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Operational Amplifier

Fortgeschrittenenpraktikum

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Abstract

The operational amplifier is an electronic component that has become indispensable in analog electronics due to its versatility. Even before and during the first digital computers, arithmetic operations could be carried out in an analogue manner by means of continuously executed operations. This made it possible to perform basic arithmetic operations as well as differentiation and integration with the help of machines.
Today, in addition to its basic functions such as amplification and calculation, the operational amplifier is also used for filters, controllers, stabilisation and signal converters. With a current-to-voltage converter, for example, tiny currents in the picoampère range can be converted into measurable voltages. Anyone who enjoys listening to or even making music will benefit from these components. The list of applications goes on and on.

Table of contents

1 Introduction to operational amplifiers

The building and measurement of circuits with operational amplifiers and other components should provide an insight into the world of analog electronics. In addition, the operation of an oscilloscope and a function generator will be taught. Please read the following pages of theory and tips on setting up the experiment before you start with the tasks.

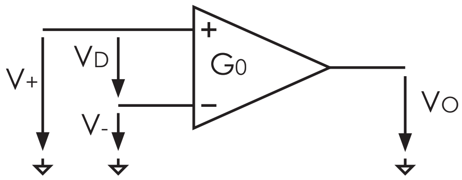
In the FP, the experiment lasts 2 afternoons and the following tasks have to be solved:

- Task 1 -> familiarise yourself with the devices, not in writing
- Task 2 or 3 -> (not both)
- Task 4 or 5 -> (not both)

2 Theoretical basics

2.1 Operational amplifier

The operational amplifier (opamp) is a very versatile electronic component which is used in analog circuit technology. It is able to apply certain mathematical operations to electrical signals - hence the name.

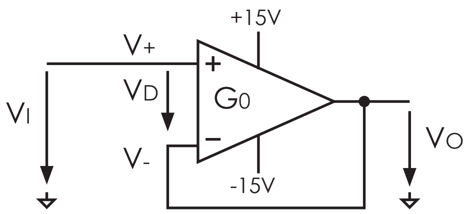


$\mathbf{V_O = V_D * G_0}$

$V_D = V_+ - V_-$ (Differential voltage)
G_0 = Open loop voltage gain
⏚ = Ground (Reference voltage 0V)

Figure 1: Ideal opamp

An ideal opamp amplifies the voltage difference between the two inputs to an infinite value and transmits the result to the output as a noise-free voltage without delay relative to earth (reference voltage = 0V). No current flows into the inputs and the output can deliver any amount of voltage and current.
For an opamp to be used sensibly, it must be wired with additional components. The feedback from the output to the inverting input plays an important role here.
The feedback is shown below on a real opamp with less than ideal properties. It also requires a power supply of typically ±15V.



$V_O = V_D * G_0$
$V_O = (V_I - V_O) * G_0$
$V_O = V_I / (1 + 1/G_0)$

$\mathbf{V_O = V_I}$ $\mathbf{V_D = 0V}$ (for $G_0 >> 1$)

Figure 2: real opamp with direct feedback

This is the simplest wiring of an opamp (voltage gain G=1).
With functioning feedback, the voltage difference between the two inputs is practically zero volts, as the open-circuit gain is very high (e.g. 10^6). This is very useful for understanding opamp circuits and making calculations.
There are some restrictions for a real opamp, which are recorded in a data sheet. There are different types depending on the application. The CA3140E is used for the following experiments (Google search: CA3140 datasheet pdf).

Further information and exercises in the book: Operational amplifiers by Joachim Federau in chapter 1+7.
We also recommend the Wikipedia page, where different designs and circuit examples are described in detail. The experiment deals with the normal voltage-amplifying opamp.
https://en.wikipedia.org/wiki/Operational_amplifier

2.2 Oscilloscope and function generator basics

The oscilloscope displays the progression of electrical voltages over time on a screen.

The older analog oscilloscopes (cathode ray oscilloscope, scope) work with a focused electron beam that is repeatedly guided from left to right across a phosphor screen and deflected vertically by the measurement voltage, leaving a luminescent image on the screen. They are only suitable for time-repeating signals, but have a very fast response and a step-free display.

Digital oscilloscopes digitise the measurement voltage with very fast AD converters and show the result on a video display. Compared to analog devices, they offer many more measurement options and the measurement data can be transferred to a computer. One-off signals can also be measured because the image is saved. Analog devices have now been superseded by digital devices.

The operation of the oscilloscopes is very similar for both types.

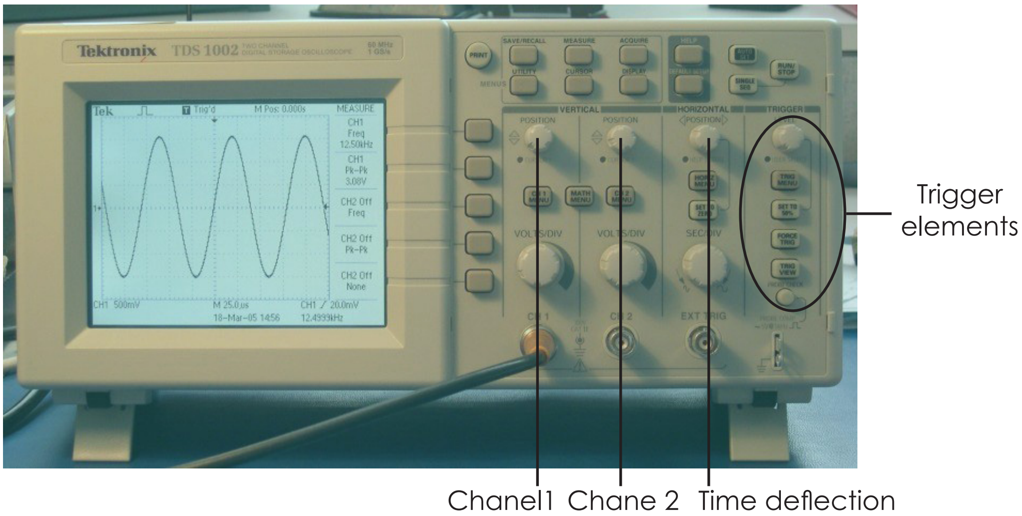


Figure 3: Digital oscilloscope main controls

Vertical elements:
Most oscilloscopes have 2 voltage inputs with sensitivity setting (volts/division), position and selectable input coupling (DC, AC, GND). With analog devices, you also have to select how the 2 channels are to be displayed simultaneously (alternating or chopper).

Horizontal elements:
The time deflection is common for both channels (time/division).
To ensure that a steady image appears on the screen, the repeating measurement signal must always be measured at the correct point of time using the so-called trigger. As a rule, the „Auto" mode, the selection of the edge direction and the level are sufficient for this. For difficult cases, other modes (normal, single), other coupling types or an external trigger signal can be selected.

Further information can be found at: https://en.wikipedia.org/wiki/Oscilloscope .

The function generator is an important device for testing electronic circuits. It provides simple periodic voltage functions at the output (waveforms: sine, triangle, square), which can be adjusted in frequency and amplitude. In addition, the output can usually be modulated in various ways (e.g. frequency sweep).
The function generator used here is analog and easy to operate.

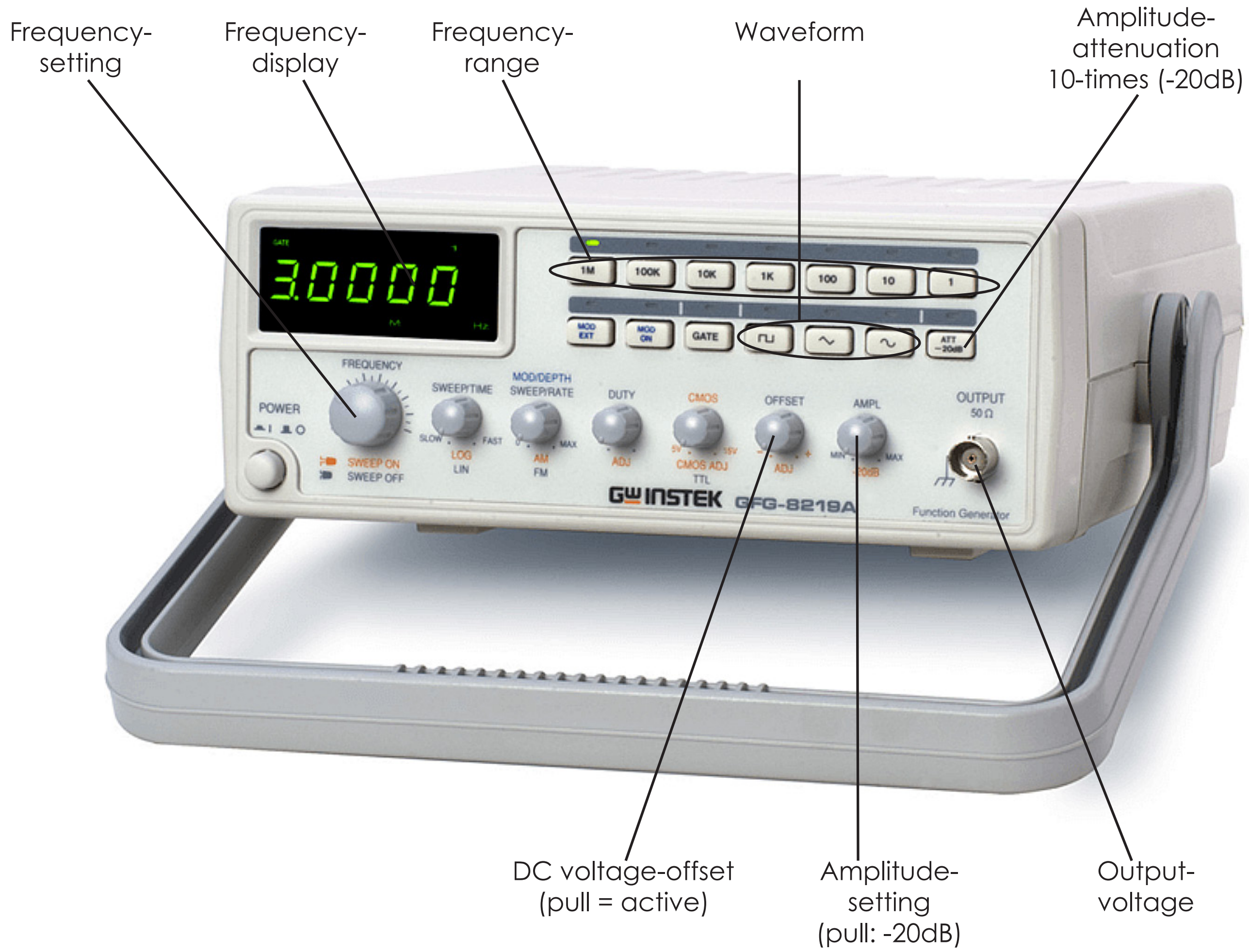


Figure 4: Function generator with important operating elements

Tip:
If very low amplitude values are to be set, the output signal can be attenuated by a factor of 10, i.e. by a total factor of 100, by pressing the „ATT -20 dB“ button and by pulling the amplitude setting button

2.3 Warnings

ATTENTION !

Voltages must always be measured against earth (0V) with the oscilloscope because all inputs on the device are earthed. Otherwise this can result in short circuits!

To remove an operational amplifier from the breadboard, use a small screwdriver and slide it sideways under the IC (integrated circuit) so that the connecting legs do not suddenly get stuck in your finger.

Please **never** attempt to measure the mains voltage with the measuring devices (multimeter, oscilloscope, etc.).

If you have any further questions, please do not hesitate to contact the assistant.

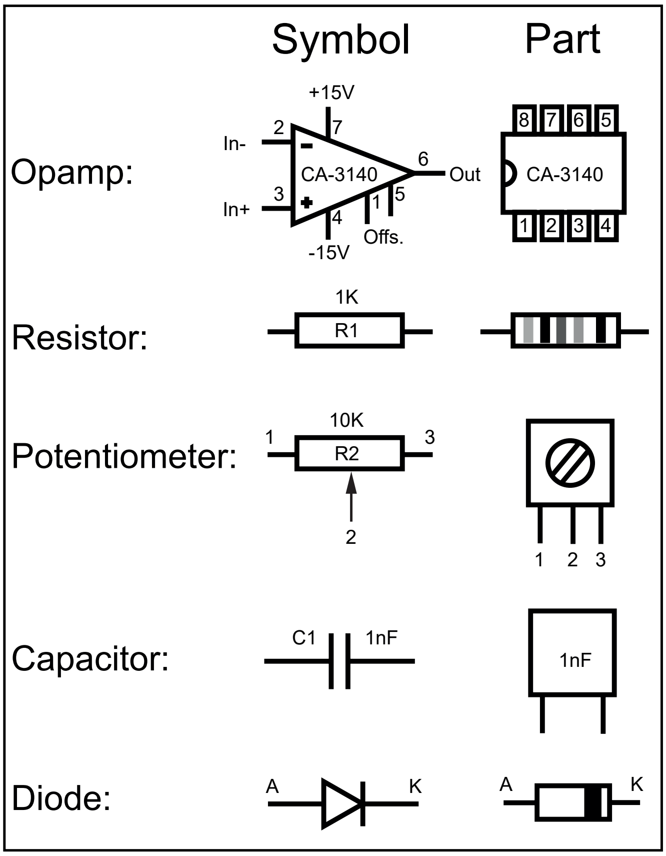
3 Experimental setup and material used

3.1 List of materials

Devices:	Computer:	To the right of the experiment
	Function generator:	GW instek GFG-8219A
	Power supply:	N1-13 Cool (or similar)
	Oscilloscope analog:	Hameg HM204-2 (Trigger is defective)
	Oszilloskop Digital:	Tektronix TDS1002
	Breadboard:	K&H SD-35 Solderless Breadboard
	Digital Voltmeter:	Voltcraft VC160 and yellow DVM (inkl. meas. cable)
	Toolbox:	1x grey plastic box
Cables:	in plastic box large:	2x BNC-BNC cable 1m
		2x BNC-wire connection 1m
		2x Banana-wire connection
		4x Banana cable 0.5m (sw, rt, gn, bl)
		1x RS232 cable (TDS1002)
Books:	in plastic box large:	Halbleiter-Schaltungstechnik, Tietze Schenk
		Operationsverstärker, Joachim Federau
		Operating instructions GW instek GFG-8219A
		Operating instructions Tektronix TDS1002
CD‘s:	in plastic box large:	CD1: Tektronix „Open Choice“
		CD2: Tietze Schenk
Small parts:	Box 1:	Resistors
		Trimming potentiometers: 10K
		Capacitors
	Box 2:	2x Screwdrivers (Trimpot)
		2x BNC T-adapters
		8x CA3140E opamps
		Diodes, LED‘s
		various connection wires

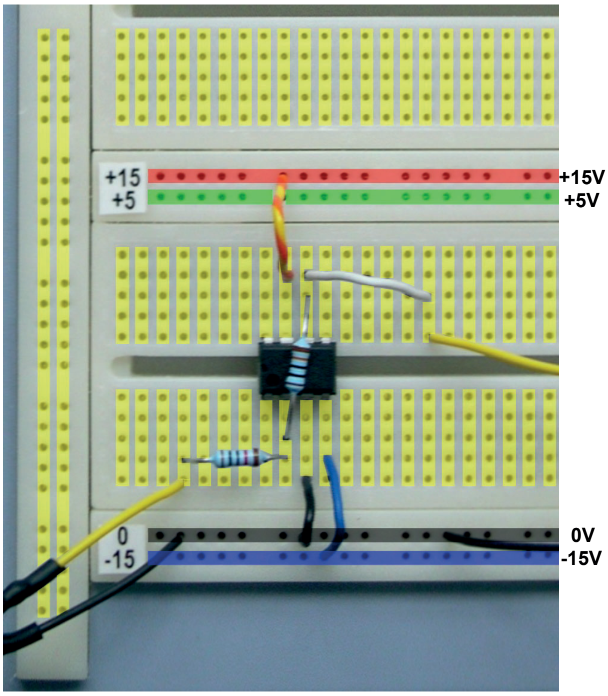
Please check the completeness of the material at the end of the experiment, thank you!

3.2 Help sheet for setting up the experiment

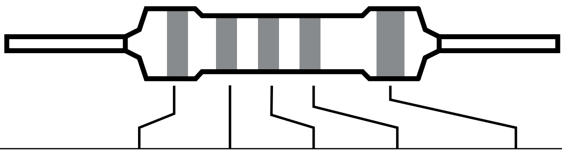


Breadboard (excerpt)

Internal connections marked in colour



Resistor-colour code



Colour		1.digit	2.digit	3.digit	Multi-plicator	Tolerance	(T. -Coeff.)
without						+/- 20%	
silver					10^{-2}	+/- 10%	
gold					10^{-1}	+/- 5%	
black		0	0	0	10^{0}		200ppm/K
brown		1	1	1	10^{1}	+/- 1%	100ppm/K
red		2	2	2	10^{2}	+/- 2%	50ppm/K
orange		3	3	3	10^{3}		15ppm/K
yellow		4	4	4	10^{4}		25ppm/K
green		5	5	5	10^{5}	+/- 0.5%	
blue		6	6	6	10^{6}	+/- 0.25%	10ppm/K
violet		7	7	7	10^{7}	+/- 0.1%	5ppm/K
grey		8	8	8	10^{8}	+/- 0.05%	
white		9	9	9	10^{9}		

Resistance series - standard values

E 6	E 12
100	100
	120
150	150
	180
220	220
	270

E 6	E 12
330	330
	390
470	470
	560
680	680
	820

Values are to be expressed with integer pos. or neg. powers of 10.

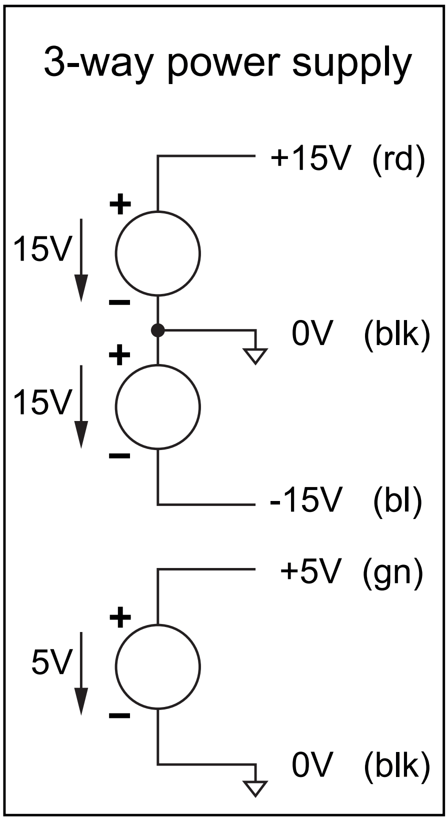


Figure 5: Information on components, breadboard and power supply

3.3 Help for setting up the experiment

Figure 5 provides the necessary information for setting up the electronic circuits
(tasks 2 to 5).

The symbolic representation of an electronic diagram must be converted into wiring with real components. Although a diagram helps to understand the function of the circuit, it is only of indirect use when building the circuit. For the wiring, the assignment of the connections (numbers, designation) from the symbol to the component is important, which can be taken from the table at the top left. The coloured backgrounds on the plug-in board on the right show how its connections are connected internally.

The colour code of the resistance values can be seen at the bottom left. To read the resistor value, the wider colour ring must be on the right (or at a greater distance from the other colour rings).
Example - brown, grey, black, red, wide ring brown corresponds to
1 8 0 * 10^2 = 18 kOhm (tolerance ±1%)
Tip: The multimeter also measures resistance values.

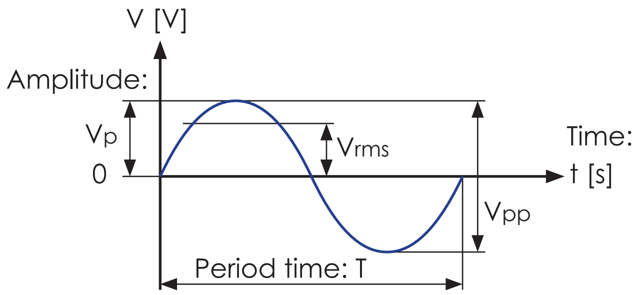
The schematic structure of the ±15V supply is shown below right. The power supply unit must be connected to the corresponding sockets on the breadboard using the banana cables. The +5V voltage source is not used in these experiments.

Important: Only switch on the power supply unit at the rear left after setting up and checking the circuit. If the circuit malfunctions, the voltage values of the ±15V supply should also be checked against 0V with the multimeter after a visual inspection of the circuit.

4. Tasks

4.1 Task 1 -> Function generator and oscilloscope

Connect the output of the function generator to channel 1 of the digital oscilloscope using a BNC cable. The analog oscilloscope is only used for size comparison because the trigger is broken. The purpose of this experiment is to familiarise yourself with the devices. Please play with the possibilities of the devices. **Task 1 should not be recorded.**



Definitions:

f = 1/T
Vpp = 2 * Vp(eak)
Vrms = Vp/Root(2) (at sinewave)

The RMS value generates the same power in a resistive load as the DC value.

Figure 6: Important parameters of a sine wave without offset voltage

a) Set the generator to the maximum amplitude (1kHz square wave) and try to obtain a stationary image (trigger).
Important trigger settings: Source (**Ch1**...), Coupling (**DC**, AC...), Mode (**Auto**/Normal), Level (turn), Edge (rising or falling).
The trigger time on the screen can be set on the digital device (arrow), but normally remains in the centre (before and after history visible).

Measure the amplitude and the period duration. Please note the „V/Division" (sample factor = x1) or the „Time/Division" settings.
Tip: the digital device has automatic measurements in the „Measure" menu or cursor measurements in the „Cursor" menu, which make measurements easier. Data can be saved and transferred to the computer via RS232.
(Programme: Tektronix „Open Choice Desktop" V1.1).
Simpler alternative: Take a screenshot with your mobile phone camera.

b) Generate a 50kHz sine wave with an AC amplitude of 100mVpp and a DC offset voltage of +1V. Sketch the curve above the zero line.
Tip: with input coupling „AC" you can only see the AC component.

c) Try to set the generator to the smallest possible amplitude (approx. 14mVpp).
f=1kHz / sine wave. (**Tip:** -20dB corresponds to attenuation by 10)
Which oscilloscope provides a cleaner image?
Limit the bandwidth of the digital scope in the „Ch1 menu" to 20MHz.
Play with the „Average function" in the „Aquire" menu of the digital scope.
Change the waveform when the average is switched on. What do you notice?

d) Measure simultaneously on the oscilloscope with 2 channels. There is also a square wave output (TTL-Out) on the rear of the generator.

4.2 Task 2 -> Non-inverting amplifier

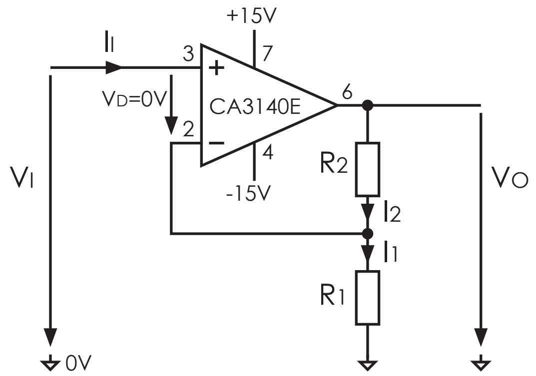


Figure 7: Non-inverting amplifier

a) Derive the formula for the output voltage V_O as a function of V_I, R_1 and R_2.
Tip: V_D=0V; I_I=0 What is the voltage across R_1?

b) What is the minimum voltage amplification G_{MIN} of the circuit? ($G=V_O/V_I$)
Which resistors would you choose for this gain?

c) Dimension the resistors R_1 and R_2 for a gain of **10 (G = Gain)**.
Available resistors: 1k 2k 10k 15k 18k 20k 30k 39k 68k 100k 200k 1M.
Tip: I_2 should not be greater than ±1mA (at V_{Omax} = ±10V).

d) Set up the circuit with **G=10** on the breadboard and connect the input to 0V with a wire. Switch on the power supply and measure and record the voltage V_O with the voltmeter.
Why is the output voltage not exactly zero volts?
Install a 10k potentiometer (as shown in Figure 8 on next page) and try to set V_O to 0V with the screwdriver. Make a note of the value.

e) Set the function generator to „10mVp / f=1kHz / sine“ and connect it to the input of the circuit. Measure the input and output simultaneously with the oscilloscope.
Is the amplification correct?
Measure the frequency response (V_O [dB] as a function of f [1kHz to 1MHz]) and plot the curve for **G=10** in the logarithmic sheet (f: 1, 2, 5, 10... suffices).
Tip: V_O[dB] = 20*log(V_O/V_I) 0dB corresponds to G=1, **20dB; G=10**, -40dB; G=0.01 etc.
Incidentally, the digital oscilloscope has an amplitude measurement (Measure)

f) What is the bandwidth of the circuit? The bandwidth is the frequency at which the amplitude falls to a factor of 1/root(2) compared to the desired amplitude (sine).
Draw the frequency response from task e) in the diagram from the CA3140 data sheet extract on page 16.
Can you see the relationship between the amplification and the bandwidth?

g) Determine the „slew rate“ (max. rate of rise of the output) in [V/us] at G=10.
Tip: Select V_I=400mVp, square wave voltage

4.3 Task 3 -> Inverting amplifier

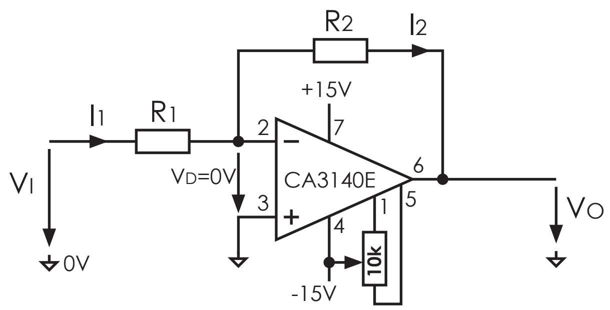


Figure 8: Inverting amplifier (with offset adjustment)

a) Derive the formula for the output voltage V_O as a function of V_I, R_1 and R_2.
Tip: V_D=0V; What is the voltage across R_1? Where does I_1 flow to?

b) What is the minimum voltage amplification G_{MIN} of the circuit? ($G=V_O/V_I$)
Which resistors would you choose for this gain? Does this make sense?

c) Dimension the resistors R_1 and R_2 for a gain of **10 (G = Gain)**.
Available resistors: 1k 2k 10k 15k 18k 20k 30k 39k 68k 100k 200k 1M.
Tip: I1 should not be greater than 1mA (VI_{max} = ±10V).

d) Build the circuit **G=10** on the breadboard (without the 10k potentiometer).
After connecting the power supply, V_O should be approximately 0V (input open).
Measure with the voltmeter and note the output voltage V_O, both with the input open and with the input grounded to 0V.
What do you notice? What could be the cause?
Now install the 10k potentiometer and try to set V_O to 0V with the screwdriver (with **G=10**, input earthed to 0V). Make a note of the value.

e) Set the function generator to „10mVp / f=1kHz / sine“ and connect it to the input of the circuit. Measure the input and output simultaneously with the ostilloscope.
Is the amplification correct?
Measure the frequency response (V_O [dB] as a function of f [1kHz to 1MHz]) and enter the curves for **G=10** in the logarithmic sheet (f: 1, 2, 5, 10... suffices).
Tip: U_A[dB] = 20*log(V_O/V_I) 0dB corresponds to G=1, **20dB; G=10**, -40dB; G=0.01 etc.
Incidentally, the digital oscilloscope has an amplitude measurement (Measure)

f) What is the bandwidth of the circuit at G=10? The bandwidth is the frequency at which the amplitude falls to a factor of 1/root(2) compared to the desired amplitude (sine). Draw the frequency responses from task e) in the diagram from the CA3140 data sheet extract on page 16. Can you see the relationship between the amplification and the bandwidth?

g) Determine the „slew rate“ (max. rate of rise of the output) in [V/us] at G=10.
Tip: Select V_I=400mVp, square wave voltage

4.4 Task 4 -> Precision rectifier

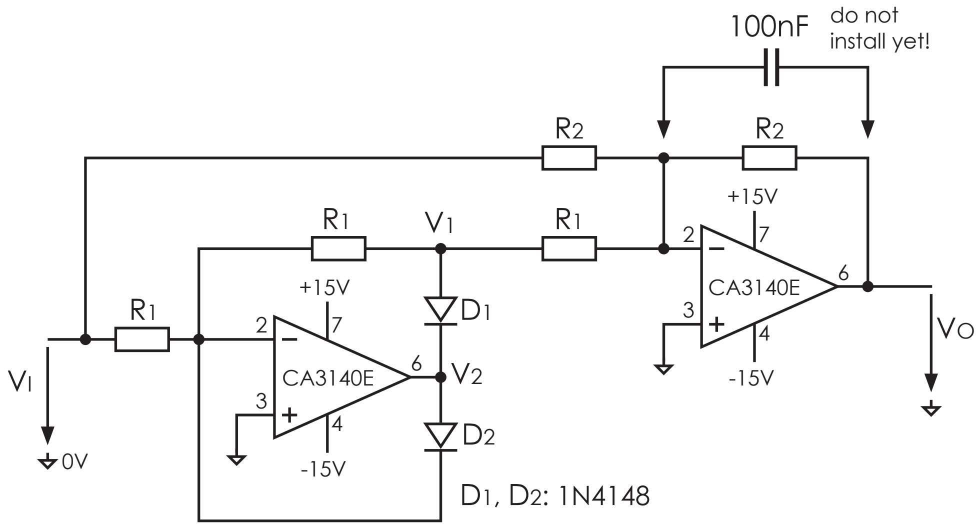


Figure 9: Precision rectifier

a) Set up the precision rectifier and apply a sine wave voltage of approx. 5 volts to the input using the function generator. (R_1=10K, R_2=20K)

b) Use the oscilloscope to measure V_I, V_1, V_2 and V_O at f=1kHz and plot them as a function of time (DC offset must be equalised on the function generator beforehand). What function does the left opamp on V_1 and the right opamp on V_O fulfil?

c) Repeat measurement b) and plot them as a function of time, but at f=100kHz. What could be responsible for the signal degradation?

d) Connect a capacitance of 100nF in parallel to the feedback resistor R_2 of the output amplifier and play with the frequency setting.
What do you find?
Calculate the arithmetic mean value of a rectified sine wave and compare it with the output voltage.

e) What happens if you reverse the polarity of the two diodes D_1 and D_2?

f) Can you build a precision rectifier with just one opamp, one diode and 2 resistors?
Tip: Measure V_1 without D_2 and the resistor R_1 that goes to the minus input of the right opamp.
- Draw the simplified circuit.
- How can the polarity of the output be changed?
- Name two disadvantages of the simplified circuit.

4.5 Task 5 -> Oscillator

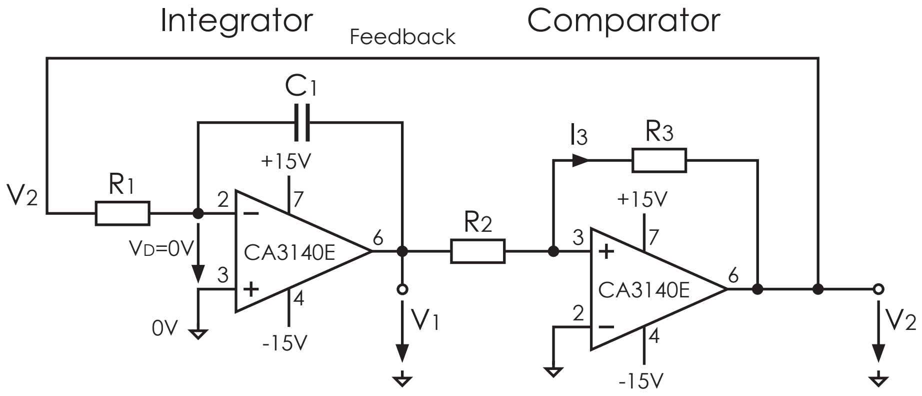


Figure 10: Oscillator

a) The opamp on the right is connected as a comparator; recognisable by the positive feedback. If there is a slightly more positive voltage at the + input than at the - input, the output goes to the positive limit (just under +15V) due to the high open-circuit gain and pulls the + input even more strongly into the positive range via R_3. If the voltage is negative, everything is the other way round.
Dimension R_2 and R_3 of the comparator so that it only switches the output at V_1 of about +/-10V (hysteresis).

b) **Only** set up the comparator and test the switching points with the function generator (use sine or triangular voltage with DC offset).
Why are the amounts of the two switching points unequal? How can you compensate for this by installing a red light-emitting diode (V_{Diode}=1.6V, long leg = anode)?

c) The opamp on the left is connected as an inverting integrator. Consider which curve the output voltage V_1 takes with a constant voltage V_2 of +15V or -15V?
Tip: This applies to the capacitor: $Q = C^* \Delta Vc = Ic^* \Delta t$ (C and Ic must be constant)
More precisely: Vc = (1/C)*Integral(Ic*dt) (initial charge zero volts)

d) Set up the integrator **alone** - place it to the left of the comparator with C_1=1nF and R_1=10kOhm. Test it with the function generator (square wave voltage at the input). Does it integrate? **Tip:** If you briefly bridge C_1 with a wire, the integration starts at zero.

e) Consider how the overall circuit of the oscillator works. Sketch V_1 and V_2 as a function of t (time). What is the amplitude of V_1 and V_2?
Dimension R_1 so that the oscillator oscillates at 10kHz (C_1=1nF).
Tip: Use one of the formula from c) for a time interval while V_2 is constant.

f) Now connect the complete circuit together as shown above. Measure and sketch V_1 and V_2 as a function of time. Do the curves agree with d)? Are the frequency and amplitude of V_1 also correct?

g) Halve the value of R_2. What effect does this have on the amplitude and frequency of V_1?
Which other component must you change and how, so that the frequency returns to 10kHz without changing the amplitude?

6. Appendix: Record sheets for tasks 2 and 3

On this page the frequency response of the non-feedback CA3140 is copied from the data sheet. The frequency axis has been added. It shows the relationship between the maximum bandwidth of an amplifier circuit and the gain.

On the next page there is a double logarithmic recording sheet in which the frequency response of tasks 2 and 3 can be plotted.

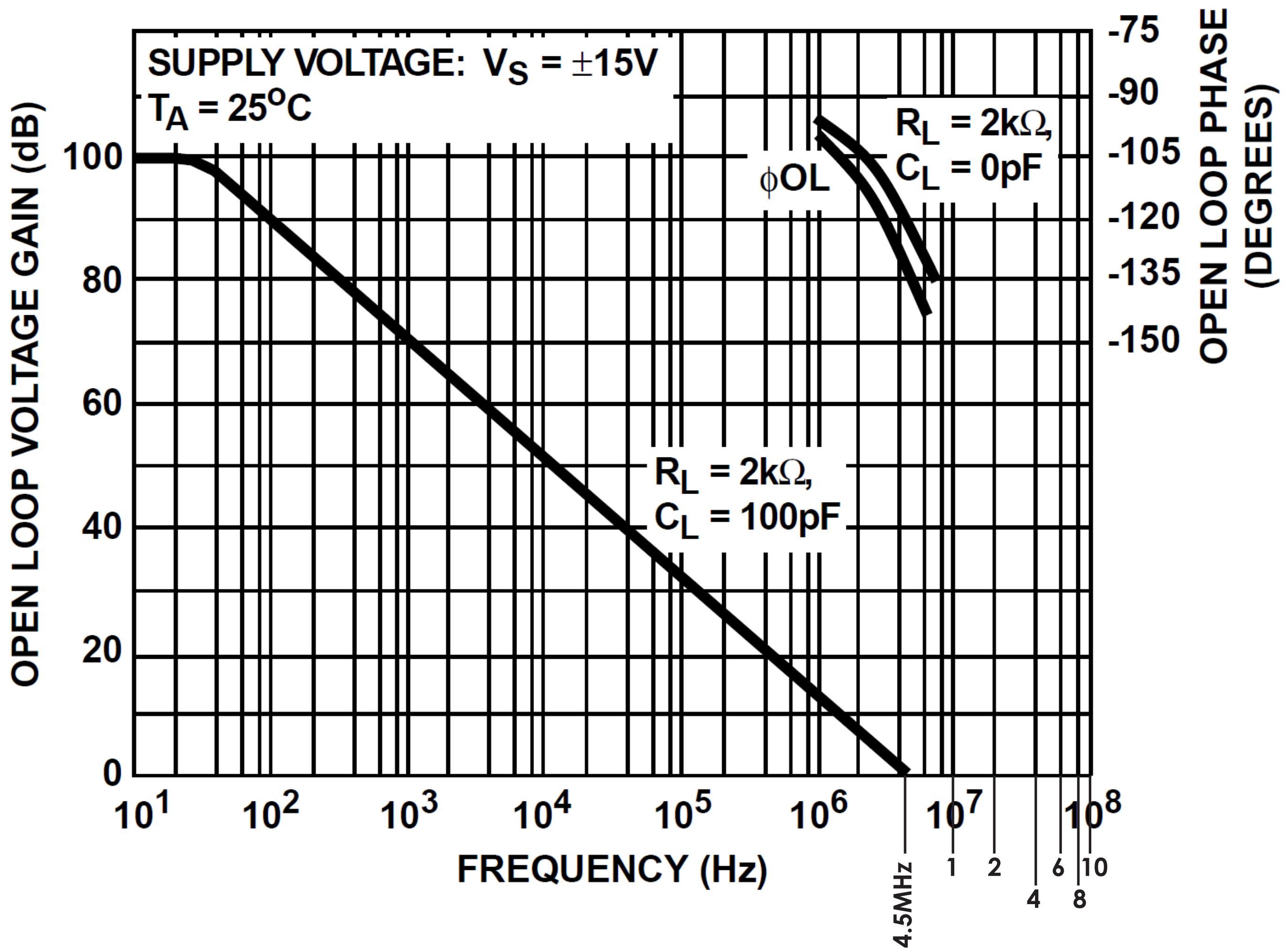


FIGURE 6. OPEN LOOP VOLTAGE GAIN AND PHASE vs FREQUENCY

Figure 11: Frequency response CA3140 „open loop“ (for tasks 2+3)

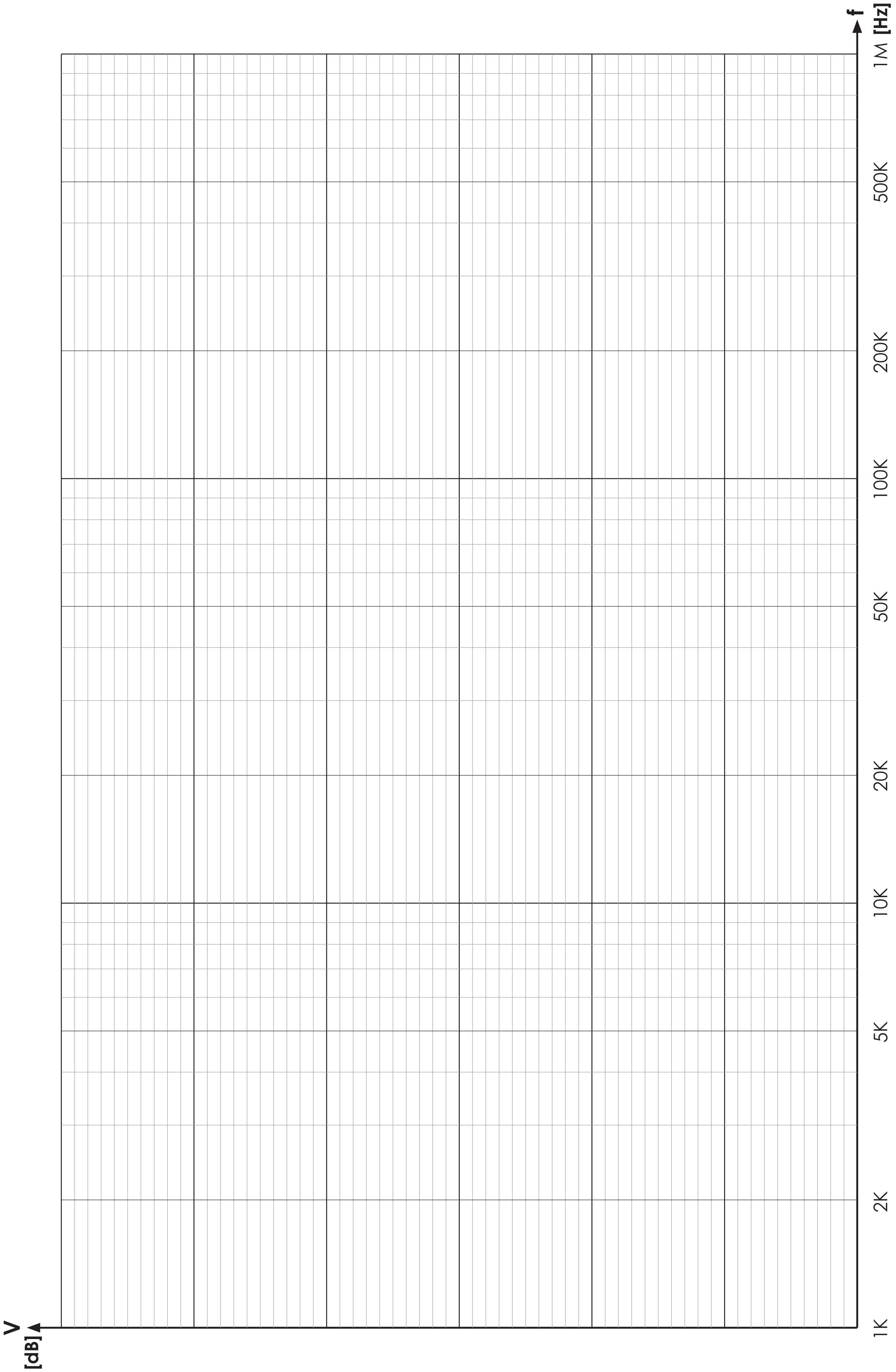


Figure 12: Double logarithmic recording sheet (for tasks 2+3)

5 Appendix / Contact

If you have any further questions about the experiment or other sources on the theory, please contact the assistant:

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