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Fortgeschrittenenpraktikum I/II

Operational Amplifier

October 23, 2026

Experiment Overview

The operational amplifier is an electronic component that has become indispensable in analogue electronics because of its versatility. Before and during the era of the first digital computers, arithmetic operations were already carried out in an analogue way with operational amplifiers: addition, subtraction, multiplication by a constant, differentiation and integration of continuously varying signals.

Today, besides amplification and analogue computation, operational amplifiers are used in filters, controllers, voltage stabilisers and signal converters. A current-to-voltage converter, for example, turns currents in the picoampere range into easily measurable voltages. Anyone who enjoys listening to or making music benefits from these components every day.

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Contents

1	Introduction	2
2	Theoretical background	2
2.1	Operational amplifier	2
2.2	Quantities used in the tasks	3
2.3	Oscilloscope and function generator	4
2.4	Safety and handling	6
3	Experimental setup and material	6
3.1	List of materials	6
3.2	Help sheet	8
3.3	Building the circuits	9
4	Tasks	9
4.1	Task 1: Function generator and oscilloscope	9
4.2	Task 2: Non-inverting amplifier	11
4.3	Task 3: Inverting amplifier	12
4.4	Task 4: Precision rectifier	13
4.5	Task 5: Oscillator	14
5	Contact	15
6	Appendix: Data sheet extract and record sheet for Tasks 2 and 3	16

1 Introduction

Building and characterising circuits with operational amplifiers and other components gives an insight into the world of analogue electronics. Along the way you will learn to operate an oscilloscope and a function generator. Please read the theory and the hints on setting up the circuits (Sections 2 and 3) before you start with the tasks.

The experiment takes two afternoons. The following tasks have to be carried out:

- Task 1: getting to know the instruments (not part of the report),
- Task 2 *or* Task 3 (not both),
- Task 4 *or* Task 5 (not both).

2 Theoretical background

2.1 Operational amplifier

The operational amplifier (op-amp) is a very versatile component of analogue circuit technology. Suitably wired, it performs mathematical operations on electrical signals (addition, subtraction, integration, ...) – hence its name.

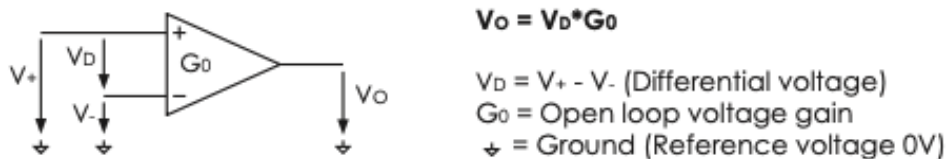


Figure 1: Circuit symbol of an ideal op-amp.

The output voltage of an op-amp is proportional to the voltage difference between its two inputs:

$$V_O = G_0 V_D, \quad (1)$$
$$V_D = V_+ - V_- \quad (\text{differential input voltage}),$$

where G_0 is the *open-loop voltage gain* and all voltages are measured with respect to ground (0 V). An *ideal* op-amp has

- an infinite open-loop gain G_0 ,
- infinite input impedance, i.e. no current flows into the inputs,
- zero output impedance, i.e. the output voltage does not depend on the load,
- infinite bandwidth and no noise.

On its own, an op-amp with such a high gain is of little use: the smallest voltage difference at the inputs drives the output to one of its limits. It becomes useful only together with external components that feed part of the output signal back to the *inverting* input (negative feedback).

A real op-amp deviates from the ideal properties; its limits are specified in the data sheet. It also needs a supply voltage, here $\pm 15\text{ V}$. The simplest feedback circuit connects the output directly to the inverting input (Figure 2):

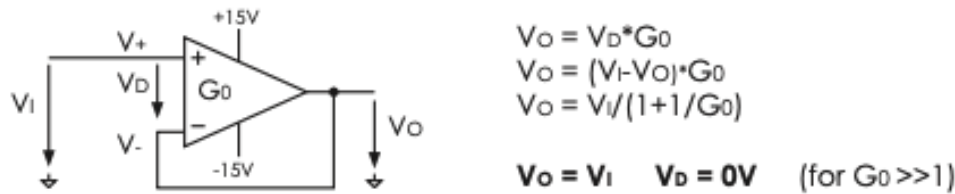


Figure 2: Real op-amp with direct feedback (voltage follower, $G = 1$).

With $V_- = V_O$ and $V_+ = V_I$, Eq. (1) gives

$$V_O = \frac{V_I}{1 + 1/G_0} \approx V_I \quad \text{and} \quad V_D = \frac{V_O}{G_0} \approx 0 \quad (G_0 \gg 1). \quad (2)$$

The CA3140 used here has a low-frequency open-loop gain of about 100 dB, i.e. $G_0 \approx 10^5$ (Figure 11). As long as the feedback works and the output is not saturated, the voltage difference between the two inputs is therefore practically zero. Together with the vanishing input currents, this rule ($V_D \approx 0$, $I_+ = I_- \approx 0$) is the key to analysing all op-amp circuits in this experiment.

Several types of op-amps exist for different applications. In this experiment the CA3140E (MOSFET inputs, bipolar output stage) is used. Its data sheet is available from the manufacturer (Renesas, formerly Intersil); search for “CA3140 datasheet”.

Further reading

- J. Federau, *Operationsverstärker – Lehr- und Arbeitsbuch zu angewandten Grundsaltungen*, Springer Vieweg, Chapters 1 and 7 (in German; copy in the lab box).
- U. Tietze, Ch. Schenk, E. Gamm, *Halbleiter-Schaltungstechnik*, Springer Vieweg (in German; copy in the lab box). English edition: U. Tietze, Ch. Schenk, *Electronic Circuits – Handbook for Design and Application*, 2nd ed., Springer, 2008.
- P. Horowitz, W. Hill, *The Art of Electronics*, 3rd ed., Cambridge University Press, 2015, Chapter 4.
- Wikipedia, *Operational amplifier*: https://en.wikipedia.org/wiki/Operational_amplifier. This experiment deals with the ordinary voltage-feedback op-amp.

2.2 Quantities used in the tasks

- **Voltage gain:** $G = V_O/V_I$, the ratio of output to input amplitude.
- **Gain in decibels:** $G_{\text{dB}} = 20 \log_{10}(V_O/V_I)$. Thus 0 dB corresponds to $G = 1$, 20 dB to $G = 10$, 40 dB to $G = 100$ and -40 dB to $G = 0.01$.

- **Bandwidth:** the frequency f_c at which the output amplitude of a sine signal has dropped to $1/\sqrt{2}$ of its low-frequency value, i.e. by 3 dB.
- **Slew rate:** the maximum rate of change of the output voltage, $SR = |dV_O/dt|_{\max}$, usually given in V/ μ s.
- **Amplitudes of a sine wave:** peak value V_p , peak-to-peak value $V_{pp} = 2V_p$ and root-mean-square value $V_{rms} = V_p/\sqrt{2}$ (Figure 6). In this manual, V_p and V_{pp} denote peak and peak-to-peak values.

2.3 Oscilloscope and function generator

An oscilloscope displays the time dependence of electrical voltages.

Analogue oscilloscopes (cathode-ray oscilloscopes) use a focused electron beam that is swept repeatedly from left to right across a phosphor screen and deflected vertically in proportion to the measured voltage. They are only suitable for repetitive signals, but they respond very fast and give a continuous (not sampled) display.

Digital oscilloscopes digitise the input voltage with very fast analogue-to-digital converters and show the result on a display. They offer many more measurement functions, the data can be transferred to a computer, and single (non-repetitive) events can be captured because the trace is stored. Digital instruments have largely replaced analogue ones. Both types are operated in a very similar way.

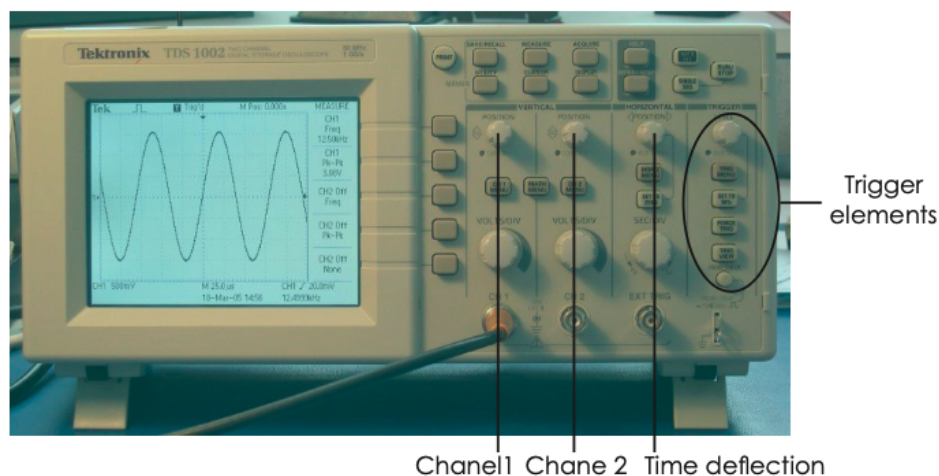


Figure 3: Main controls of the digital oscilloscope.

Vertical controls: Most oscilloscopes have two input channels, each with a sensitivity setting (volts per division), a vertical position control and a selectable input coupling (DC, AC, GND). With DC coupling the full signal is displayed; with AC coupling the DC component is blocked by a capacitor. On analogue instruments you also have to select how the two channels are displayed simultaneously (alternate or chopped).

Horizontal controls: The time base (time per division) is common to both channels.

Trigger: To obtain a stable image of a repetitive signal, each sweep must start at the same point of the signal. This is achieved by the trigger. In most cases the “Auto” mode together with the choice of the trigger source, the slope (rising or falling edge) and the trigger level is sufficient. For difficult signals, other modes (Normal, Single), other trigger couplings or an external trigger signal can be used.

Further information: <https://en.wikipedia.org/wiki/Oscilloscope>

The **function generator** is an essential instrument for testing electronic circuits. It provides periodic voltages (sine, triangle, square) with adjustable frequency, amplitude and DC offset. In addition, the output can usually be modulated (e.g. frequency sweep). The analogue function generator used here is easy to operate (Figure 4). Its output impedance is $50\ \Omega$.

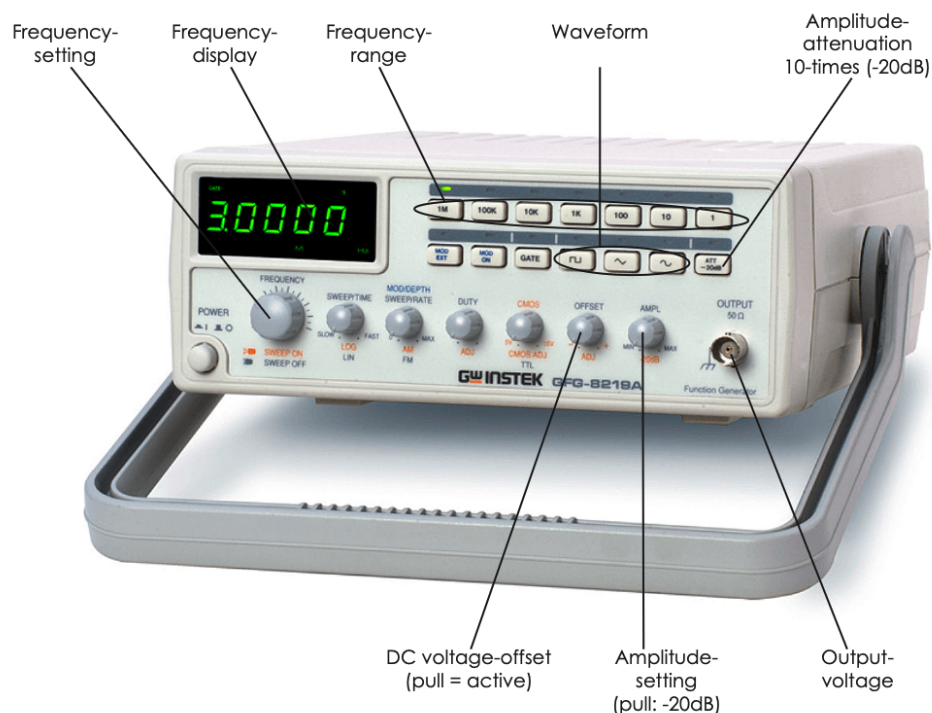


Figure 4: Function generator with its most important controls.

Tip: For very small amplitudes, press the “ATT –20 dB” button (attenuation by a factor of 10) and, in addition, pull the amplitude knob (another factor of 10). The total attenuation is then a factor of 100 (–40 dB).

2.4 Safety and handling

ATTENTION!

- The ground (outer conductor) of every oscilloscope input is connected to protective earth. Always connect the ground lead of a measuring cable to the circuit ground (0 V) only. Connecting it to any other point of the circuit causes a short circuit.
- **Never** try to measure the mains voltage with any of the instruments (multimeter, oscilloscope, ...).
- Build or modify a circuit only while the power supply is switched off.

To remove an op-amp from the breadboard, slide a small screwdriver under the IC (integrated circuit) from the side and lever it out gently. Pulling it out with your fingers bends the pins, and the IC can suddenly come loose so that the pins stick into your finger.

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

3 Experimental setup and material

3.1 List of materials

Instruments:

- Computer: to the right of the experiment
- Function generator: GW Instek GFG-8219A
- Power supply: N1-13 Cool (or similar)
- Analogue oscilloscope: Hameg HM204-2 (trigger is defective)
- Digital oscilloscope: Tektronix TDS1002
- Breadboard: K&H SD-35 solderless breadboard
- Digital multimeters: Voltcraft VC160 and yellow DVM (incl. measuring leads)
- Toolbox: 1 grey plastic box

Cables (in the large plastic box):

- 2 BNC–BNC cables, 1 m
- 2 BNC–wire cables, 1 m
- 2 banana–wire cables
- 4 banana cables, 0.5 m (black, red, green, blue; labelled sw, rt, gn, bl on the help sheet)
- 1 RS232 cable (for the TDS1002)

Books and manuals (in the large plastic box):

- U. Tietze, Ch. Schenk, *Halbleiter-Schaltungstechnik*

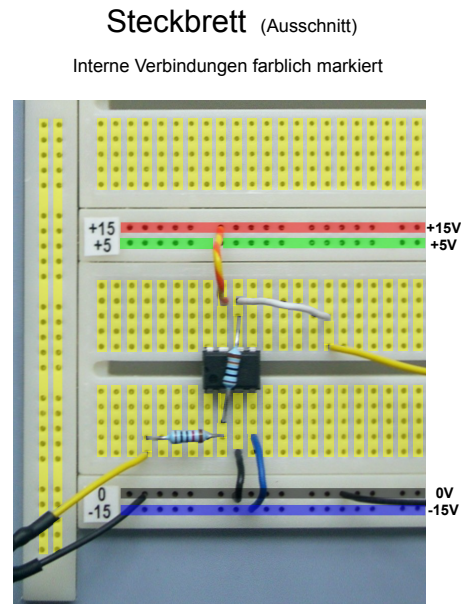
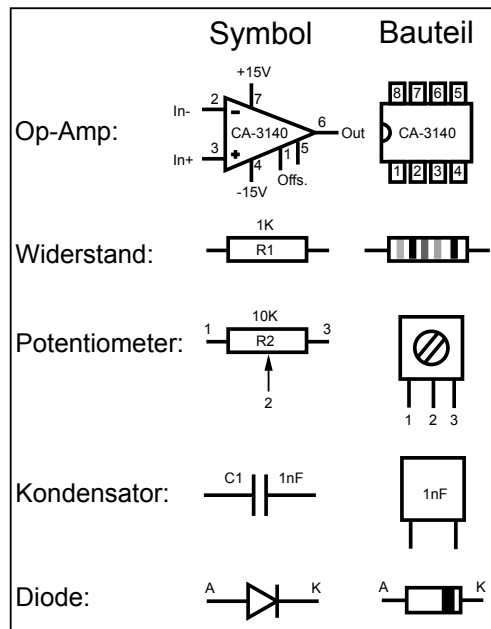
- J. Federau, *Operationsverstärker*
- Operating manual GW Instek GFG-8219A
- Operating manual Tektronix TDS1002

Small parts:

- Box 1:
 - resistors
 - trimming potentiometers, 10 k Ω
 - capacitors
- Box 2:
 - 2 small screwdrivers (for the trimming potentiometers)
 - 2 BNC T-adapters
 - 8 CA3140E op-amps
 - diodes, LEDs
 - various connecting wires

Please check that all material is complete at the end of the experiment. Thank you!

3.2 Help sheet



Widerstands-Farbcode

Farbe	1.Ziffer	2.Ziffer	3.Ziffer	Multiplikator	Toleranz	(T. -Koeff.)
ohne					+/- 20%	
silber				10^{-2}	+/- 10%	
gold				10^{-1}	+/- 5%	
schwarz	0	0	0	10^0		200ppm/K
braun	1	1	1	10^1	+/- 1%	100ppm/K
rot	2	2	2	10^2	+/- 2%	50ppm/K
orange	3	3	3	10^3		15ppm/K
gelb	4	4	4	10^4		25ppm/K
grün	5	5	5	10^5	+/- 0.5%	
blau	6	6	6	10^6	+/- 0.25%	10ppm/K
violett	7	7	7	10^7	+/- 0.1%	5ppm/K
grau	8	8	8	10^8	+/- 0.05%	
weiss	9	9	9	10^9		

Widerstandsreihen - Normwerte

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

Werte sind mit ganzzahligen pos. oder neg. Potenzen von 10 zu multiplizieren.

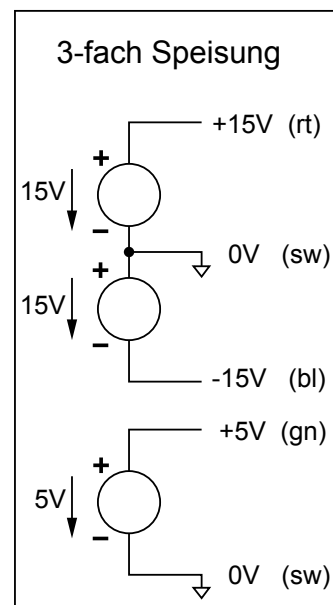


Figure 5: Help sheet: pin assignment and symbols of the components, breadboard, resistor colour code and power supply (in German).

3.3 Building the circuits

Figure 5 contains the information needed to build the circuits of Tasks 2 to 5. The help sheet is in German; the most important terms are: *Bauteil* = component, *Widerstand* = resistor, *Kondensator* = capacitor, *Steckbrett* = breadboard, *Farbcode* = colour code, *Ziffer* = digit, *Normwerte* = standard values, *3-fach Speisung* = triple power supply.

A circuit diagram shows how a circuit works, but it is only of indirect help when wiring the real components. For the wiring, you need the assignment of the connections (pin numbers, designations) between the symbol and the component; this is given in the table at the top left of the help sheet. The coloured stripes on the breadboard picture (top right) show which holes of the breadboard are connected internally.

The resistor colour code is shown at the bottom left. To read the value, hold the resistor so that the tolerance ring (wider, or set slightly apart from the other rings) is on the right.

Example: brown, grey, black, red and a wide brown ring correspond to

$$1\ 8\ 0 \times 10^2\ \Omega = 18\ \text{k}\Omega \quad (\text{tolerance } \pm 1\%).$$

The multimeter can also measure resistances.

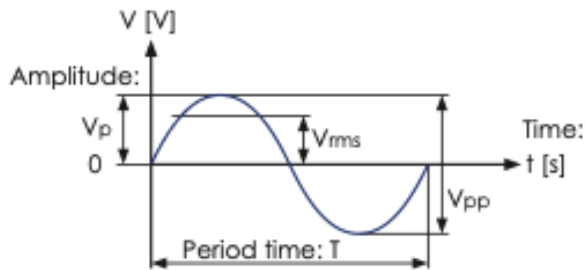
The bottom right of the help sheet shows the triple power supply. Connect the $\pm 15\ \text{V}$ and $0\ \text{V}$ outputs of the power supply to the corresponding sockets of the breadboard with the banana cables. The $+5\ \text{V}$ output is not used in this experiment.

Important: Switch on the power supply (mains switch at the rear left) only after the circuit has been built and checked. If the circuit does not work, first inspect it visually, then measure the supply voltages $+15\ \text{V}$ and $-15\ \text{V}$ against $0\ \text{V}$ directly at the op-amp pins with the multimeter.

4 Tasks

4.1 Task 1: Function generator and oscilloscope

Connect the output of the function generator to channel 1 of the digital oscilloscope with a BNC cable. Since its trigger is defective, the analogue oscilloscope is only used for comparison. The purpose of this task is to become familiar with the instruments; feel free to explore their functions. Task 1 is not part of the report.



Definitions:

$$f = 1/T$$

$$V_{pp} = 2 * V_p(\text{eak})$$

$$V_{rms} = V_p / \text{Root}(2) \text{ (at sinewave)}$$

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

Figure 6: Important parameters of a sine wave without DC offset.

- a) Set the generator to a 1 kHz square wave with maximum amplitude and obtain a stable image (trigger).

Important trigger settings: source (CH1, ...), coupling (DC, AC, ...), mode (Auto/Normal), level (knob) and slope (rising or falling edge).

On the digital oscilloscope, the horizontal position of the trigger point on the screen can be shifted (arrow), but it is normally left in the centre so that the signal before and after the trigger event is visible.

Measure the amplitude and the period. Take the "volts/div" setting (probe factor $\times 1$) and the "time/div" setting into account.

Tip: the digital oscilloscope offers automatic measurements in the "Measure" menu and cursor measurements in the "Cursor" menu. Data can be transferred to the computer via RS232 (program: Tektronix "OpenChoice Desktop" V1.1). A simpler alternative is to take a photo of the screen with your mobile phone.

- b) Generate a 50 kHz sine wave with an AC amplitude of 100 mV_{pp} and a DC offset of +1 V. Sketch the signal together with the zero line.

Tip: with AC input coupling only the AC component is displayed.

- c) Set the generator to the smallest possible amplitude (approx. 14 mV_{pp}), sine wave, $f = 1$ kHz (see the attenuation tip below Figure 4).

Which oscilloscope gives the cleaner image?

Limit the bandwidth of the digital oscilloscope to 20 MHz in the "CH1 Menu".

Try the "Average" function in the "Acquire" menu of the digital oscilloscope. Change the waveform while averaging is switched on. What do you observe?

- d) Measure two signals simultaneously with both channels of the oscilloscope. A square-wave output (TTL OUT) is available on the rear panel of the generator.

4.2 Task 2: Non-inverting amplifier

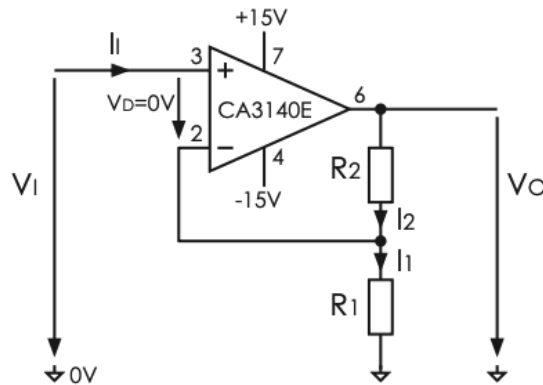


Figure 7: Non-inverting amplifier.

- Derive the output voltage V_O as a function of V_I , R_1 and R_2 .
Tip: $V_D \approx 0$ V and $I_I \approx 0$. What is the voltage across R_1 ?
- What is the minimum voltage gain $G_{\min}$ ($G = V_O/V_I$) of this circuit? Which resistor values realise it?
- Dimension R_1 and R_2 for a gain of $G = 10$.
Available resistors: 1 k Ω , 2 k Ω , 10 k Ω , 15 k Ω , 18 k Ω , 20 k Ω , 30 k Ω , 39 k Ω , 68 k Ω , 100 k Ω and 200 k Ω and 1 M Ω .
Tip: $|I_2|$ should not exceed 1 mA at the maximum output voltage $V_{O,\max} = \pm 10$ V.
- Build the circuit with $G = 10$ on the breadboard and connect the input to 0 V with a wire. Switch on the power supply, then measure and record the output voltage V_O with the multimeter.
Why is the output voltage not exactly zero?
Add the 10 k Ω potentiometer for offset adjustment (between pins 1 and 5, wiper connected to pin 4, as shown in Figure 8) and try to set V_O to 0 V with the screw-driver. Record the remaining output voltage.
- Set the function generator to a sine wave with 10 mV_p and $f = 1$ kHz and connect it to the input of the circuit. Measure input and output simultaneously with the oscilloscope (the "Measure" menu provides amplitude measurements).
Is the gain as expected?
Measure the frequency response, i.e. the gain in dB (Section 2.2) as a function of f from 1 kHz to 1 MHz, and plot it for $G = 10$ on the semi-logarithmic sheet in Figure 12. The frequencies 1, 2, 5, 10, 20, 50, ... kHz are sufficient; add points close to the bandwidth limit.
- Determine the bandwidth f_c of the circuit (Section 2.2).
Draw your measured frequency response from e) into the open-loop gain diagram of the CA3140 (data-sheet extract, Figure 11 on page 16).

Can you see a relationship between the gain and the bandwidth?

- g) Determine the slew rate (Section 2.2) in $V/\mu s$ at $G = 10$.

Tip: use a square wave with $V_I = 400\text{ mV}_p$ and measure the slope of the output edges. A slew-rate-limited edge is a straight ramp, whereas a bandwidth-limited edge has an exponential shape.

4.3 Task 3: Inverting amplifier

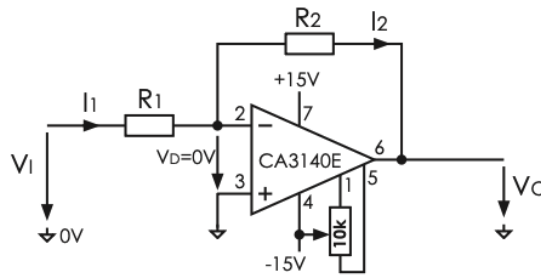


Figure 8: Inverting amplifier with offset adjustment.

- Derive the output voltage V_O as a function of V_I , R_1 and R_2 .
Tip: $V_D \approx 0\text{ V}$. What is the voltage across R_1 ? Where does the current I_1 flow?
- What is the smallest possible magnitude of the voltage gain, $|G|_{\min}$ ($G = V_O/V_I$), of this circuit? Which resistor values realise it? Does this make sense?
- Dimension R_1 and R_2 for a gain of $|G| = 10$ (i.e. $G = -10$).
Available resistors: 1 k Ω , 2 k Ω , 10 k Ω , 15 k Ω , 18 k Ω , 20 k Ω , 30 k Ω , 39 k Ω , 68 k Ω , 100 k Ω and 200 k Ω and 1 M Ω .
Tip: $|I_1|$ should not exceed 1 mA at the maximum output voltage $V_{O,\max} = \pm 10\text{ V}$ (i.e. at $V_{I,\max} = \pm 1\text{ V}$).
- Build the circuit with $|G| = 10$ on the breadboard, first without the 10 k Ω potentiometer.
After switching on the power supply, V_O should be approximately 0 V (input open).
Measure and record the output voltage V_O with the multimeter, once with the input open and once with the input connected to 0 V.
What do you observe? What could be the cause?
Now add the 10 k Ω potentiometer and try to set V_O to 0 V with the screwdriver (input connected to 0 V). Record the remaining output voltage.
- Set the function generator to a sine wave with 10 mV $_p$ and $f = 1\text{ kHz}$ and connect it to the input of the circuit. Measure input and output simultaneously with the oscilloscope (the “Measure” menu provides amplitude measurements).
Is the gain as expected?

Measure the frequency response, i.e. the gain in dB (Section 2.2) as a function of f from 1 kHz to 1 MHz, and plot it for $|G| = 10$ on the semi-logarithmic sheet in Figure 12. The frequencies 1, 2, 5, 10, 20, 50, ... kHz are sufficient; add points close to the bandwidth limit.

- f) Determine the bandwidth f_c of the circuit at $|G| = 10$ (Section 2.2).

Draw your measured frequency response from e) into the open-loop gain diagram of the CA3140 (data-sheet extract, Figure 11 on page 16).

Can you see a relationship between the gain and the bandwidth?

- g) Determine the slew rate (Section 2.2) in V/ μ s at $|G| = 10$.

Tip: use a square wave with $V_I = 400 \text{ mV}_p$ and measure the slope of the output edges. A slew-rate-limited edge is a straight ramp, whereas a bandwidth-limited edge has an exponential shape.

4.4 Task 4: Precision rectifier

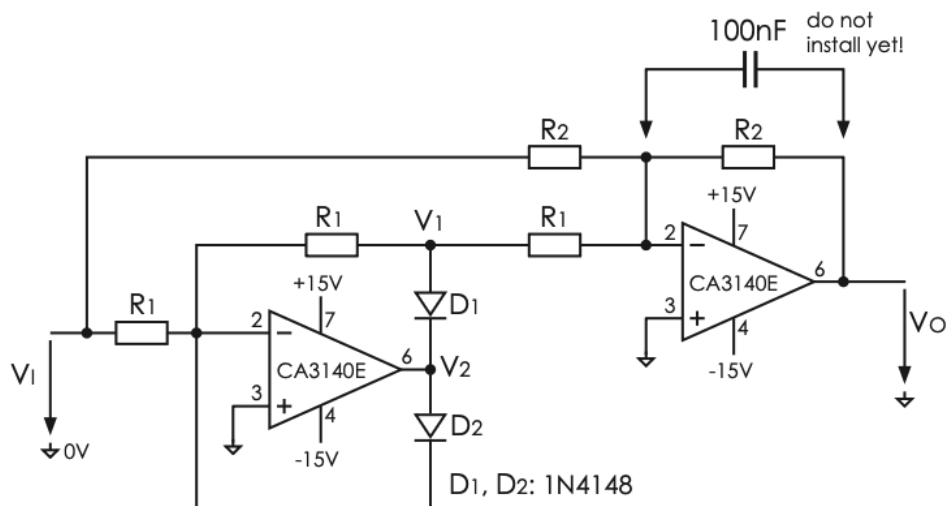


Figure 9: Precision full-wave rectifier.

- a) Build the precision rectifier with $R_1 = 10 \text{ k}\Omega$ and $R_2 = 20 \text{ k}\Omega$ (without the 100 nF capacitor). Apply a sine wave with an amplitude of approx. 5 V_p from the function generator to the input.
- b) Make sure beforehand that the DC offset of the function generator is switched off (offset knob pushed in, Figure 4). Measure V_I , V_1 , V_2 and V_O with the oscilloscope at $f = 1 \text{ kHz}$ and sketch them as functions of time.
- What is the function of the left op-amp (output V_1) and of the right op-amp (output V_O)?
- c) Repeat measurement b) at $f = 100 \text{ kHz}$ and sketch the signals as functions of time.

What could be responsible for the signal distortion?

- d) Connect a capacitor of 100 nF in parallel to the feedback resistor R_2 of the output stage and vary the frequency.

What do you observe?

Calculate the arithmetic mean value of a full-wave rectified sine wave with amplitude V_p and compare it with the measured output voltage.

- e) What happens if you reverse the polarity of both diodes D_1 and D_2 ?
- f) Can you build a precision rectifier with only one op-amp, one diode and two resistors?

Tip: measure V_1 after removing D_2 and the resistor R_1 that leads to the inverting input of the right op-amp.

- Draw the simplified circuit.
- How can the polarity of the output be reversed?
- Name two disadvantages of the simplified circuit.

4.5 Task 5: Oscillator

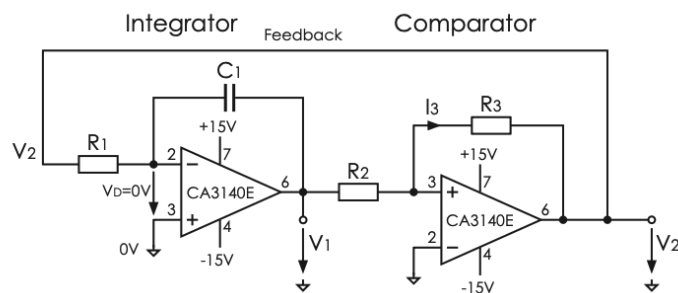


Figure 10: Oscillator consisting of an integrator and a comparator.

- a) The right op-amp is wired as a comparator with hysteresis (Schmitt trigger), recognisable by the *positive* feedback via R_3 . If the voltage at the non-inverting input (+) is slightly more positive than at the inverting input (−), the high open-loop gain drives the output to its positive limit (somewhat below +15 V, see the data sheet). Via R_3 this pulls the non-inverting input even further into the positive range, so the state is stable. For a negative voltage difference, everything is reversed.

Dimension R_2 and R_3 such that the output switches only when V_1 reaches about ± 10 V (hysteresis).

- b) Build only the comparator and test its switching points with the function generator (sine or triangle wave, use the DC offset).

Why do the magnitudes of the two switching points differ? How can you compensate for this by adding a red light-emitting diode (forward voltage $V_{LED} \approx 1.6$ V; long lead = anode)?

- c) The left op-amp is wired as an inverting integrator. Consider the shape of the output voltage V_1 for a constant input voltage V_2 of $+15\text{ V}$ or -15 V .

Tip: for a capacitor,

$$Q = C \Delta V_C = I_C \Delta t \quad (C \text{ and } I_C \text{ constant}),$$

or, more generally,

$$V_C(t) = \frac{1}{C} \int_0^t I_C(t') dt' \quad (\text{capacitor uncharged at } t = 0).$$

- d) Build the integrator alone, to the left of the comparator, with $C_1 = 1\text{ nF}$ and $R_1 = 10\text{ k}\Omega$. Test it with the function generator (square wave at the input).

Does it integrate? Tip: the input offset makes the output drift slowly into saturation. Briefly short-circuiting C_1 with a wire discharges the capacitor, so that the integration starts again from zero.

- e) Consider how the complete oscillator works. Sketch V_1 and V_2 as functions of time t . What are the amplitudes of V_1 and V_2 ?

Dimension R_1 such that the oscillator runs at $f = 10\text{ kHz}$ ($C_1 = 1\text{ nF}$).

Tip: apply one of the formulae from c) to a time interval during which V_2 is constant.

- f) Now connect the complete circuit as shown in Figure 10. Measure V_1 and V_2 and sketch them as functions of time. Do the curves agree with your prediction from e)? Do the frequency and the amplitude of V_1 agree as well?

- g) Halve the value of R_2 . How does this affect the amplitude and the frequency of V_1 ?

Which other component must be changed, and how, so that the frequency returns to 10 kHz without changing the amplitude?

5 Contact

If you have further questions about the experiment or need additional literature on the theory, please contact the assistant:

Andreas Tonin
andreas.tonin@unibas.ch
Room 2.21

6 Appendix: Data sheet extract and record sheet for Tasks 2 and 3

Figure 11 shows the open-loop frequency response (gain and phase) of the CA3140 without feedback, copied from the data sheet; the frequency axis labels have been added. It shows the relationship between the maximum bandwidth of an amplifier circuit and its gain.

Figure 12 is a semi-logarithmic record sheet (logarithmic frequency axis, gain in dB) for plotting the frequency responses measured in Tasks 2 and 3.

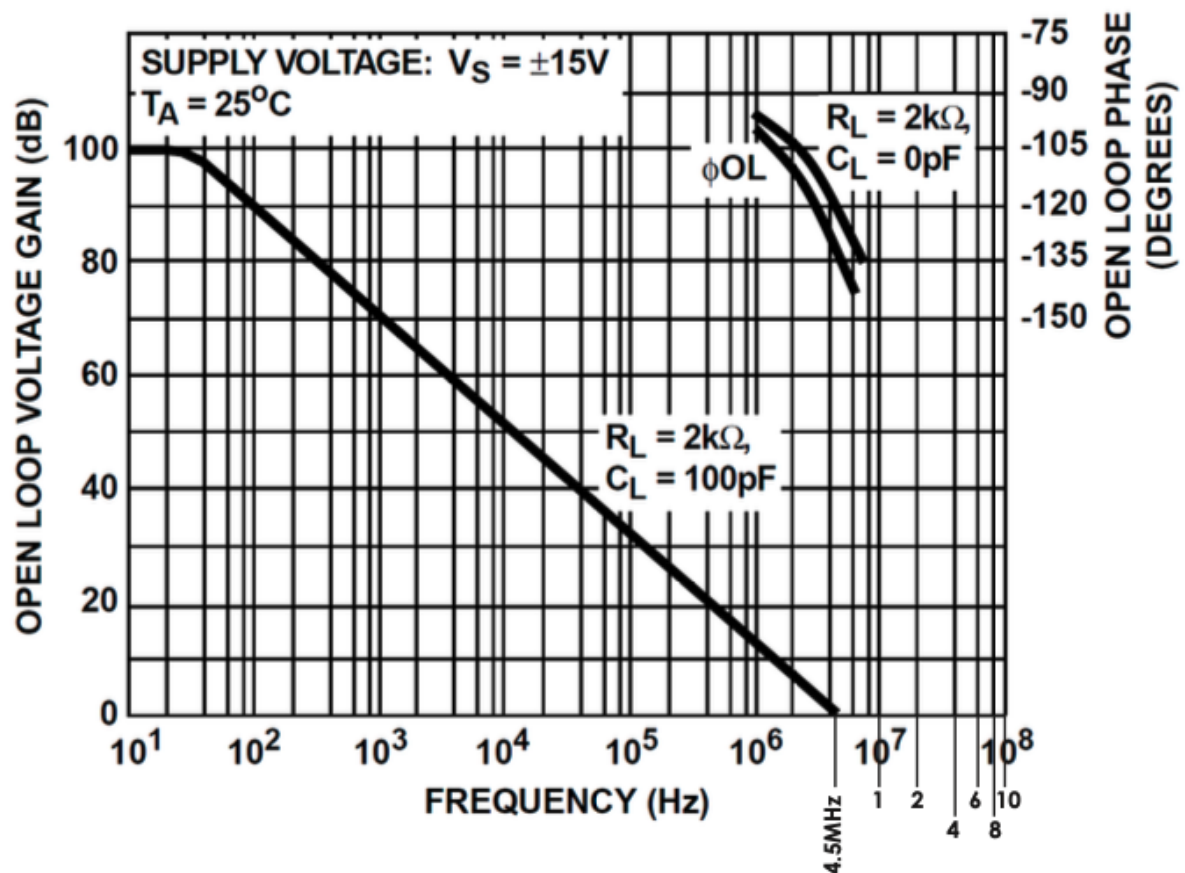


FIGURE 6. OPEN LOOP VOLTAGE GAIN AND PHASE vs FREQUENCY

Figure 11: Open-loop voltage gain and phase of the CA3140 versus frequency (data-sheet extract, for Tasks 2 and 3).

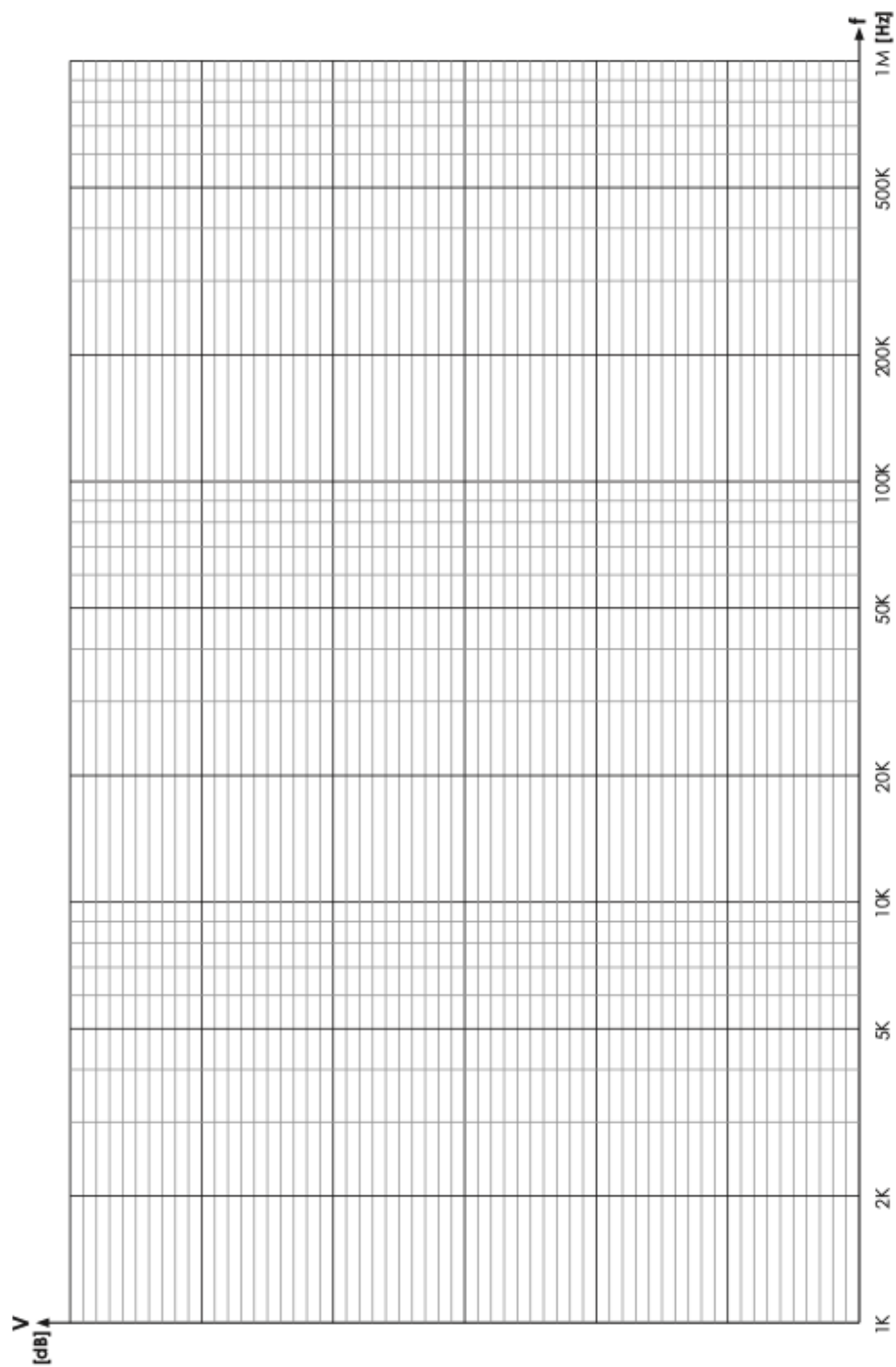
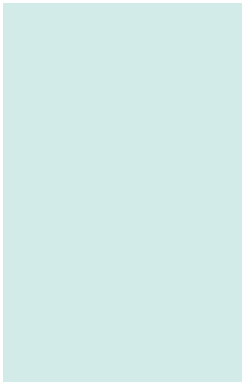


Figure 12: Record sheet for the frequency response (for Tasks 2 and 3).



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