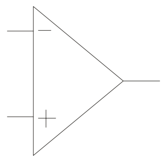
Discrete assembly of an operational amplifier as a transistor circuit

Objects of the experiment

- Assembling an operational amplifier from transistors.
- Investigating the inverting and non-inverting configuration of the amplifier.

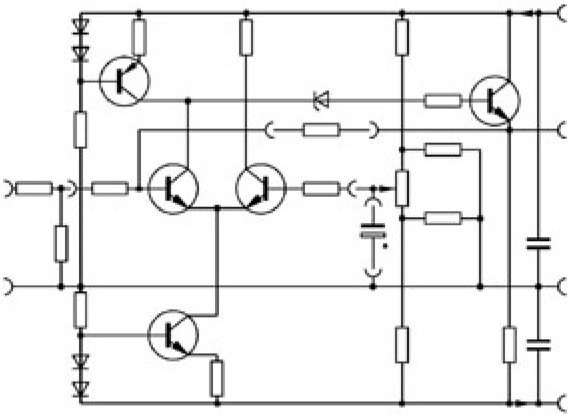
Principles

Today's electronic applications place great demands on amplifiers. Operational amplifiers are versatile building blocks of modern electronics. Usually they are treated as black boxes, pictured only by their schematic symbol.



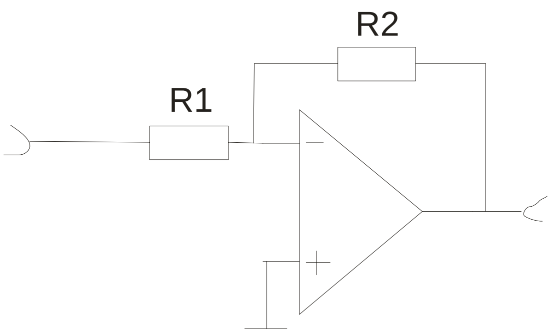
Depending on external circuitry, such an OpAmp can be used in a variety of ways, inverting amplifier, non-inverting amplifier, comparator, integrator and so on.

In this experiment, the internal operation of such an operational amplifier is investigated by assembling it from discrete elements in a transistor based circuit:

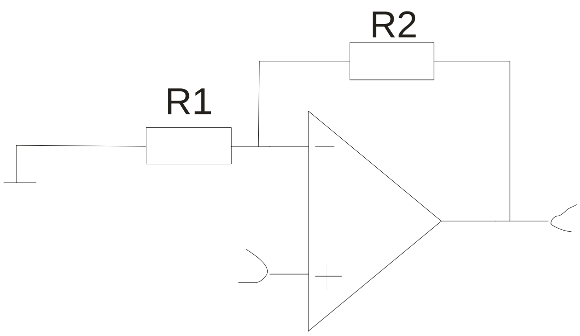


The key components of this circuit are a difference amplifier on the input side and a emitter follower stage on the output side. This operational amplifier is used in the experiment in two different configurations:

either as a inverting amplifier



or as a non-inverting amplifier



Both variants are build in this experiment. The gain and the phase relation of the output signals are determined with respect to input signals in inverting and non-inverting operation.

The OpAmp building block tries to approximate an ideal amplifier, having infinite gain. The gain of the whole amplifier built is then controlled by the resistors R1 and R2. For the inverting case the amplification is given by:

$$g = \frac{R2}{R1} \qquad \text{(I)}$$

For the non-inverting case the amplification is given by:

$$g = \frac{R2}{R1} + 1 \qquad \text{(II)}$$

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To derive the equations just assume the OpAmp block to be ideal, with any finite output voltage the difference voltage between the "+" and "-" input is close to zero and there is no current flowing in or out of the inputs. To build an amplifier with a well defined gain, the resistors R1 and R2 are added. R2 is called the feedback resistor, as it brings back the output signal to the input.

In the inverting amplifier, the ideal OpAmp will now set it's output voltage in such a way, that there is no current flowing into the inputs, and the '-' input is close to the '+' input, set to ground.

The following relation is valid:

$$U_{in}/R_1 = -U_{out}/R_2 \quad \text{or} \quad U_{out} = -U_{in} \times \frac{R_2}{R_1}$$

For the non-inverting amplifier, the '-' input is not at ground, but following the input voltage, so we get the equations

$$U_{in}/R_1 = (U_{out} - U_{in})/R_2 \quad \text{or} \quad U_{out} = U_{in} \times \left(\frac{R_2}{R_1} + 1\right)$$

Inside the OpAmp

The circuit of the setup is shown in Fig 1, R1 and R2 set the total gain as already discussed. The remainder is the Operational amplifier circuit, trying to have infinite gain.

The two transistors T1 and T2 form the heart of the circuit. This transistor configuration is called a difference amplifier. Both transistors are connected with their emitters, as long as both input voltages are the same, there will be an equal amount of current flowing through the collectors.

The transistors T3 and T4 together with the diodes act as a constant current source. T3 sinks a bit more current than T4 sources, so T3 sinks the sum of the currents passing through both transistors, T4 sources the current through T1, and T2 takes the remaining current. Any small variation of the input voltage difference will vary the current through T1's collector. This current difference will be translated to a voltage difference by the resistance connected to the collector. This is the current source T4, having (nearly) infinite resistance, so there is a large voltage amplification.

The transistor T5 operates as output amplifier. The potentiometer "set point" is used to adjust the offset of the circuit. Thus slight differences of the base-emitter voltages of the transistors T1 and T2 can be compensated.

The inputs In+ and In- of the operational amplifier are the bases of the transistors T1 and T2. Any voltage difference between them will be amplified. This voltage amplification will be controlled by two resistors R1 and R2. The amount of the amplification (i.e. gain) is fixed and given by g = R2/R1. For example, R1 = 1 kΩ and R2 = 100 kΩ will give a gain of 100.

Since it is hard to adjust the function generator to really low voltage levels a voltage divider is used before the resistor R1. This 1 kΩ/10 kΩ divider scales down the signal of the function generator by a factor of 10. This voltage U1 is measured at the first channel of the oscilloscope as input signal. The output signal UA is measured at the second channel of the oscilloscope.

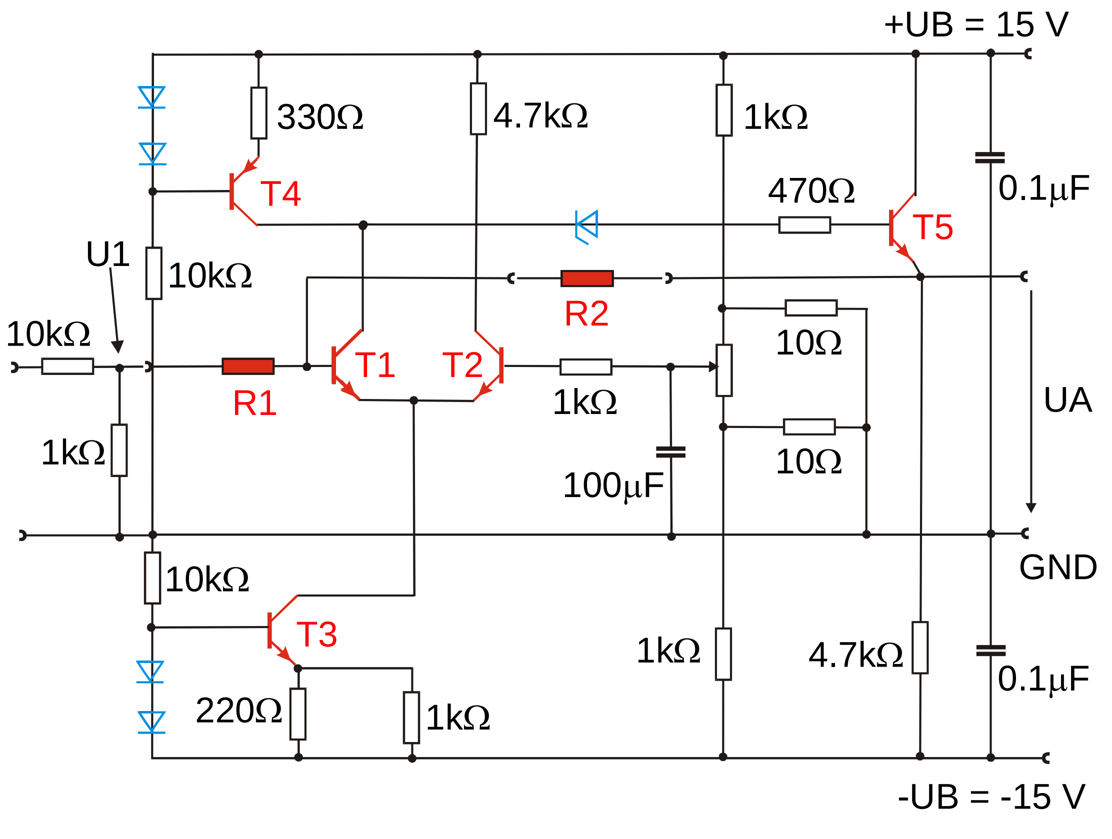

Fig. 1: Schematic representation

Apparatus

2 Rastered socket panel DIN 576 75
4 Resistor 10 kOhm, 0.5 W 577 07
1 Resistor 100 kOhm, 0.5 W 577 10
2 Resistor 10 Ohm, 2 W 577 20
1 Resistor 220 Ohm, 2 W 577 36
1 Resistor 330 Ohm, 2 W 577 38
1 Resistor 470 Ohm, 2 W 577 40
8 Resistor 1 kOhm, 2 W 577 44
2 Resistor 4.7 kOhm, 2 W 577 52
1 10-Turn potentiometer 1 kOhm 577 93
2 Capacitor 0.1 µF, 100 V 578 31
1 Capacitor 100 µF, bipolar, 35 V 578 39
4 Si Diode 1N 4007 .... 578 51
1 Diode ZPD 6.2 .... 578 55
3 Transistor BC 550, e.b., NPN 578 69
1 Transistor BC 550, e.t., NPN 578 71
1 Transistor BC 560, e.t., PNP 578 72
5 Set of 10 Bridging Plugs 501 48
1 Function generator S 12 .... 522 621
1 DC Power supply 0 to ±15 V.............................. 521 45
1 Two-Channel Oscilloscope 303 .... 575 211
2 Screened cable BNC/4 mm plug 575 24
5 Connecting Lead 25 cm Black 500 414
2 Connecting Lead 50 cm Black 500 424
1 Connecting Lead 100 cm Black 500 444
1 Pair cables 50 cm, red/blue 501 45
1 Pair cables 100 cm, red/blue 501 46

Additionally recommended:

1 Analog-Digital-TRMS Multimeter C.A 5011 ...... 531 181
1 Pair cables 50 cm, red/blue 501 45

Setup

The wiring diagram of the operational amplifier for the inverting operation is shown in Fig. 1 schematically. The corresponding experimental setup is shown in Fig. 2.

Both types of operational amplifiers can be set up. The changes to be made for the non-inverting case are shown in Fig. 3.

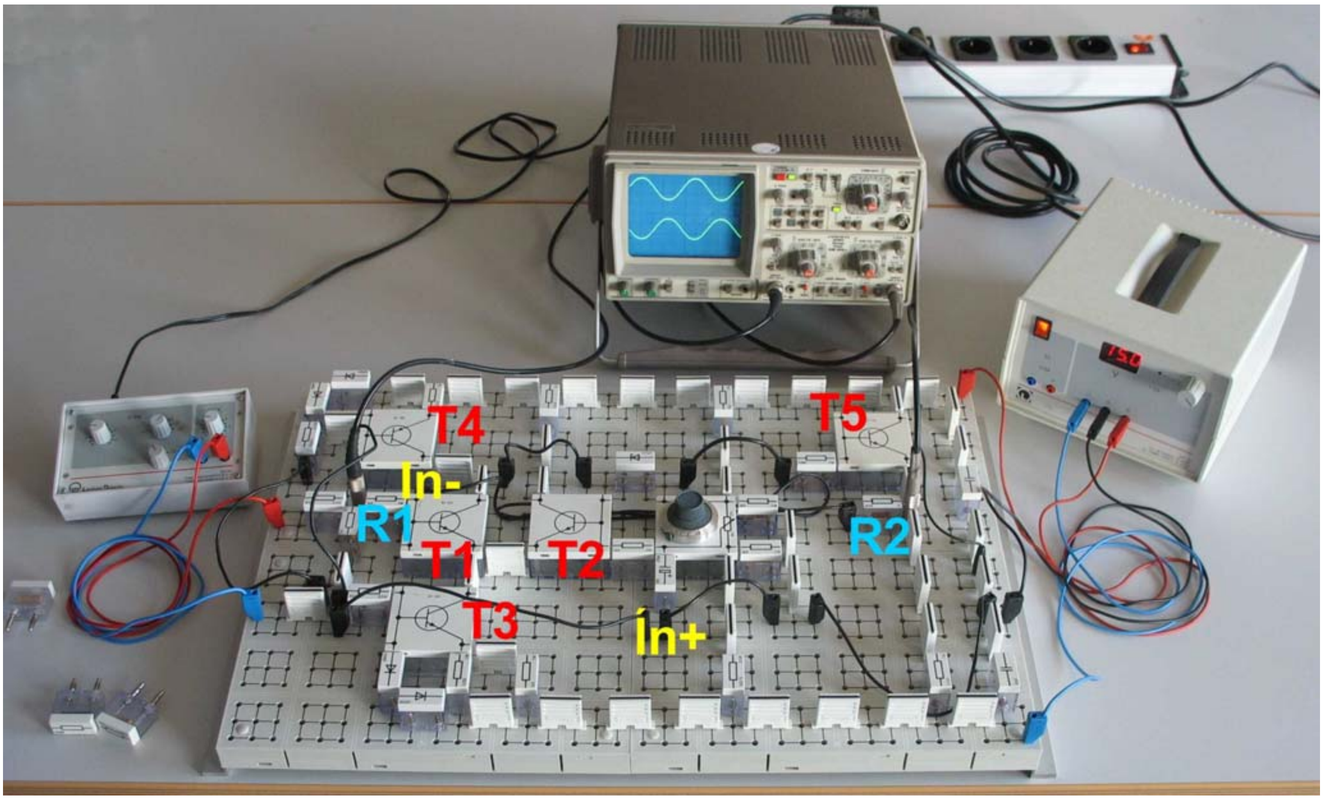

Fig. 2: Experimental setup of the operational amplifier for the inverting case (for wiring diagram see Fig. 1).

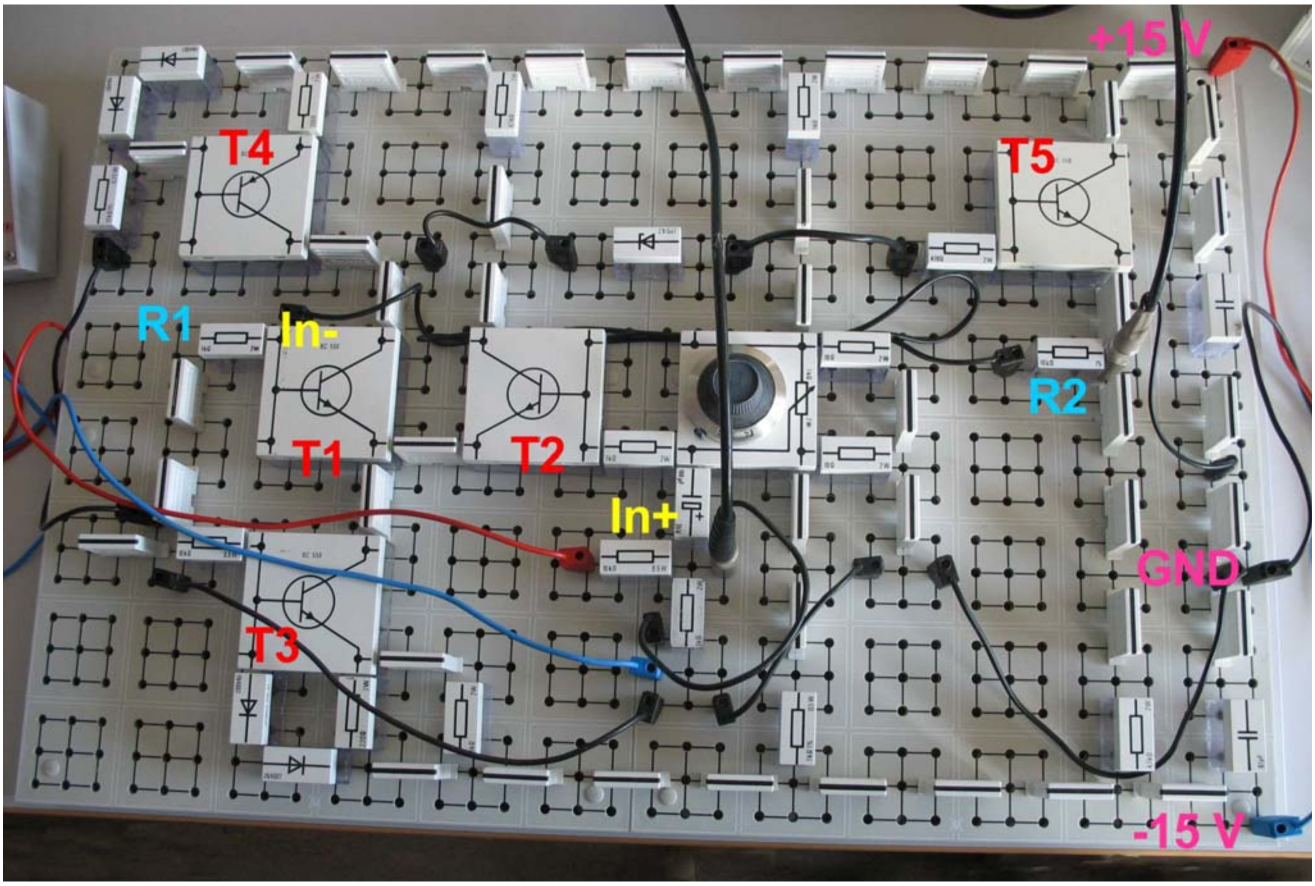

Fig. 3: Experimental setup of the operational amplifier for the non-inverting case (compare Fig. 2 for the setup of the inverting case).

Carrying out the experiment

Apply a voltage UB of +-15 V to the circuit as shown in Fig. 2. Set the of the function generator settings as: frequency approx. f ~ 1 kHz, wave form: sine signal, amplitude: ~1 V.

a) inverting operational amplifier

- Adjust the output voltage of the function generator, e.g. 20 mV.
- Measure the voltage U1 and UA for the resistor combination R1 = 1 kΩ and R2 = 100 kΩ (Fig. 4).
- Determine the amplification UA/U1.
- Repeat the measurement for the resistor combinations R1 = 1 kΩ and R2 = 10 kΩ and R1 = 1 kΩ and R2 = 1 kΩ.

b) non-inverting operational amplifier

- Change the operational amplifier circuit of the inverting setup to the non-inverting case as shown in Fig. 3.
- Measure the voltage U1 and UA for the resistor combination R1 = 1 kΩ and R2 = 100 kΩ (Fig. 5).
- Determine the amplification UA/U1.
- Repeat the measurement for the resistor combinations R1 = 1 kΩ and R2 = 10 kΩ and R1 = 1 kΩ and R2 = 1 kΩ..

Measuring example

a) inverting operational amplifier

Table 1: Measured input voltage U1, output voltage UA and amplification UA/U1 for different resistor combinations R1 and R2.

R1 / kΩ	R2 / kΩ	U1 / mV	UA / V	UA / U1
1	100	20	-2.00	-100
1	10	20	-0.20	-10
1	1	20	-0.02	-1

b) non-inverting operational amplifier

Table 2: Measured input voltage U1, output voltage UA and amplification UA/U1 for different resistor combinations R1 and R2.

R1 / kΩ	R2 / kΩ	U1 / mV	UA / V	UA / U1
1	100	20	2.01	100.5
1	10	20	0.22	11
1	1	20	0.04	2

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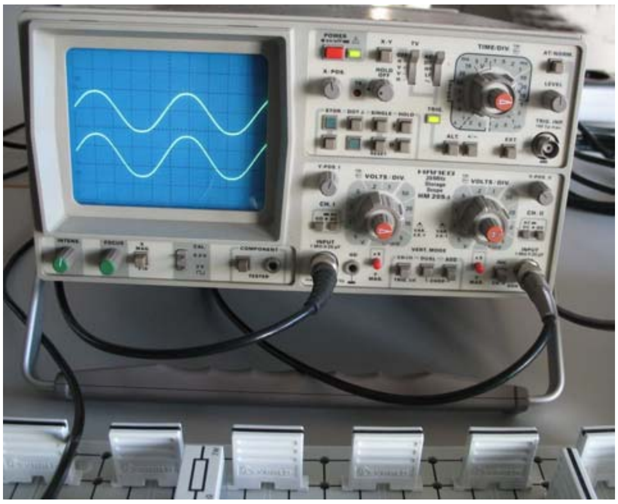
Fig. 4: Input signal (top of oscilloscope screen) and output signal (bottom top of oscilloscope screen) of the operational amplifier (inverting case).

Fig. 5: Input signal (top of oscilloscope screen) and output signal (bottom top of oscilloscope screen) of the operational amplifier (non inverting case).



Evaluation and results

Table 3 and table 4 compare the measured voltage amplification with the theoretical values according equation (I) or (II). Depending on the experimental setup of the operational amplifier (i.e. Fig. 2 or Fig. 3) the input signal is amplified according to the used resistor combination. As can be seen from Fig. 4 and Fig. 5 the input signal is either in-phase or inverted with the output signal both for the inverting and the non-inverting setup.

a) inverting operational amplifier

Table 3: Comparison of the gain according equation (I) and the measured amplification UA/U1 for various resistor combinations R1 and R2.

$\frac{R1}{k\Omega}$	$\frac{R2}{k\Omega}$	$\frac{R2}{R1}$	$\frac{UA}{U1}$
1	100	100	-100
1	10	10	-10
1	1	1	-1

b) non-inverting operational amplifier

Table 4: Comparison of the gain according equation (II) and the measured amplification UA/U1 for various resistor combinations R1 and R2.

$\frac{R1}{k\Omega}$	$\frac{R2}{k\Omega}$	$\frac{R2}{R1}+1$	$\frac{UA}{U1}$
1	100	101	100.5
1	10	11	11
1	1	2	2

Supplementary information

The amplification of an operational amplifier depends on the frequency f of the input signal. Fig. 6 shows the frequency dependency of the gain g (i.e. the amplification) as function of the frequency f for various resistor values R2. From this plot can be seen that the amplification does not show a significant frequency dependence for the frequency range of the function generator and the used resistors R2. Slowing down the amplifier could be done by adding an additional capacitor of 100 nF from the collector of T1 to ground, to show the gain dependence of the bandwidth, but this is beyond the scope of this leaflet.

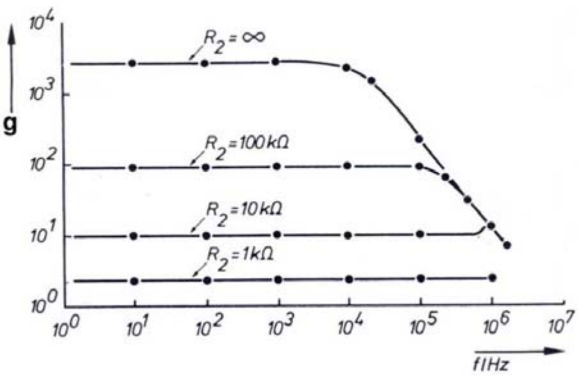


Fig. 6: Gain g (amplification) as function of the frequency f for various resistors R2.