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Lab05: Operational Amplifiers 1

Practical Example Operational Amplifier (Op-Amp) as Linear Amplifier

1. Audio pre-amplifier (e.g., guitar pedal, microphone preamp).
2. Amplification of sensor signals (temperature, strain gauge, photodiode).
3. Medical equipment such as ECG front-end amplifiers.

Practical Example Op-Amp as Active Filter

1. Active crossover filters in hi-fi and car audio systems.
2. Anti-aliasing filters before ADCs and reconstruction filters after DACs.
3. Noise-reduction filters in measurement and sensor systems.

Golden Rules

Explain the Golden Rules of the operational amplifier.

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How can the circuit be improved?

Draw an improved version and explain it.

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Inverting Operational Amplifier

Gain of Op-Amp

Build the following circuit in figure 2 with the power supply and a multimeter.

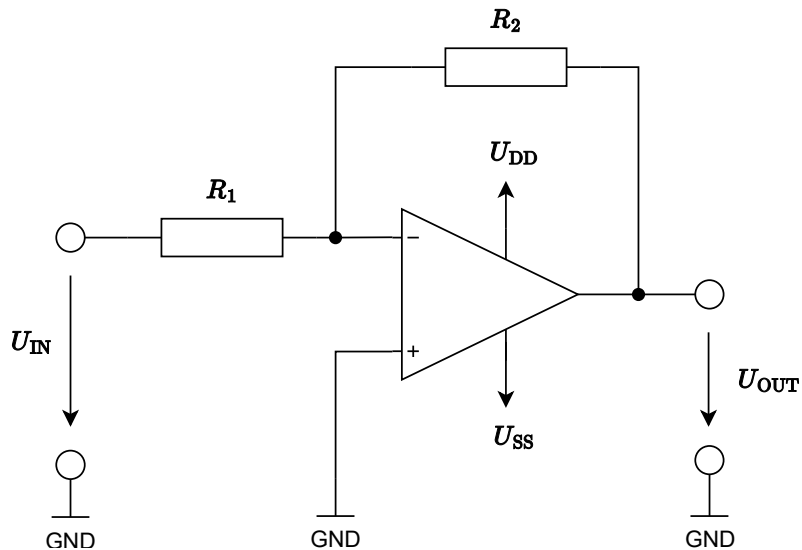


Fig. 2: Inverting Op-Amp

$$U_{DD} = 10 \text{ V}, U_{SS} = -10 \text{ V}, R_1 = 100 \text{ k}\Omega$$

Calculate the necessary value for R_2 , so that the output U_{OUT} is +1.5 V.
Use the supply voltage of the operational amplifier for U_{IN} .

$$U_{IN} =$$

$$R_2 =$$

Analysis of inverting input currents

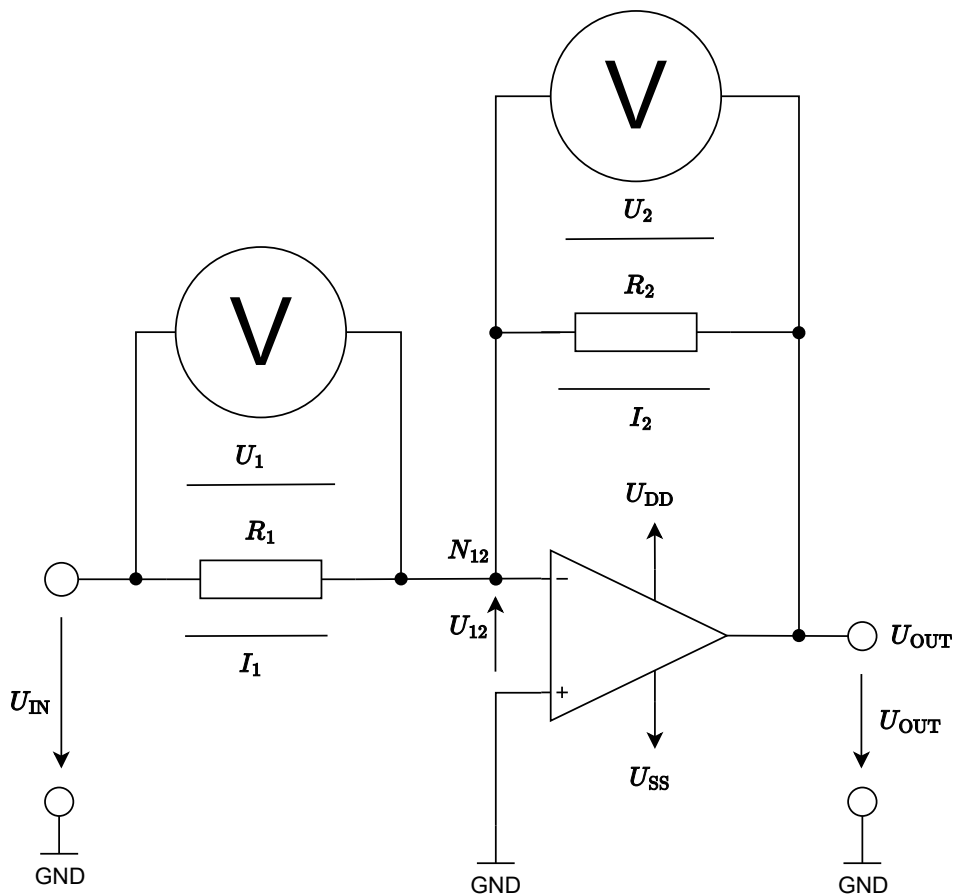


Fig. 3: Inverting Op-Amp: Analysis of currents of the inverting input

$U_{DD} = 10 \text{ V}$, $U_{SS} = -10 \text{ V}$, $R_1 = 100 \text{ k}\Omega$
 Use the values from figure 2 for U_{IN} , U_{OUT} , R_2 .

Complete the reference arrows in the schematic of the circuit.

Determine the the currents I_1 and I_2 indirectly by measuring the voltage across known resistors and calculate the algebraic sum of the currents at node N_{12} using Kirchhoff's Current Law (KCL).

$$U_1 =$$

$$U_2 =$$

$$I_1 =$$

$$I_2 =$$

$$I_{N12} =$$

Analysis of inverting input voltages

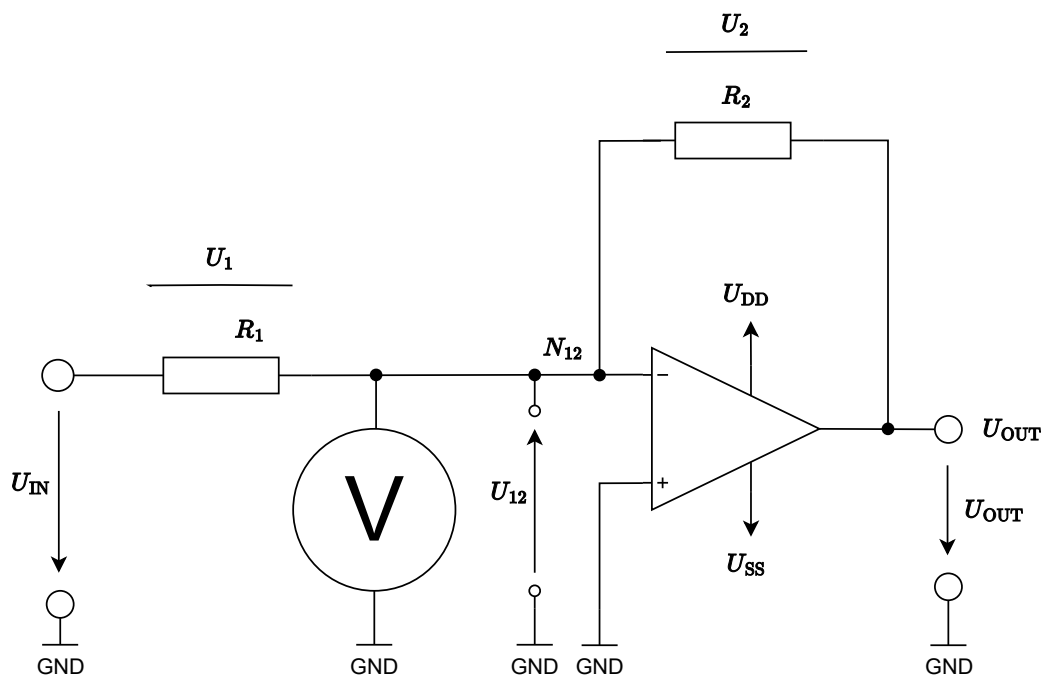


Fig. 4: Inverting Op-Amp: Analysis of virtual GND of the inverting input

$U_{DD} = 10 \text{ V}$, $U_{SS} = -10 \text{ V}$, $R_1 = 100 \text{ k}\Omega$
 Use the values from figure 2 for U_{IN} , U_{OUT} , R_2 .

Complete the reference arrows in the schematic of the circuit.

Take the values for U_1 , U_2 , U_{OUT} from figure 3.

Calculate the voltage U_{12} using Kirchhoff's Voltage Law (KVL) within one of the possible circuit loops.

Mark the chosen loop in the circuit.

Verify your calculated result by measuring U_{12} .

$$U_1 =$$

$$U_2 =$$

$$U_{IN} =$$

$$U_{OUT} =$$

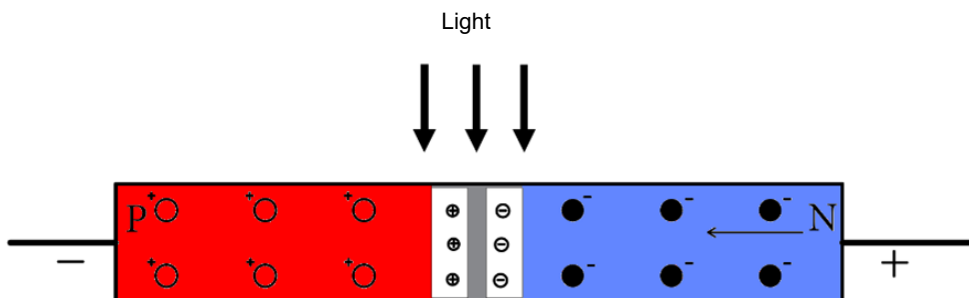
$$\text{Calculated } U_{12} =$$

$$\text{Measured } U_{12} =$$

Photodiode as current source

A photodiode is a special type of diode which, **in the absence of light**, exhibits a **current-voltage relationship** very similar to that of a standard diode (see the **dark current** characteristic in the $I - V$ diagram).

When illuminated, it generates additional electron-hole pairs within the crystal.



Photodiodes are often operated **in reverse bias**, where the charge carriers (electrons and holes) generated by the incident light cause an increased **reverse** current flow (**third quadrant** of the I-V diagram). The higher the light intensity, the greater the reverse current. **Forward bias operation** is also possible, where the photodiode behaves like a solar cell (**first quadrant** of the I-V diagram).

Applications include remote controls (IR range), galvanic isolation (optocouplers), light measurement, positioning, and light barriers.

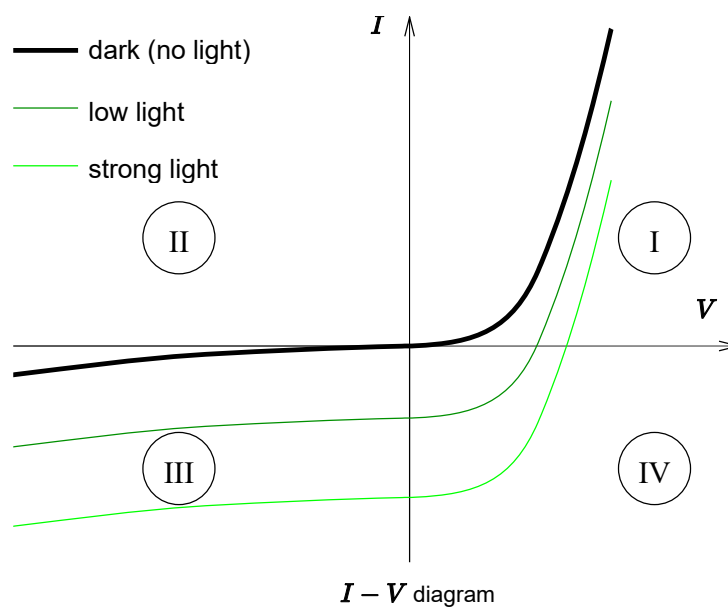


Fig. 5: Inverting Op-Amp: Operating principle of a photodiode

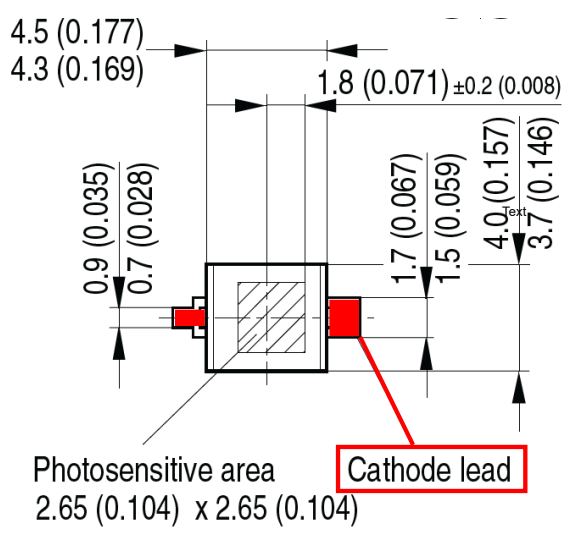
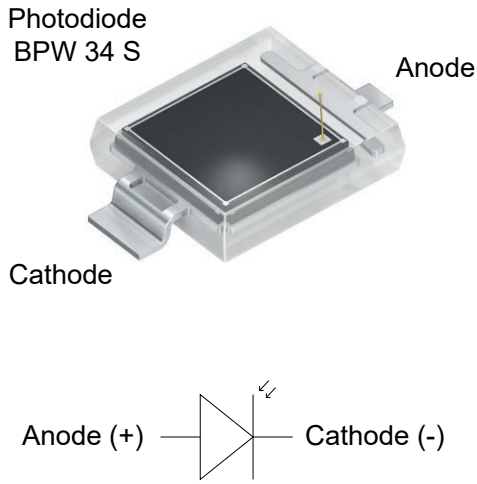
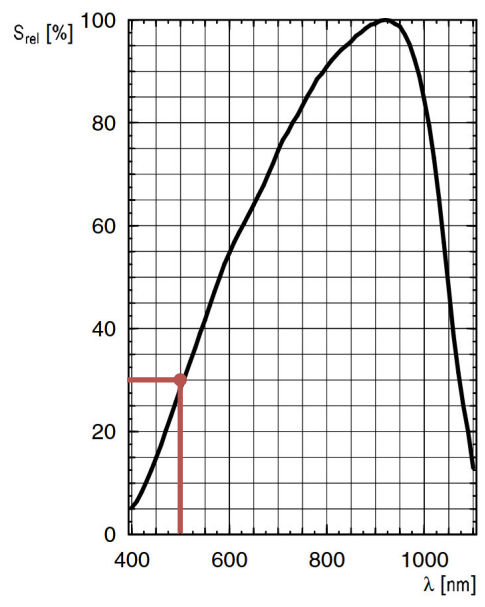
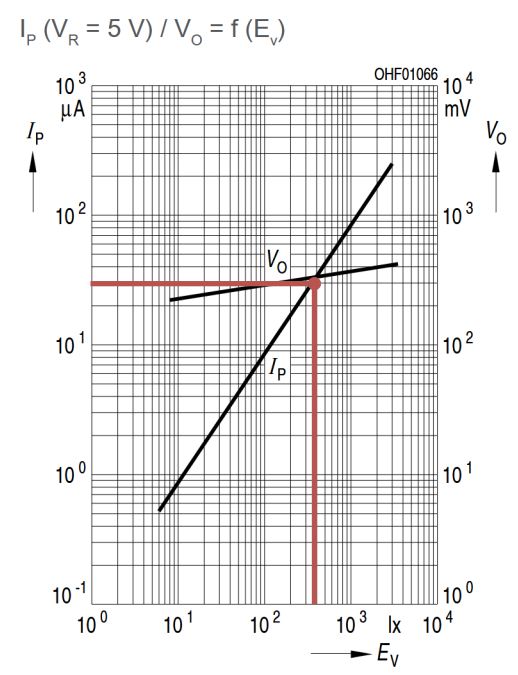


Fig. 6: Inverting Op-Amp: Photodiode BPW 34 S



Sensitivity in % as a function of the wavelength of light



Optocurrent I_P and open-circuit voltage V_O as a function of the illuminance

Fig. 7: Inverting Op-Amp: Diagramms of BPW 34 S

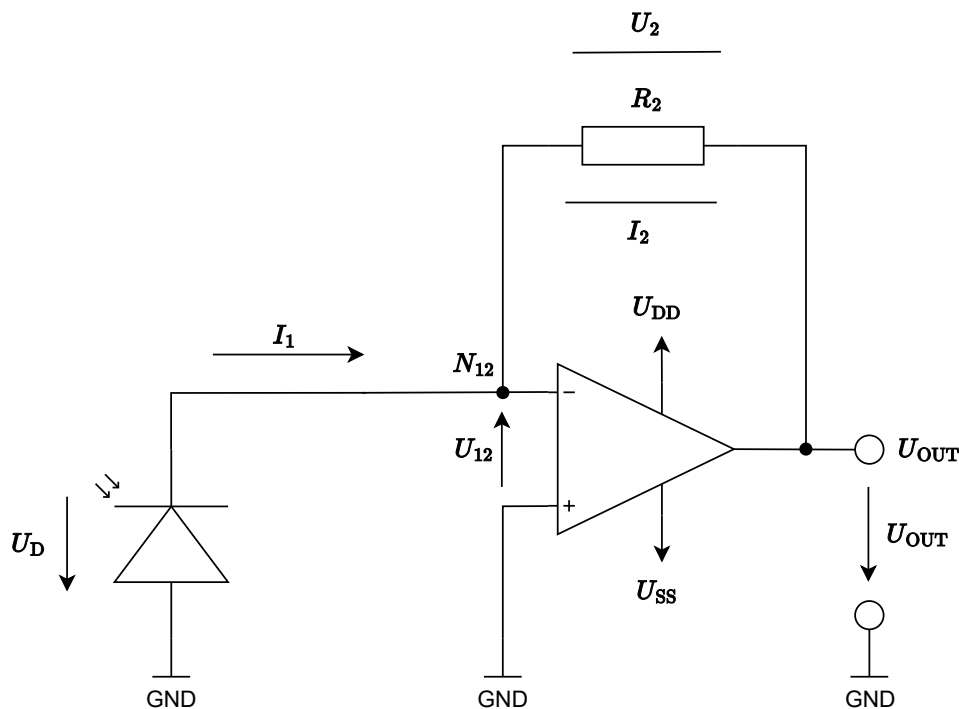


Fig. 8: Inverting Op-Amp: Photo Diode as current source

$$U_{DD} = 10 \text{ V}, U_{SS} = -10 \text{ V}$$

We are assuming a well-lit room with an illuminance of 300 lx, lit by a white LED. White light is a mixture of many wavelengths across the visible spectrum, roughly 380 to 780 nm. For a typical white LED, the spectrum usually comes from a blue LED chip with a peak around 450 nm, plus a broader phosphor emission that spreads across green, yellow, and red wavelengths. For an easier calculation, we take a mean value of 500 nm which is close to the peak value of the blue LED and 300 lx for the illumination. (500 nm is in reality a greenish light and not blue)

The graph in figure 7 shows that the photodiode sensitivity at 500 nm is only 30%. The maximum current (100%) at 300 lx is 30 μA .

We can now estimate the current we would expect from the photodiode at 300 lx:

$$I_1 = 30 \mu\text{A} * 0.3 = 9 \mu\text{A}$$

$$I_1 \approx 10 \mu\text{A}$$

30% of 30 μA is roughly 10 μA .

We will assume a current of 10 μA at 300 lx for our calculations.

Complete the arrows in the circuit diagram in figure 8.

Calculate R_2 so that $U_{OUT} = 5 \text{ V}$ at 300 lx. Take a resistor from the E6 series that is as close as possible to the calculated value.

Also enter the values for I_1 , I_2 , U_2 and U_{OUT} .

$$I_1 =$$

$$I_2 =$$

$$U_2 =$$

$$U_{\text{OUT}} =$$

$$R_2 =$$

What value would you expect for U_D in figure 8 and why?

$$U_D =$$

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What value would you expect for U_D at 300 lx when the photodiode is not connected to the Op-Amp or any other electronic component (open-circuit voltage) and why?

$U_D =$

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Measure or calculate the values given in the table below.

Illumination	U_{OUT} [V] measured	I_1 [μ A] calculated	I_2 [μ A] calculated	U_D [mV] Op-Amp circuit	U_D [mV] open-circuit *) measured
dark (cover the photodiode)					X
300 lx (room light)					
bright (use torch from mobile phone)					X

*) The photodiode must be disconnected from the Op-Amp circuit

Tab. 1: Photodiode measured and calculated values

Non-inverting Operational Amplifier

Op-Amp as current source

An Op-Amp can not only amplify voltages and currents, it can also act as a current source itself. Here is the schematic of a typical Op-Amp current source:

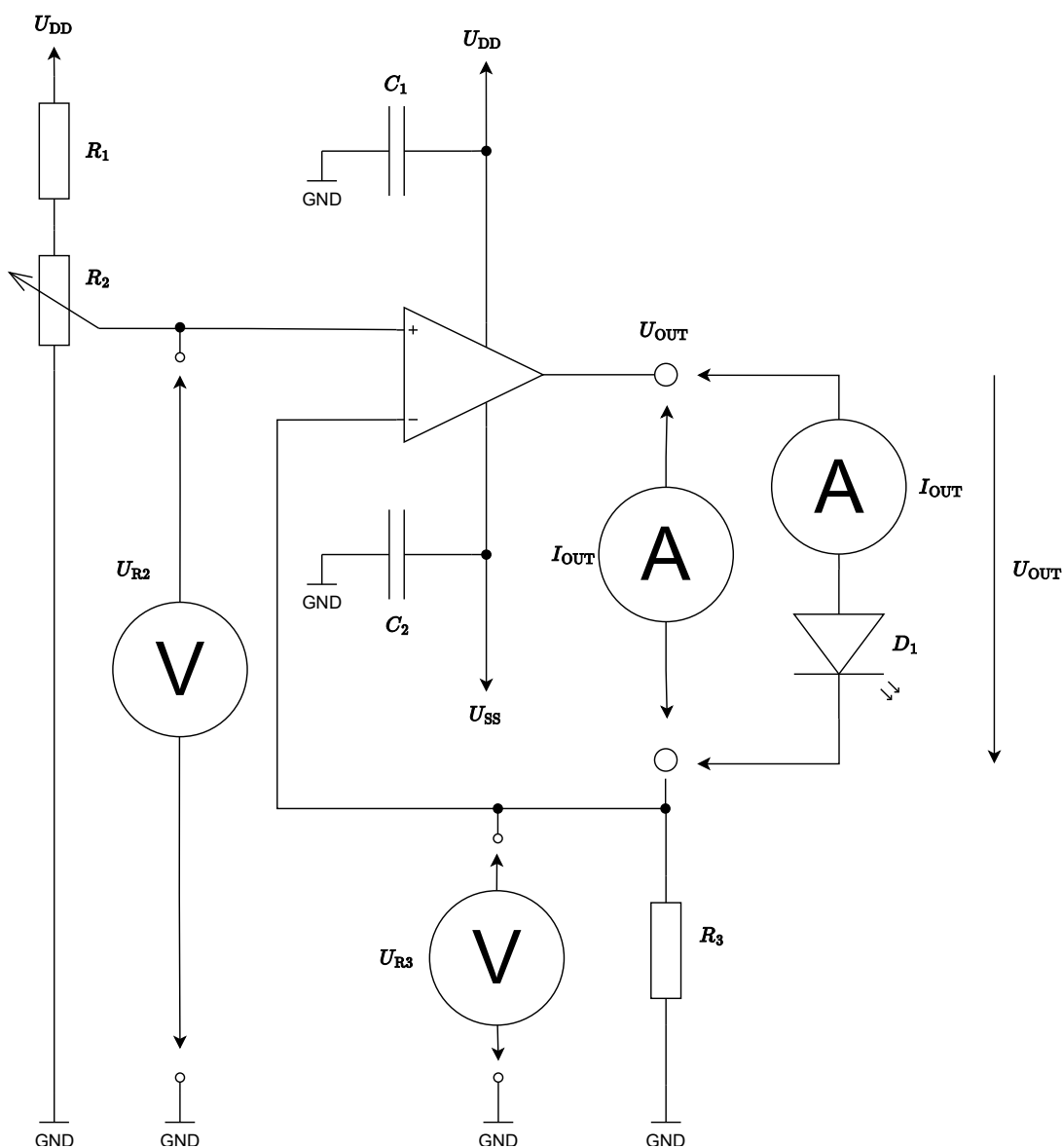


Fig. 9: Non-inverting Op-Amp: current source

$$U_{DD} = 10 \text{ V}, U_{SS} = -10 \text{ V}, R_1 = 100 \text{ k}\Omega, R_2 = 10 \text{ k}\Omega, R_3 = 100 \text{ }\Omega, C_1 = 100 \text{ nF}, C_2 = 100 \text{ nF}$$

Op-Amp as non-inverting low-pass filter

We can also use an operational amplifier as an active filter. There are two typical circuit configurations: the Sallen-Key circuit, which uses a non-inverting operational amplifier, and the multiple-feedback circuit, which uses an inverting operational amplifier.

We use the Sallen-Key circuit as it is easier to understand and the gain of the operational amplifier can be determined independently of the cut-off frequency.

The cut-off frequency can be calculated using the following formula:

$$f_c = \frac{1}{2\pi\sqrt{R_1 \cdot C_1 \cdot R_2 \cdot C_2}}$$

Here is an schematic of a typical low-pass filter using the Sallen-Key circuit:

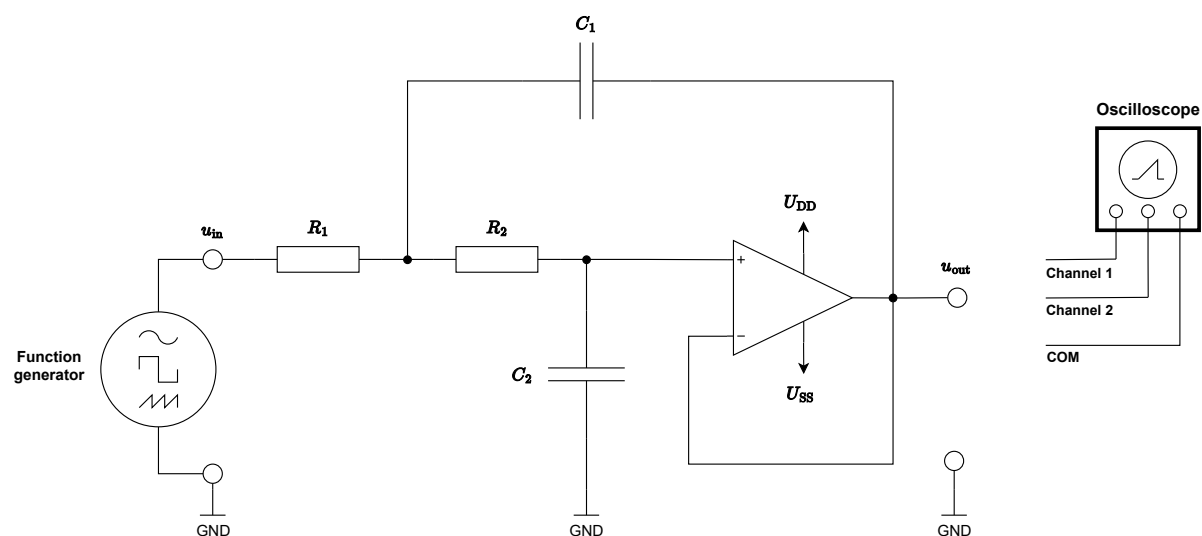


Fig. 10: Non-inverting Op-Amp: Sallen-Key Low-pass filter

$$U_{DD} = 10 \text{ V}, U_{SS} = -10 \text{ V}, R_1 = 10 \text{ k}\Omega, C_1 = 10 \text{ nF}, R_2 = 15 \text{ k}\Omega, C_2 = 4,7 \text{ nF}$$

Complete the schematic and calculate the cut-off frequency of the given circuit.

$$f_c =$$

What gain do you expect from the filter circuit, and why?

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Measure the values given in the table below.

Use the function generator with a sine wave of 6 V amplitude.

Plot the filter response on the logarithmic graph paper provided.

$\frac{f}{f_c}$	0,2	0,4	0,6	0,8	1,0	2,0	4,0	6,0	10,0
$\frac{u_{in}}{V}$ *)	6,0	6,0	6,0	6,0	6,0	6,0	6,0	6,0	6,0
$\frac{u_{out}}{V}$									

*) Sine wave

Tab. 3: Op-Amp as current source: Frequency Response Data