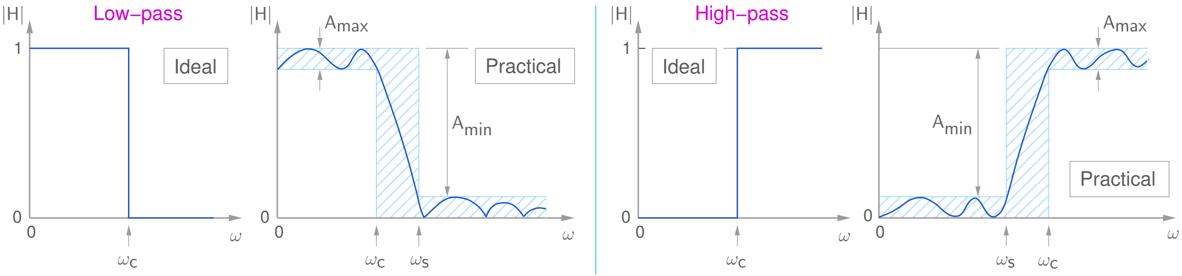
Practical filters



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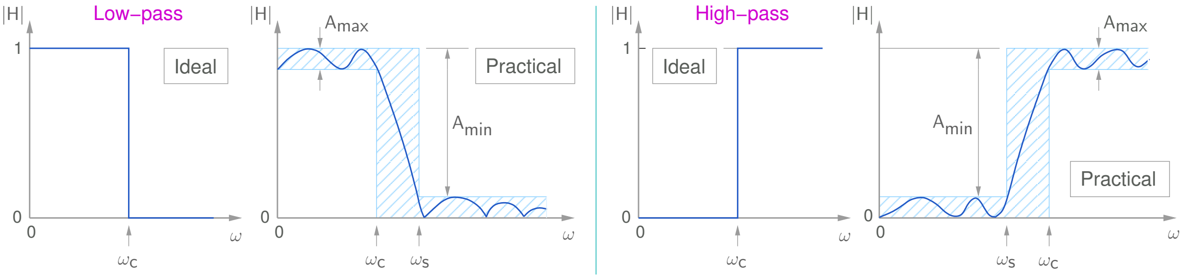

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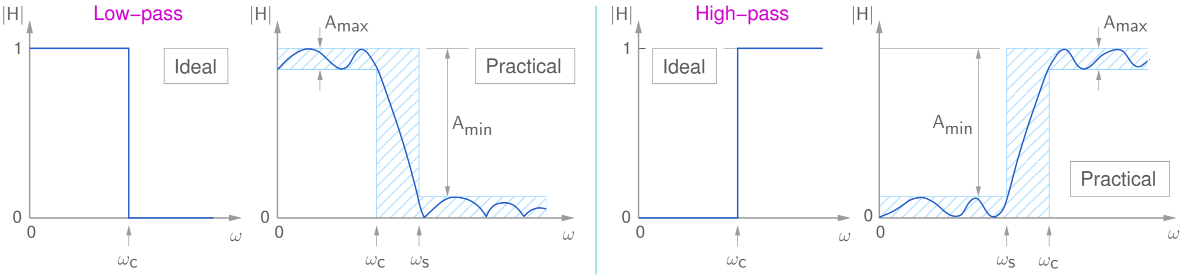

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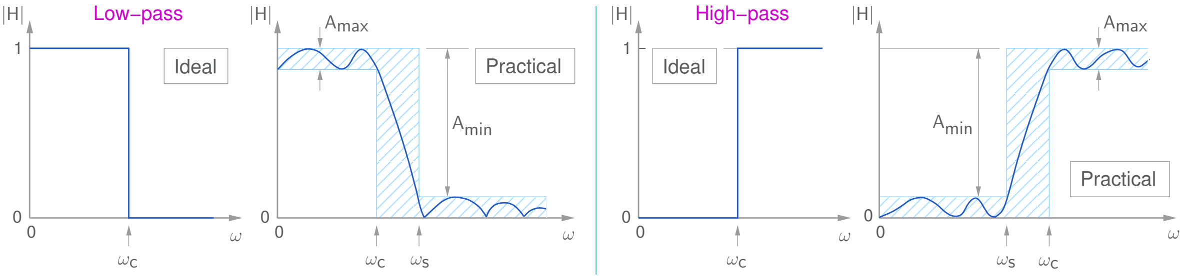

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* $\omega_c < \omega < \omega_s$: transition band.

For a low-pass filter, $H(s) = \dfrac{1}{\displaystyle\sum_{i=0}^{n} a_i (s/\omega_c)^i}$.

Coefficients (a_i) for various types of filters are tabulated in handbooks. We now look at $|H(j\omega)|$ for two commonly used filters.

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$$C_n(x) = \cos\left[n\cos^{-1}(x)\right] \quad \text{for } x \leq 1,$$

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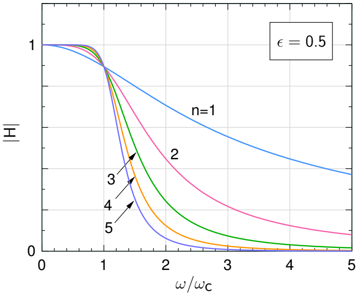
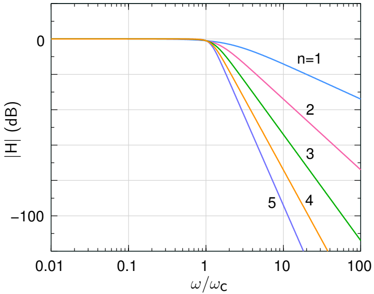
$H(s)$ for a high-pass filter can be obtained from $H(s)$ of the corresponding low-pass filter by $(s/\omega_c) \rightarrow (\omega_c/s)$.

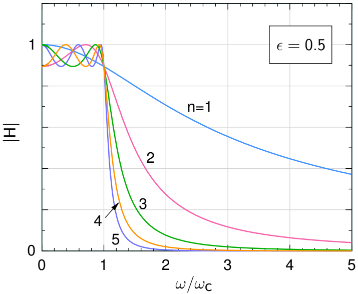
Practical filters (low-pass)

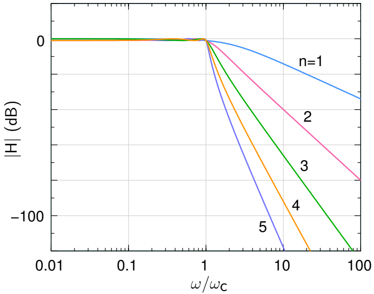
Butterworth filters:





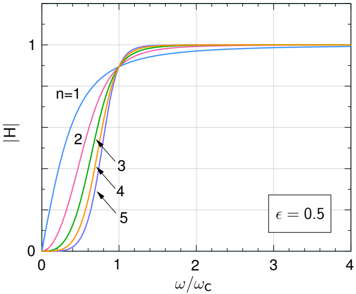
Chebyshev filters:

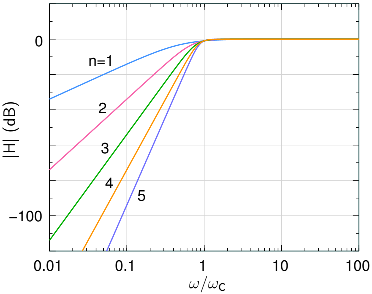




Practical filters (high-pass)

Butterworth filters:





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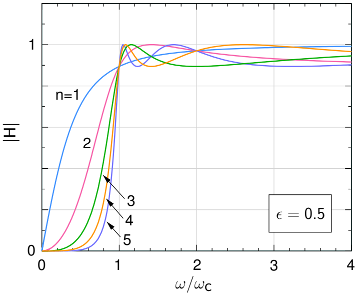
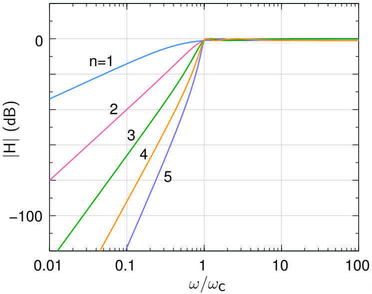
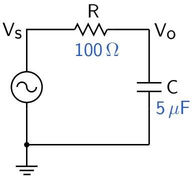




Passive filter example



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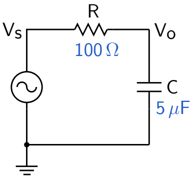
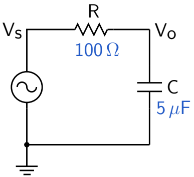


$$H(s) = \frac{(1/sC)}{R + (1/sC)} = \frac{1}{1 + (s/\omega_0)},$$

with $\omega_0 = 1/RC \rightarrow f_0 = \omega_0/2\pi = 318\,\text{Hz}$

(Low–pass filter)

Passive filter example



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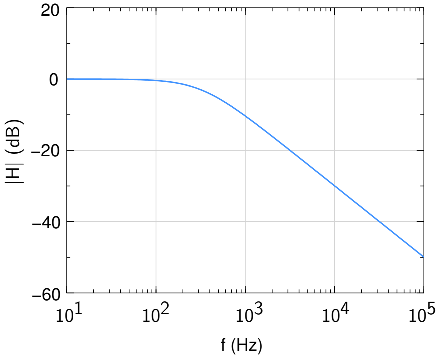
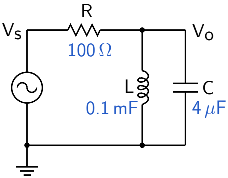


(SEQUEL file: `ee101_rc_ac_2.sqproj`)

Passive filter example



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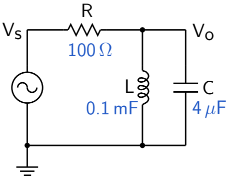
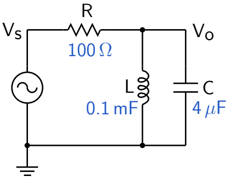


$$H(s) = \frac{(sL) \parallel (1/sC)}{R + (sL) \parallel (1/sC)} = \frac{s(L/R)}{1 + s(L/R) + s^2LC}$$

with $\omega_0 = 1/\sqrt{LC} \to f_0 = \omega_0/2\pi = 7.96\,\mathrm{kHz}$

(Band–pass filter)

Passive filter example



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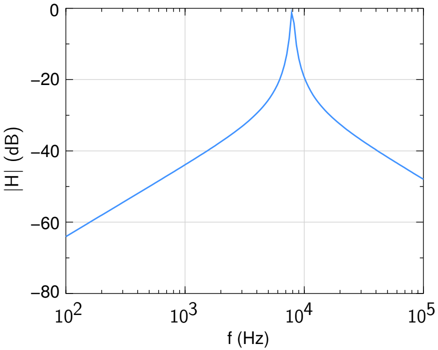

(SEQUEL file: `ee101_rlc_3.sqproj`)

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* Op-amp filters can be easily incorporated in an integrated circuit.

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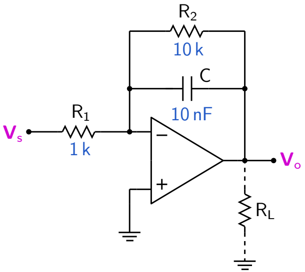
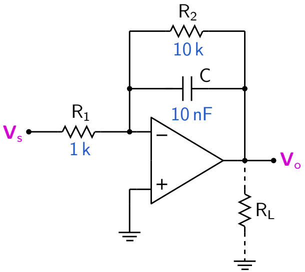
* Op-amp filters can be designed without using inductors. This is a significant advantage since inductors are bulky and expensive. Inductors also exhibit nonlinear behaviour (arising from the core properties) which is undesirable in a filter circuit.
* With op-amps, a filter circuit can be designed with a pass-band gain.
* Op-amp filters can be easily incorporated in an integrated circuit.
* However, there are situations in which passive filters are still used.
  - high frequencies at which op-amps do not have sufficient gain
  - high power which op-amps cannot handle

Op-amp filters: example



Op-amp filters: example

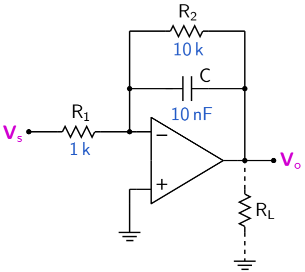


Op-amp filters are designed for op-amp operation in the linear region
→ Our analysis of the inverting amplifier applies, and we get,

$$\mathbf{V_o} = -\frac{R_2 \parallel (1/sC)}{R_1}\,\mathbf{V_s} \quad (\mathbf{V_s} \text{ and } \mathbf{V_o} \text{ are phasors})$$

$$H(s) = -\frac{R_2}{R_1}\,\frac{1}{1 + sR_2C}$$

Op-amp filters: example



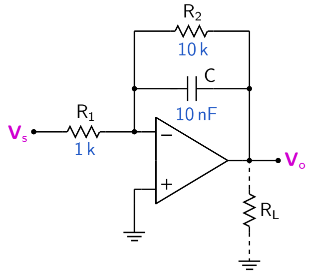
Op-amp filters are designed for op-amp operation in the linear region
→ Our analysis of the inverting amplifier applies, and we get,

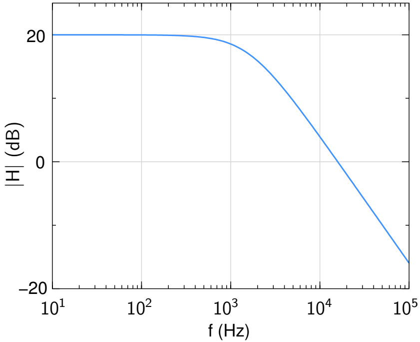
$$\mathbf{V_o} = -\frac{R_2 \parallel (1/sC)}{R_1}\,\mathbf{V_s} \quad (\mathbf{V_s} \text{ and } \mathbf{V_o} \text{ are phasors})$$

$$H(s) = -\frac{R_2}{R_1}\,\frac{1}{1 + sR_2C}$$

This is a low-pass filter, with $\omega_0 = 1/R_2C$ (i.e., $f_0 = \omega_0/2\pi = 1.59\,\text{kHz}$).

Op-amp filters: example



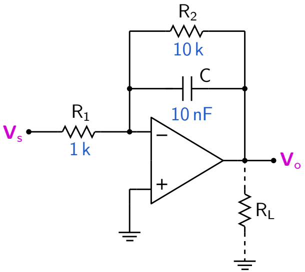


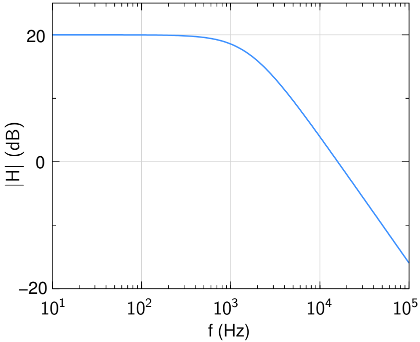
Op-amp filters are designed for op-amp operation in the linear region
$\rightarrow$ Our analysis of the inverting amplifier applies, and we get,

$$\mathbf{V_o} = -\frac{R_2 \parallel (1/sC)}{R_1}\,\mathbf{V_s} \quad (\mathbf{V_s} \text{ and } \mathbf{V_o} \text{ are phasors})$$

$$H(s) = -\frac{R_2}{R_1}\,\frac{1}{1+sR_2C}$$

This is a low-pass filter, with $\omega_0 = 1/R_2C$ (i.e., $f_0 = \omega_0/2\pi = 1.59\,\text{kHz}$).





Op-amp filters are designed for op-amp operation in the linear region
→ Our analysis of the inverting amplifier applies, and we get,

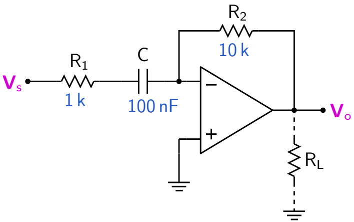
$$\mathbf{V_o} = -\frac{R_2 \parallel (1/sC)}{R_1}\,\mathbf{V_s}$$ ($\mathbf{V_s}$ and $\mathbf{V_o}$ are phasors)

$$H(s) = -\frac{R_2}{R_1}\,\frac{1}{1 + sR_2C}$$

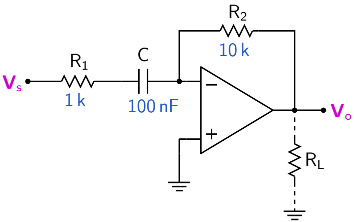
This is a low-pass filter, with $\omega_0 = 1/R_2C$ (i.e., $f_0 = \omega_0/2\pi = 1.59\,\text{kHz}$).

(SEQUEL file: `ee101_op_filter_1.sqproj`)

Op-amp filters: example

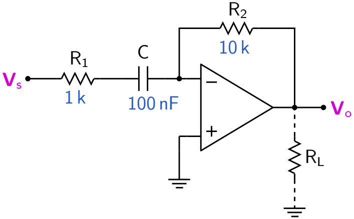


Op-amp filters: example



$$H(s) = -\frac{R_2}{R_1 + (1/sC)} = -\frac{sR_2C}{1 + sR_1C}\ .$$

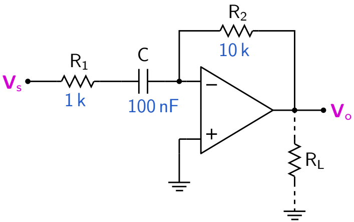
Op-amp filters: example

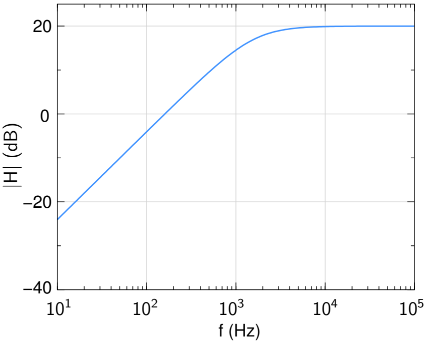


$$H(s) = -\frac{R_2}{R_1 + (1/sC)} = -\frac{sR_2 C}{1 + sR_1 C}\,.$$

This is a high-pass filter, with $\omega_0 = 1/R_1 C$ (i.e., $f_0 = \omega_0/2\pi = 1.59\,\mathrm{kHz}$).

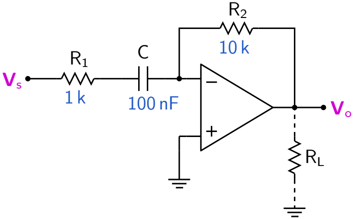
Op-amp filters: example

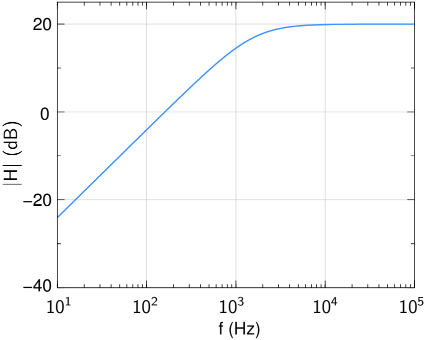




$$H(s) = -\frac{R_2}{R_1 + (1/sC)} = -\frac{sR_2C}{1 + sR_1C}\,.$$

This is a high-pass filter, with $\omega_0 = 1/R_1C$ (i.e., $f_0 = \omega_0/2\pi = 1.59\,\text{kHz}$).



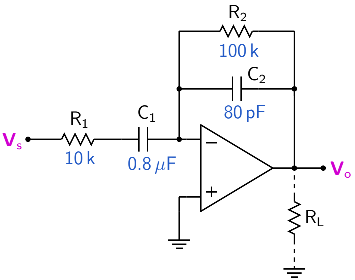


$$H(s) = -\frac{R_2}{R_1 + (1/sC)} = -\frac{sR_2C}{1 + sR_1C}\,.$$

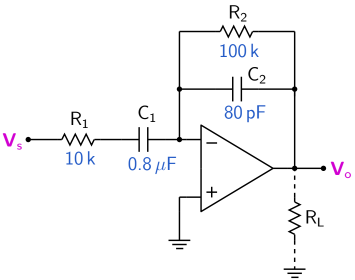
This is a high-pass filter, with $\omega_0 = 1/R_1C$ (i.e., $f_0 = \omega_0/2\pi = 1.59\,\text{kHz}$).

(SEQUEL file: `ee101_op_filter_2.sqproj`)

Op-amp filters: example

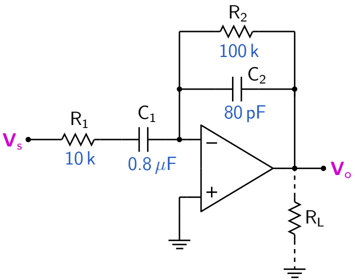


Op-amp filters: example



$$H(s) = -\frac{R_2 \parallel (1/sC_2)}{R_1 + (1/sC_1)} = -\frac{R_2}{R_1}\,\frac{sR_1C_1}{(1+sR_1C_1)(1+sR_2C_2)}\,.$$

Op-amp filters: example

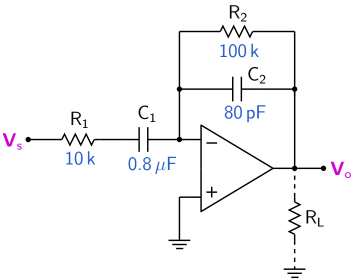


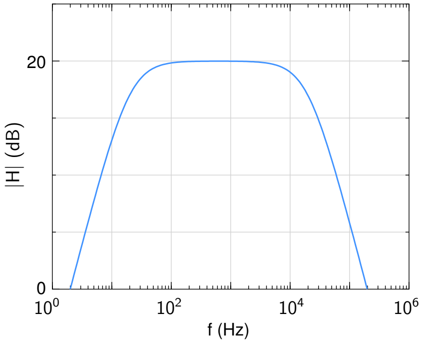
$$H(s) = -\frac{R_2 \parallel (1/sC_2)}{R_1 + (1/sC_1)} = -\frac{R_2}{R_1}\,\frac{sR_1C_1}{(1+sR_1C_1)(1+sR_2C_2)}\,.$$

This is a band-pass filter, with $\omega_L = 1/R_1C_1$ and $\omega_H = 1/R_2C_2$.

$\rightarrow f_L = 20\,\text{Hz},\ f_H = 20\,\text{kHz}.$

Op-amp filters: example

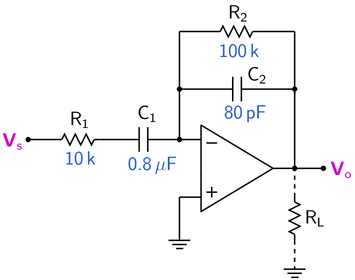


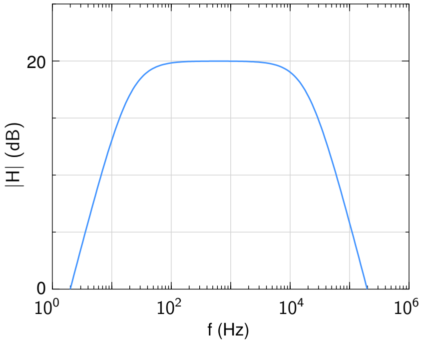


$$H(s) = -\frac{R_2 \parallel (1/sC_2)}{R_1 + (1/sC_1)} = -\frac{R_2}{R_1}\,\frac{sR_1C_1}{(1+sR_1C_1)(1+sR_2C_2)}\,.$$

This is a band-pass filter, with $\omega_L = 1/R_1C_1$ and $\omega_H = 1/R_2C_2$.

$\rightarrow f_L = 20\,\text{Hz},\; f_H = 20\,\text{kHz}.$





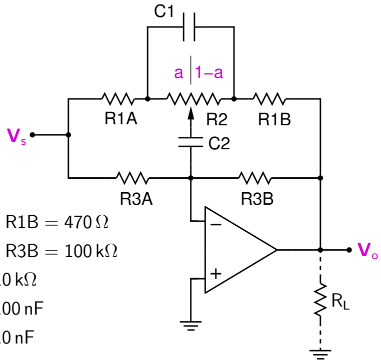
$$H(s) = -\frac{R_2 \parallel (1/sC_2)}{R_1 + (1/sC_1)} = -\frac{R_2}{R_1}\,\frac{sR_1C_1}{(1+sR_1C_1)(1+sR_2C_2)}\,.$$

This is a band-pass filter, with $\omega_L = 1/R_1C_1$ and $\omega_H = 1/R_2C_2$.

$\rightarrow f_L = 20\,\text{Hz},\; f_H = 20\,\text{kHz}.$

(SEQUEL file: `ee101_op_filter_3.sqproj`)

Graphic equalizer



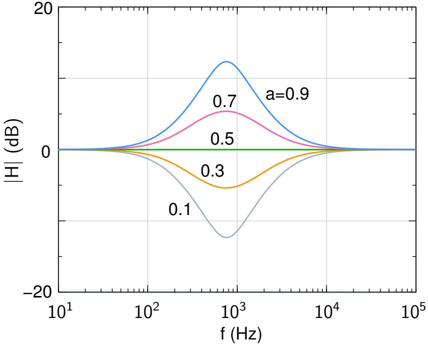
R1A = R1B = 470 Ω

R3A = R3B = 100 kΩ

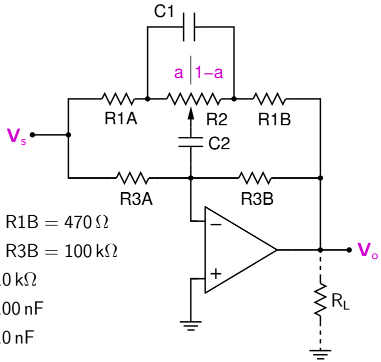
R2 = 10 kΩ

C1 = 100 nF

C2 = 10 nF



(Ref.: S. Franco, "Design with Op Amps and analog ICs")



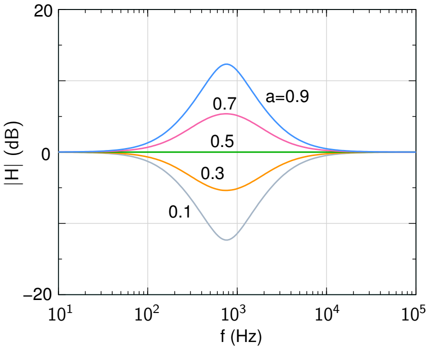
R1A = R1B = 470 Ω

R3A = R3B = 100 kΩ

R2 = 10 kΩ

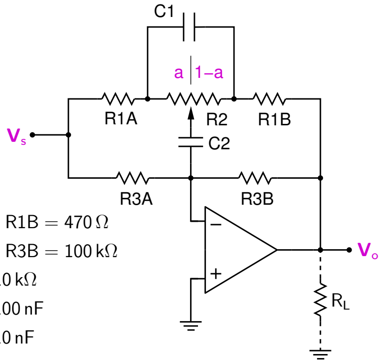
C1 = 100 nF

C2 = 10 nF



(Ref.: S. Franco, "Design with Op Amps and analog ICs")

* Equalizers are implemented as arrays of narrow-band filters, each with an adjustable gain (attenuation) around a centre frequency.



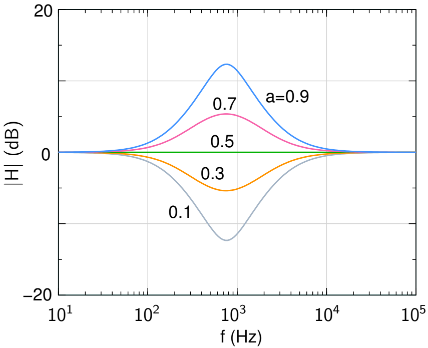
R1A = R1B = 470 Ω

R3A = R3B = 100 kΩ

R2 = 10 kΩ

C1 = 100 nF

C2 = 10 nF

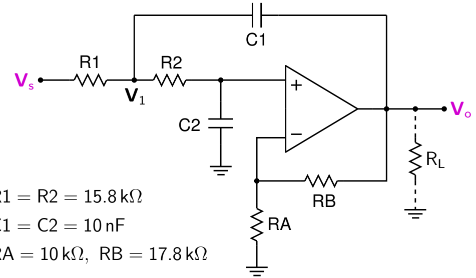


(Ref.: S. Franco, "Design with Op Amps and analog ICs")

- Equalizers are implemented as arrays of narrow-band filters, each with an adjustable gain (attenuation) around a centre frequency.
- The circuit shown above represents one of the equalizer sections.
  (SEQUEL file: `ee101_op_filter_4.sqproj`)


EQ-20 GRAPHIC EQUALIZER
ADVANCED EQ
NUMBER
WRITE
LIGHT
SELECT
MEMORY
30
60
120
200
400
800
1.6 k
3.2 k
6.4 k
12.8 k
(Hz)
LEVEL
+15
0
−15
(dB)
MANUAL
PEAK
POWER
EQ-20
EFFECT ON / OFF
MANUAL / MEMORY
BOSS

Sallen-Key filter example (2nd order, low-pass)

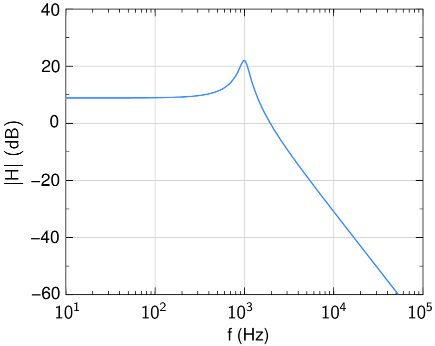


$R1 = R2 = 15.8\,k\Omega$

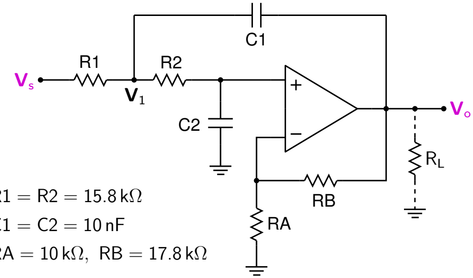
$C1 = C2 = 10\,nF$

$RA = 10\,k\Omega,\ RB = 17.8\,k\Omega$

(Ref.: S. Franco, "Design with Op Amps and analog ICs")



Sallen-Key filter example (2nd order, low-pass)

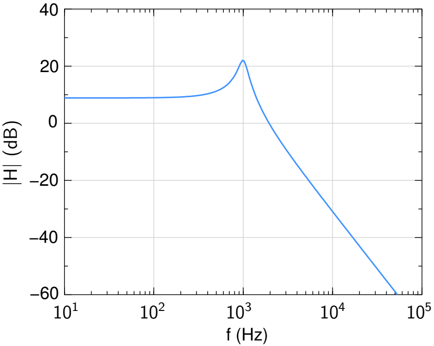


R1 = R2 = 15.8 kΩ

C1 = C2 = 10 nF

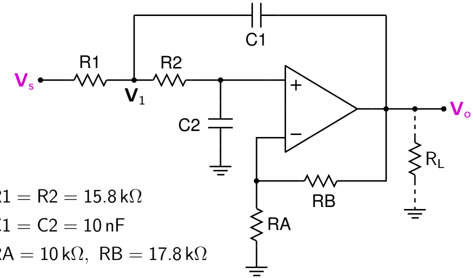
RA = 10 kΩ, RB = 17.8 kΩ

(Ref.: S. Franco, "Design with Op Amps and analog ICs")



$$\mathbf{V}_+ = \mathbf{V}_- = \mathbf{V}_o \frac{R_A}{R_A + R_B} \equiv \mathbf{V}_o / K \,.$$

Sallen-Key filter example (2nd order, low-pass)

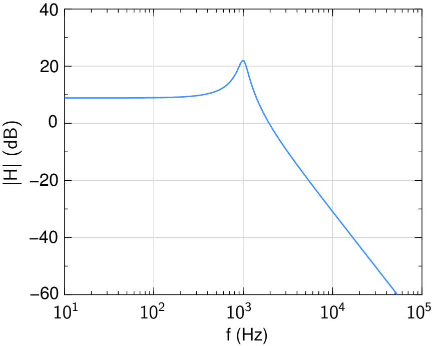


R1 = R2 = 15.8 kΩ

C1 = C2 = 10 nF

RA = 10 kΩ, RB = 17.8 kΩ

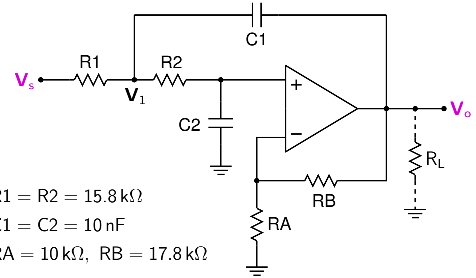
(Ref.: S. Franco, "Design with Op Amps and analog ICs")



$$\mathbf{V}_+ = \mathbf{V}_- = \mathbf{V}_o \frac{R_A}{R_A + R_B} \equiv \mathbf{V}_o / K \,.$$

Also, $\mathbf{V}_+ = \dfrac{(1/sC_2)}{R_2 + (1/sC_2)} \mathbf{V}_1 = \dfrac{1}{1 + sR_2 C_2} \mathbf{V}_1 \,.$

Sallen-Key filter example (2^{nd} order, low-pass)

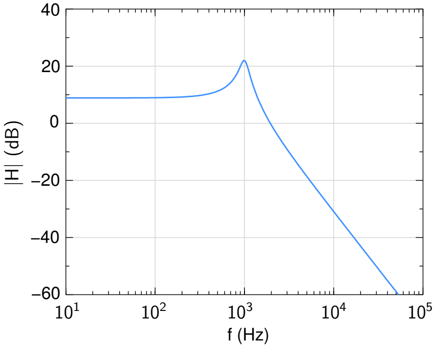


R1 = R2 = 15.8 kΩ

C1 = C2 = 10 nF

RA = 10 kΩ, RB = 17.8 kΩ

(Ref.: S. Franco, "Design with Op Amps and analog ICs")

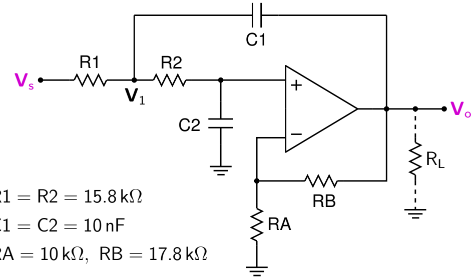


$$\mathbf{V}_+ = \mathbf{V}_- = \mathbf{V}_o \frac{R_A}{R_A + R_B} \equiv \mathbf{V}_o / K \,.$$

Also, $\mathbf{V}_+ = \dfrac{(1/sC_2)}{R_2 + (1/sC_2)} \mathbf{V}_1 = \dfrac{1}{1 + sR_2C_2} \mathbf{V}_1 \,.$

KCL at $\mathbf{V}_1 \rightarrow \dfrac{1}{R_1}(\mathbf{V}_s - \mathbf{V}_1) + sC_1(\mathbf{V}_o - \mathbf{V}_1) + \dfrac{1}{R_2}(\mathbf{V}_+ - \mathbf{V}_1) = 0 \,.$

Sallen-Key filter example (2nd order, low-pass)

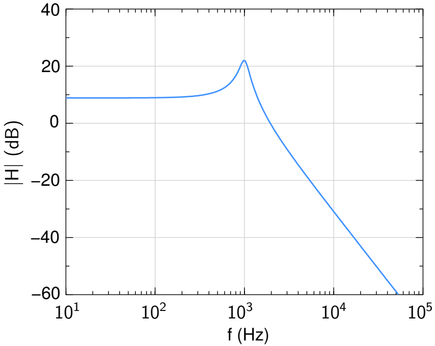


R1 = R2 = 15.8 kΩ

C1 = C2 = 10 nF

RA = 10 kΩ, RB = 17.8 kΩ

(Ref.: S. Franco, "Design with Op Amps and analog ICs")



$$\mathbf{V}_+ = \mathbf{V}_- = \mathbf{V}_o \frac{R_A}{R_A + R_B} \equiv \mathbf{V}_o / K \,.$$

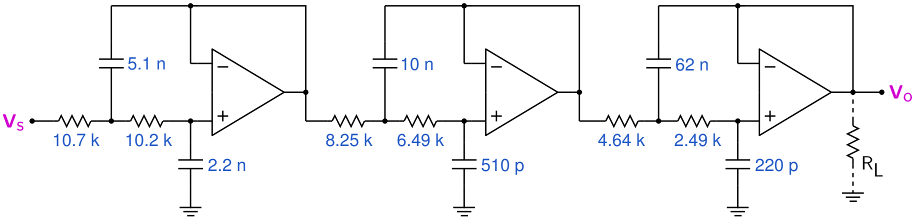
Also, $\mathbf{V}_+ = \dfrac{(1/sC_2)}{R_2 + (1/sC_2)} \mathbf{V}_1 = \dfrac{1}{1 + sR_2C_2} \mathbf{V}_1 \,.$

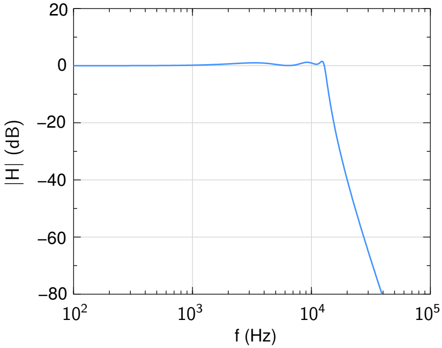
KCL at $\mathbf{V}_1 \rightarrow \dfrac{1}{R_1}(\mathbf{V}_s - \mathbf{V}_1) + sC_1(\mathbf{V}_o - \mathbf{V}_1) + \dfrac{1}{R_2}(\mathbf{V}_+ - \mathbf{V}_1) = 0 \,.$

Combining the above equations, $H(s) = \dfrac{K}{1 + s\,[(R_1 + R_2)C_2 + (1 - K)R_1C_1] + s^2 R_1C_1R_2C_2} \,.$

(SEQUEL file: `ee101_op_filter_5.sqproj`)

Sixth-order Chebyshev low-pass filter (cascade design)

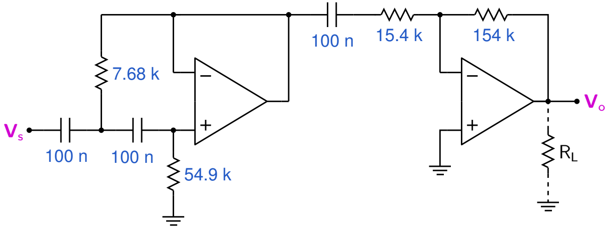




(Ref.: S. Franco, "Design with Op Amps and analog ICs")

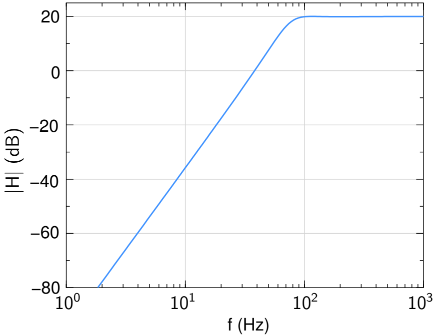
SEQUEL file: ee101_op_filter_6.sqproj

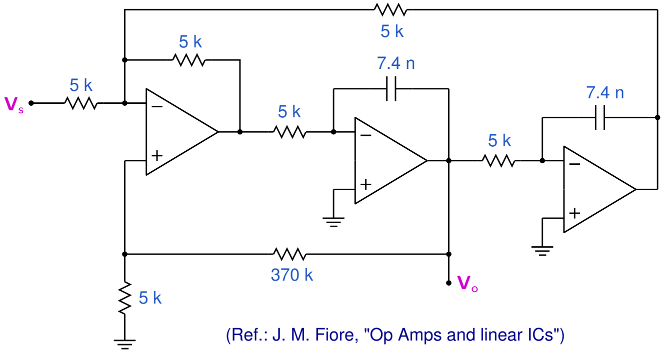
Third-order Chebyshev high-pass filter

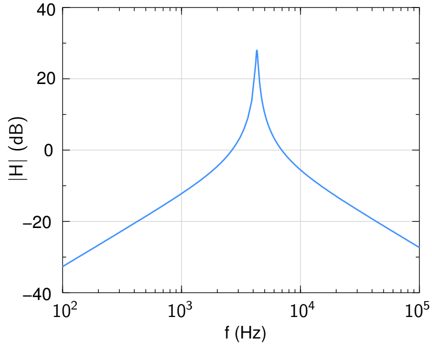


(Ref.: S. Franco, "Design with Op Amps and analog ICs")

SEQUEL file: ee101_op_filter_7.sqproj



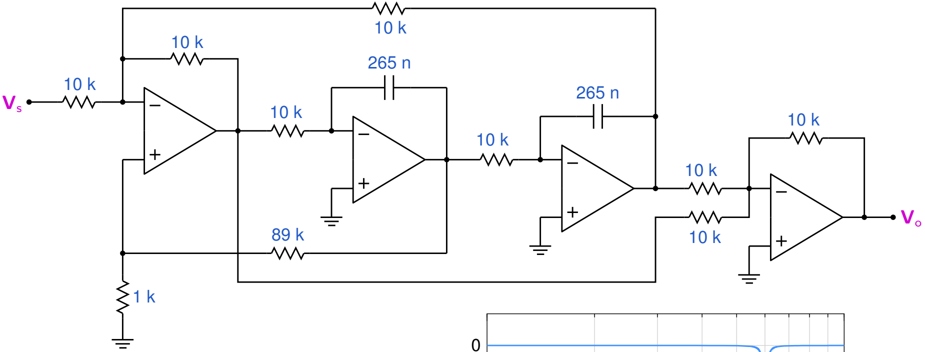




(Ref.: J. M. Fiore, "Op Amps and linear ICs")

SEQUEL file: ee101_op_filter_8.sqproj

Notch filter example



(Ref.: J. M. Fiore, "Op Amps and linear ICs")

SEQUEL file: ee101_op_filter_9.sqproj