EE413
Lab 005
the Operational Amplifier

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Abstract

This lab is meant to show the practical use of the operational amplifier in analog circuit design. Several common circuit configurations will be discussed.

Contents

1 Circuit prototyping setup

The circuit was build on a solderless breadboard, using through-hole parts. A classic 741 op amp was used with a +/-15V power supply. No decoupling caps was used and signal lines were not properly terminated.
For measurements the following instruments was used; HP34401A bench multimeter, HP33120A signal generator and Agilent E3631A lab power supply.

2 Inverting DC Amplifier

2.1 Theory

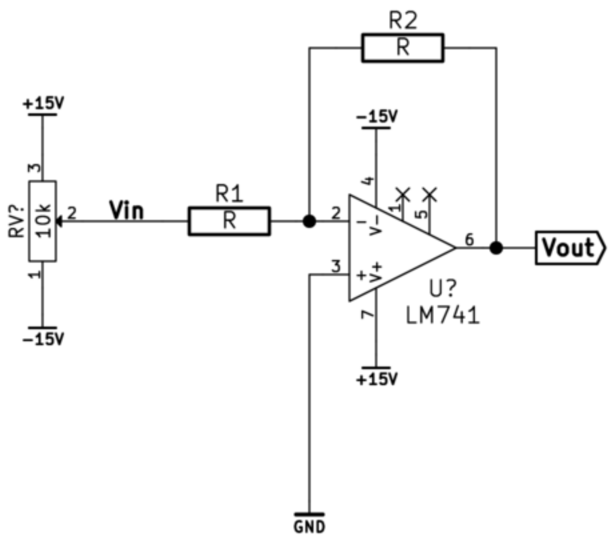

Figure 1: Inverting DC amplifier

The basic topology for an inverting amplifier is shown in Figure 1. Gain A_v, can be expressed as a ratio of the feedback impedance to the input impedance. Op amp action makes the negative input appear as a "virtual earth" summing node. The voltage drops across the resistors scale linearly with their value, and since the op amp compensates to ensure equality in the summing junction, the net effect is an amplified and inverted output.

$$A_v = \frac{R_2}{R_1} \tag{1}$$

The circuit gain for ideal components is therefore;
For $R_2 = 100k\Omega$:

$$A_v = \frac{V_{out}}{V_{in}} = -\frac{R_2}{R_1} \tag{2}$$
$$= \frac{100k\Omega}{10k\Omega} = 10\times \tag{3}$$
$$= 20 \times \log\frac{10}{1} = 20dB \tag{4}$$

For $R_2 = 10k\Omega$:

$$A_v = \frac{V_{out}}{V_{in}} = -\frac{R_2}{R_1} \tag{5}$$
$$= \frac{10k\Omega}{10k\Omega} = 10\times \tag{6}$$
$$= 20 \times \log\frac{1}{1} = 0dB \tag{7}$$

In both cases, the signal phase is inverted 180°.

2.2 Measurements

Measured values for the test setup are shown in Table 1 and Table 2.

U_{in} (V)	U_{out} (V)	Av (×)
-0.103	+1.087	-10.35
-1.008	+10.236	-10.15
+1.004	-10.104	-10.06

Table 1: $R_2 = 100k\Omega$

U_{in} (V)	U_{out} (V)	Av (×)
-0.1003	+0.112	-1.116
-1.000	+1.038	-1.038
+1.005	-1.027	-1.022

Table 2: $R_2 = 10k\Omega$

For $R_2 = 100k\Omega$, the actual measured in circuit values of R_2 and R_1 were

119kΩ and 11.7kΩ, respectively. Calculated circuit gain for non-ideal, real components;

$$A_v = \frac{V_{out}}{V_{in}} = -\frac{R_2}{R_1} \tag{8}$$
$$= \frac{119k\Omega}{11.7k\Omega} = 10.17\times \tag{9}$$
$$= 20 \times \log \frac{\frac{119k\Omega}{11.7k\Omega}}{1} = 20.15dB \tag{10}$$

For $R_2 = 10k\Omega$, the actual measured in circuit values of R_2 and R_1 were 12.17kΩ and 11.7kΩ, respectively. Calculated circuit gain for non-ideal, real components;

$$A_v = \frac{V_{out}}{V_{in}} = -\frac{R_2}{R_1} \tag{11}$$
$$= \frac{12.17k\Omega}{11.7k\Omega} = 1.04\times \tag{12}$$
$$= 20 \times \log \frac{\frac{12.17k\Omega}{11.7k\Omega}}{1} = 0.34dB \tag{13}$$

3 Inverting AC Amplifier

3.1 Theory

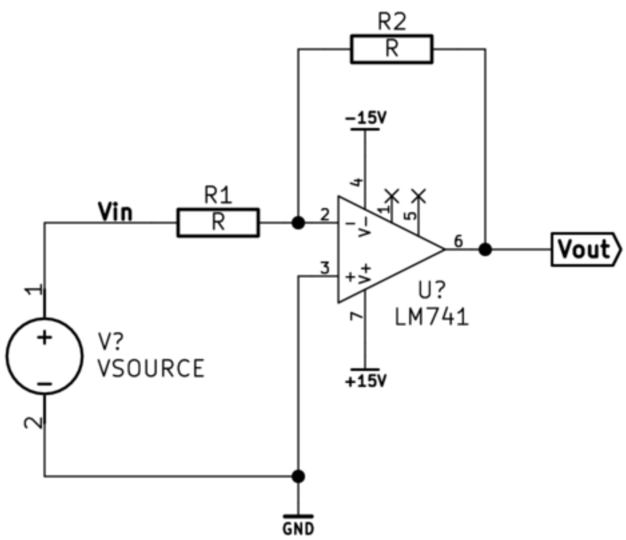

Figure 2: Inverting AC amplifier

The basic topology for an inverting AC amplifier is shown in Figure 2.

$$A_v = 1 + \frac{R_2}{R_1} \tag{14}$$

The circuit gain for ideal components is;
For $R_2 = 100k\Omega$:

$$A_v = \frac{V_{out}}{V_{in}} = -\frac{R_2}{R_1} \tag{15}$$
$$= \frac{100k\Omega}{10k\Omega} = 10\times \tag{16}$$
$$= 20 \times \log \frac{10}{1} = 20dB \tag{17}$$

For $R_2 = 10k\Omega$:

$$A_v = \frac{V_{out}}{V_{in}} = -\frac{R_2}{R_1} \tag{18}$$
$$= \frac{10k\Omega}{10k\Omega} = 10\times \tag{19}$$
$$= 20 \times \log \frac{1}{1} = 0dB \tag{20}$$

In both cases, the signal phase is inverted 180°.

3.2 Measurements

3.3 Oscilloscope shots

Oscilloscope photos in figure 3 and figure 4 show the amplifier input on channel one the amplifier output on channel two. Channel two volts/div is set to compensate for the high impedance 10:1 probe setting.

4 Non-inverting DC Amplifier

4.1 Theory

The basic topology for an non-inverting DC amplifier is shown in Figure 5. Gain A_v, is set by the attenuation-factor of the circuit in the feedback-loop. A fraction of the output is fed back, causing the op amp to compensate and in effect amplify.

$$A_v = 1 + \frac{R_2}{R_1} \tag{21}$$

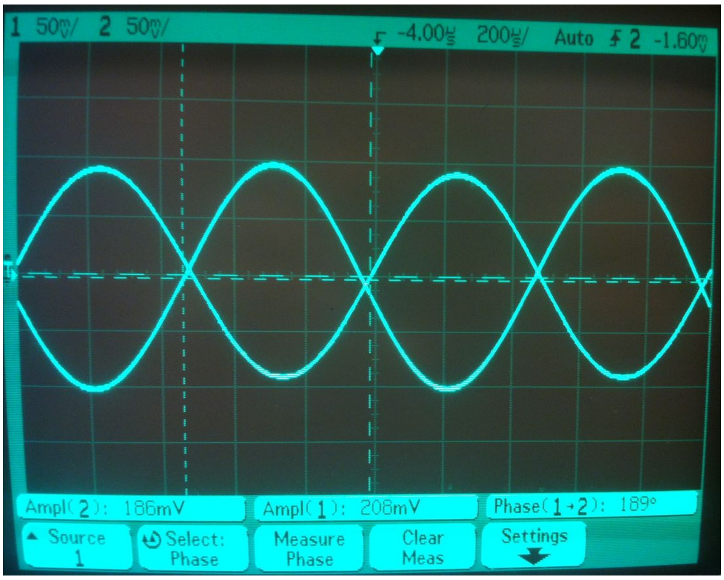

Figure 3: Inverting AC amplifier - 20dB gain

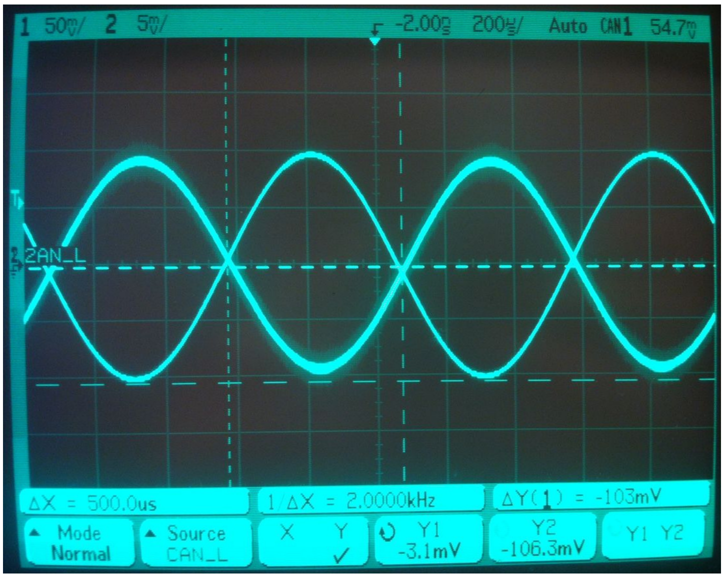

Figure 4: Inverting AC amplifier - unity gain

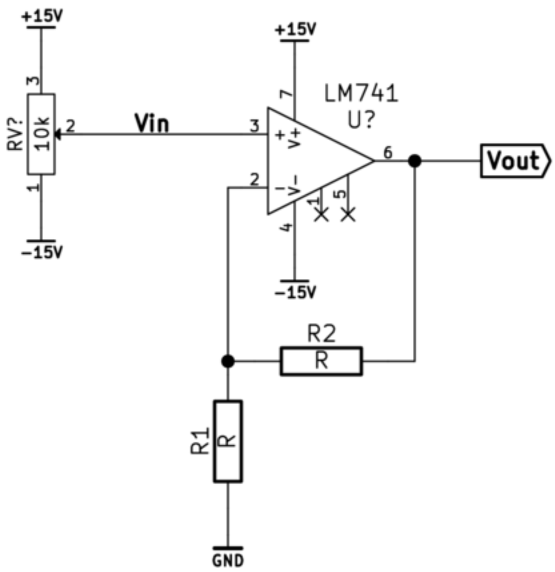

Figure 5: Non-inverting DC amplifier

4.2 Measurements

Measured values for the test setup are shown in Table 3 and Table 4.

U_{in} (V)	U_{out} (V)	Av ($\times$)
+0.1007	+0.2164 2	.15
+1.002	+2.048 2	.04
-1.005	-2.03 2	.019

Table 3: $R_2 = 10k\Omega$

U_{in} (V)	U_{out} (V)	Av ($\times$)
+0.1009	+1.178	11.67
+1.1013	+11.3	11.15
-1.004	-11.09	11.05

Table 4: $R_2 = 100k\Omega$

5 Non-inverting AC Amplifier

5.1 Theory

The lab circuit for the non-inverting AC amplifier is identical to the non-inverting DC amplifier. The basic topology is shown in figure 6.

5.2 Measurements

5.3 Oscilloscope shots

Oscilloscope photos in figure 7 and figure 8 show the amplifier input on channel one the amplifier output on channel two. Channel volts/div is set to compensate for the high impedance 10:1 probe setting.

6 Active full wave rectifier

6.1 Theory

Compared to a passive rectifier circuit, the active rectifier does not suffer from the “deadzone” when the signal is too small to turn on the rectifying diode. The op amp compensates for the diode forward voltage drop. The circuit output is a full wave rectified version of the signal, with a frequency limit mostly set by the op amp bandwidth. Diode D2 prevents the op amp

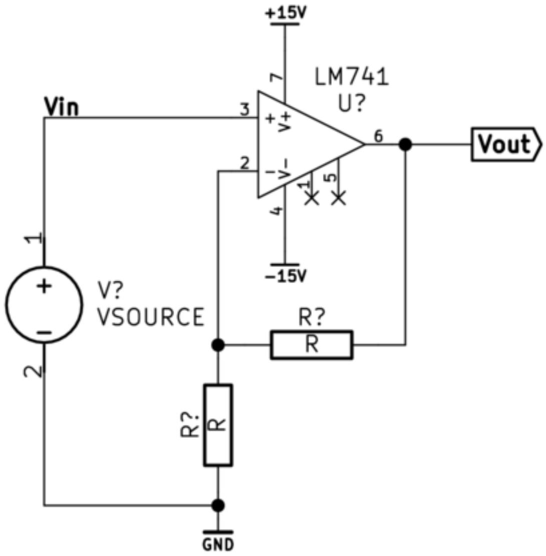

Figure 6: Non-inverting AC amplifier

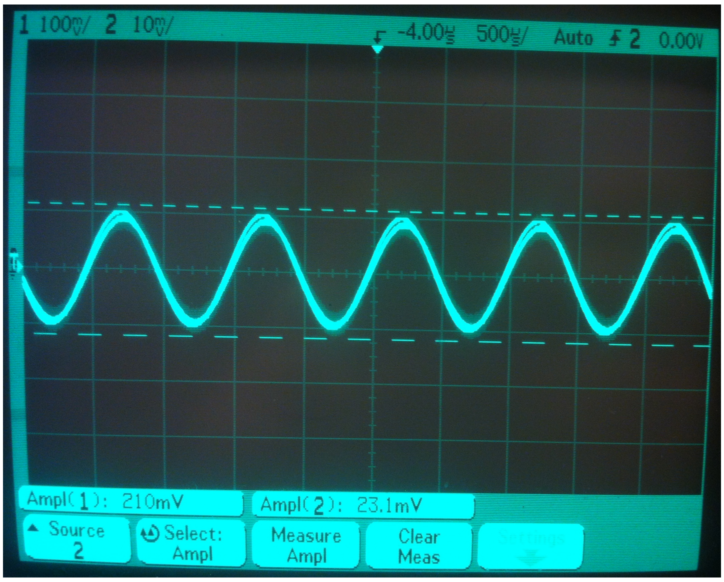

Figure 7: Non-inverting AC amplifier - 6dB gain

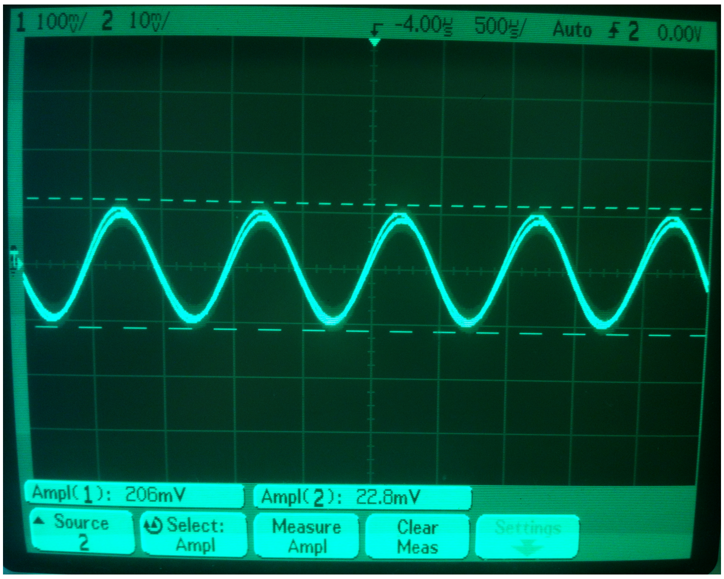

Figure 8: Non-inverting AC amplifier - 20dB gain

from hitting the rail hard when D1 is reverse biased. This makes the recovery and rise time faster when D1 biases on and this in turn improves circuit response times.

6.2 Oscilloscope shots

Oscilloscope photos in Figure 10 and Figure 11 show the input signal on channel one and the full wave rectifier output on channel two. Channel volts/div is set to compensate for the high impedance 10:1 probe setting.

7 Low pass filter

7.1 Theory

The basic topology for a first order active low pass filter is shown in Figure 12. Gain A_v, can be expressed as a ratio of the feedback impedance to the input impedance.

$$A_v = \frac{Z_f}{Z_i} \tag{22}$$

The circuit transfer function is;

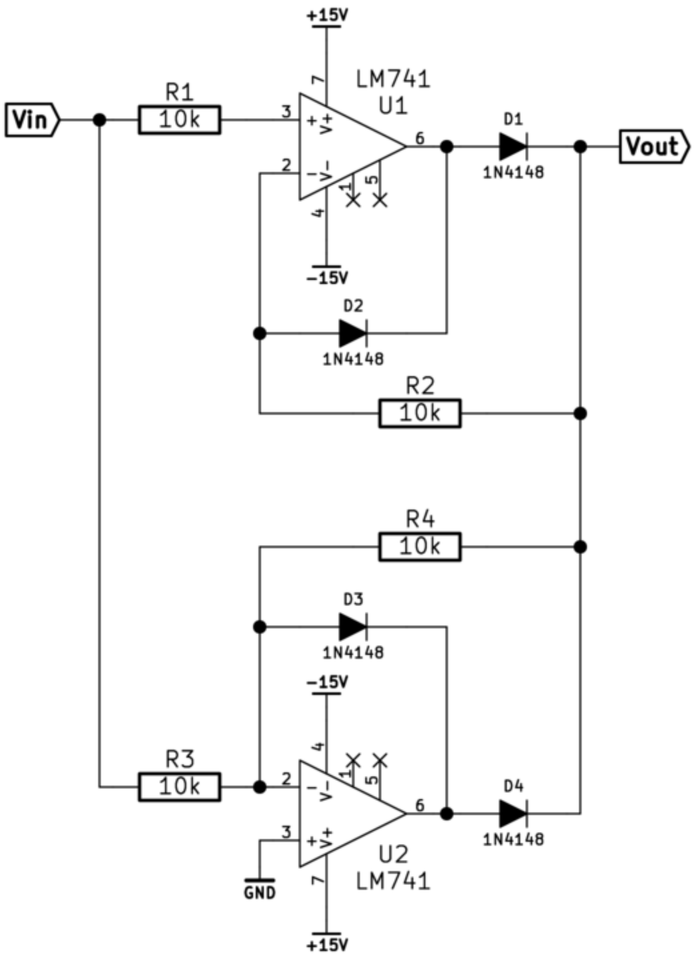

Figure 9: Active full wave rectifier

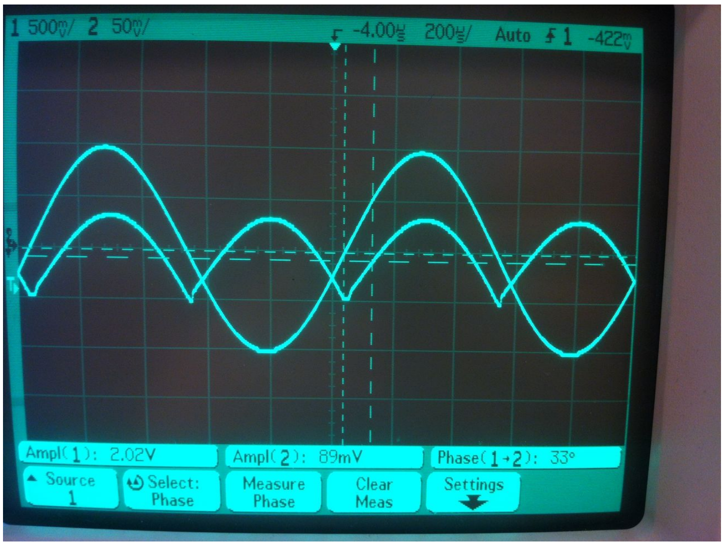

Figure 10: Full wave rectifier - input and rectified output

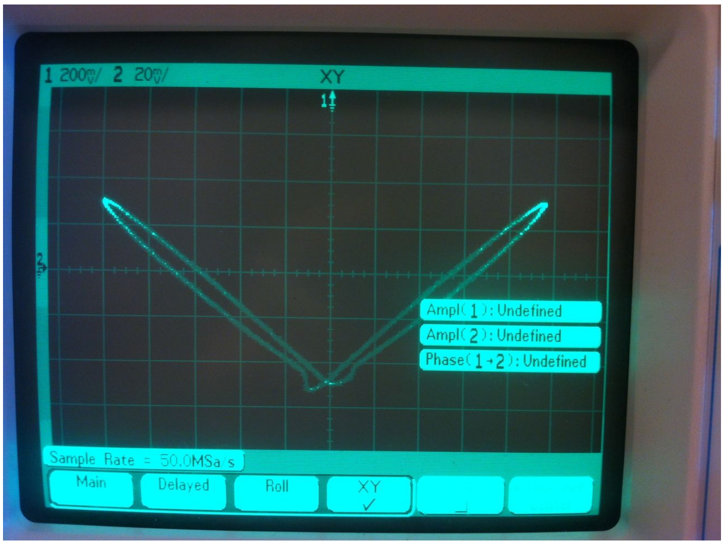

Figure 11: Full wave rectifier - X/Y-view

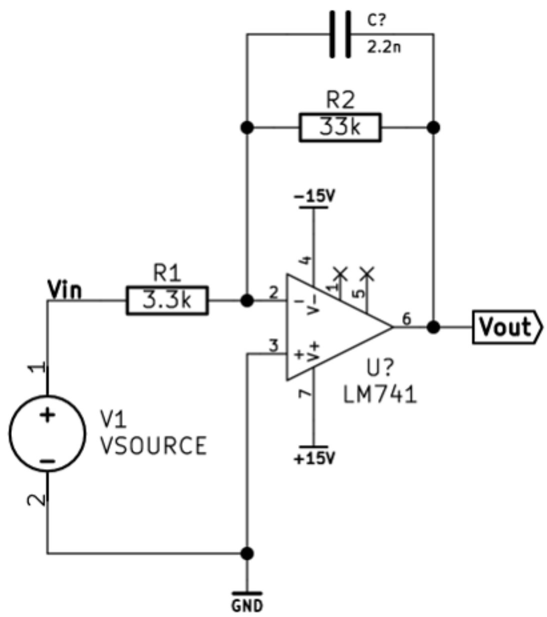

Figure 12: Low pass filter

$$
\begin{aligned}
A_v = \frac{V_{out}}{V_{in}} &= -\frac{Z_f}{Z_i} && (23)\\
&= \frac{R_2}{R_1} \times \frac{1}{\sqrt{1 + (\omega R_2 C)^2}} && (24)\\
&= \frac{33k\Omega}{3.3k\Omega} \times \frac{1}{\sqrt{1 + (\omega \times 33k\Omega \times 2.2nF)^2}} && (25)
\end{aligned}
$$

7.2 Measurements

The measured frequency response is shown as a bode plot in Figure 13 and the phase is shown in Figure 14.

7.3 Oscilloscope shots

Oscilloscope photos in figure 15 show the low pass filter input and output with a 5kHz input signal. Figure 16 shows the low pass filter input and output with a 10kHz input signal. Channel two volts/div is set to compensate for the high impedance 10:1 probe setting.

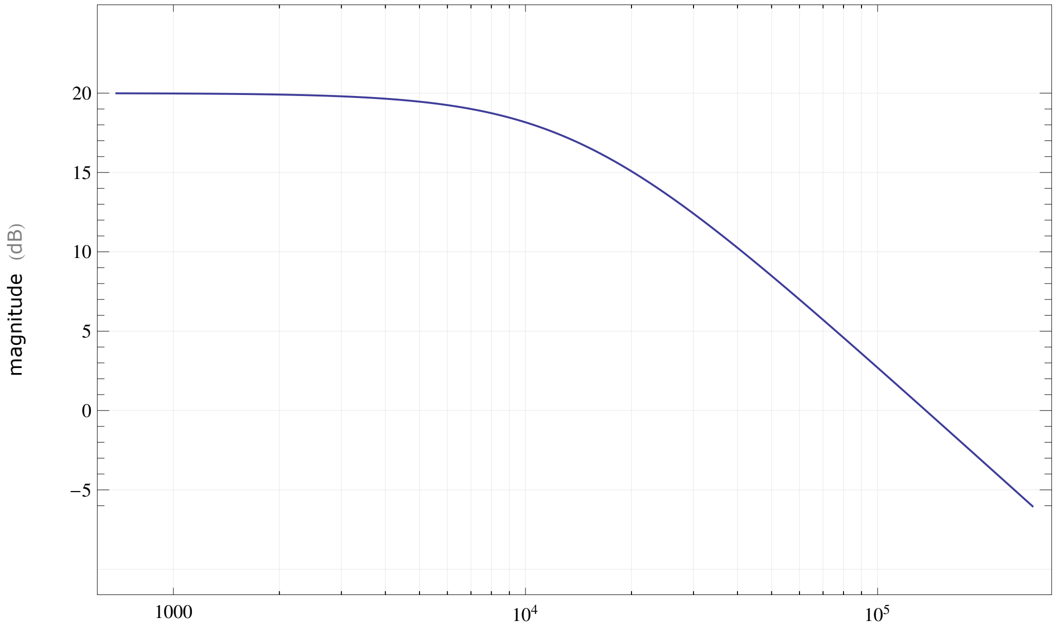

Figure 13: Low pass filter frequency response

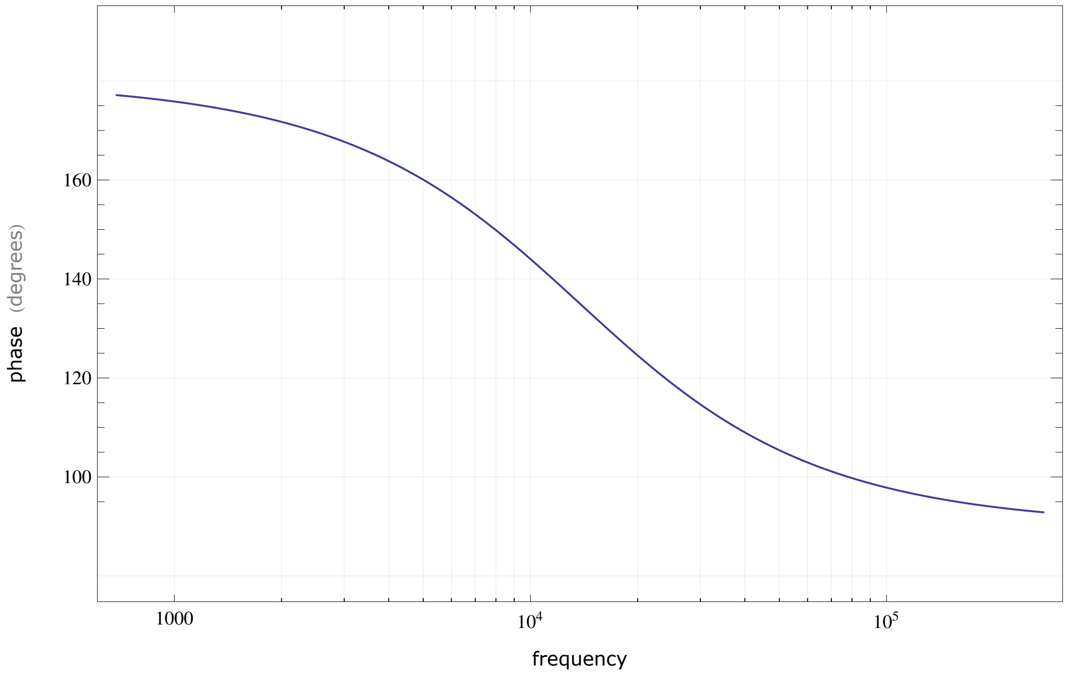

Figure 14: Low pass filter phase response

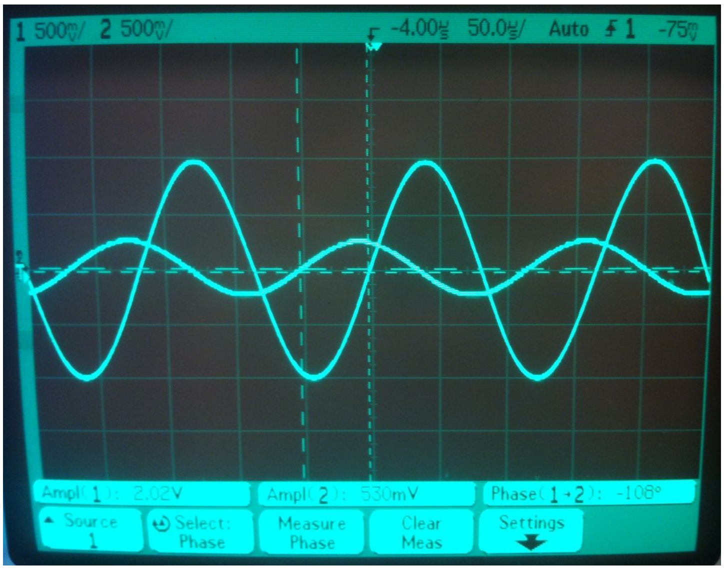

Figure 15: Low pass filter - 5kHz input signal

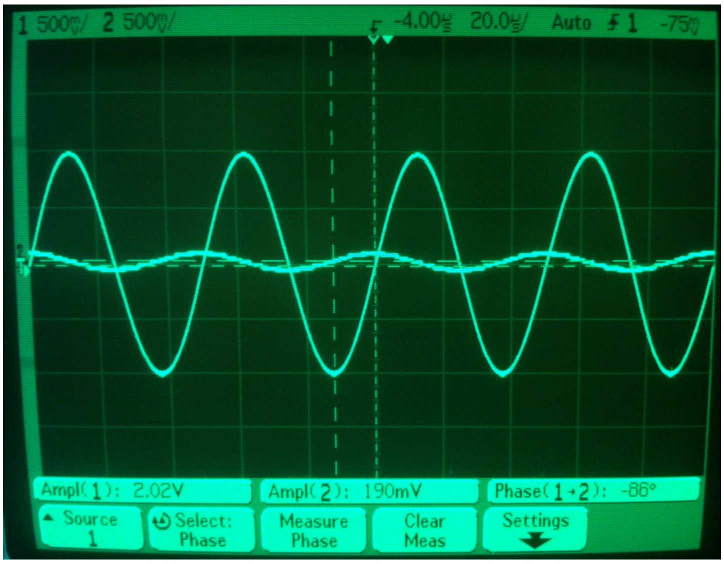

Figure 16: Low pass filter - 10kHz input signal

8 Zener diode clipper

8.1 Theory

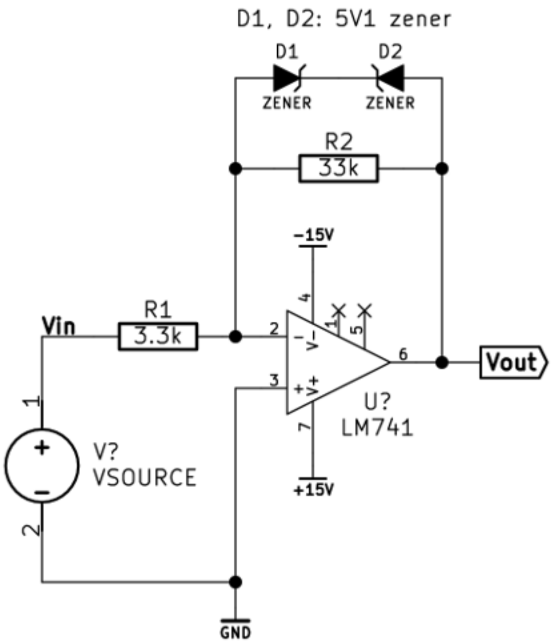

Figure 17: Zener diode clipper

The schematic for a inverting amplifier with a diode amplitude limiting clipper is shown in Figure 17.

8.2 Measurements

Circuit functionality was tested by increasing the signal amplitude until limiting occured.

8.3 Oscilloscope shots

Oscilloscope photos in figure 18 to figure 24 shows the transfer function of the zener clipper as an X/Y-graph. The curvature of the graph is the zener diodes gradually turning on as the input signal voltage rises to their conducting voltage.

9 Results

The measurement errors and differences between the theoretical calculations using ideal components is to be expected. With 5and a crude prototyping

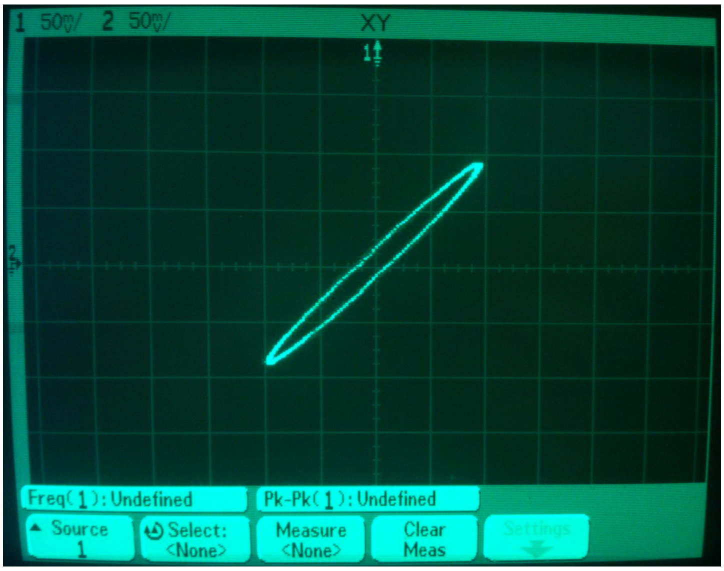

Figure 18: Zener diode clipper photo 1

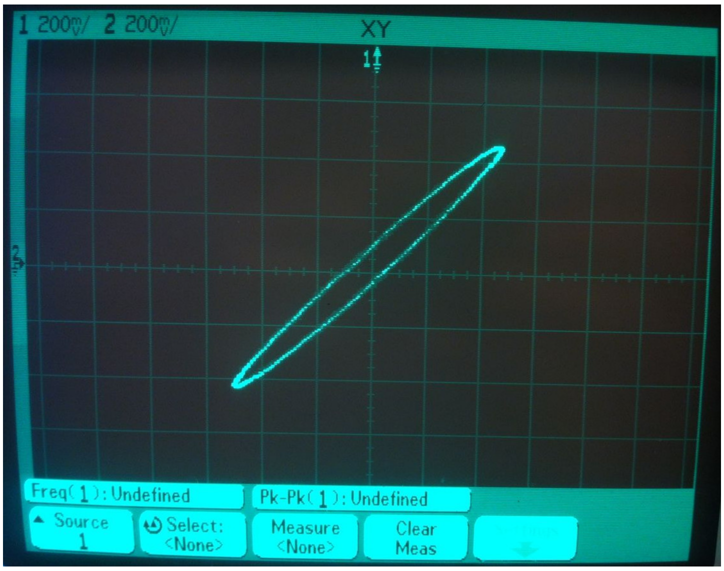

Figure 19: Zener diode clipper photo 2

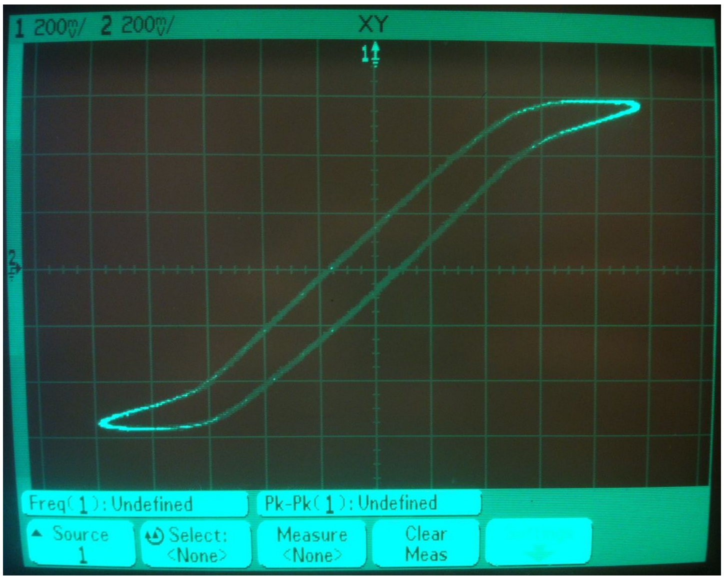

Figure 20: Zener diode clipper photo 3

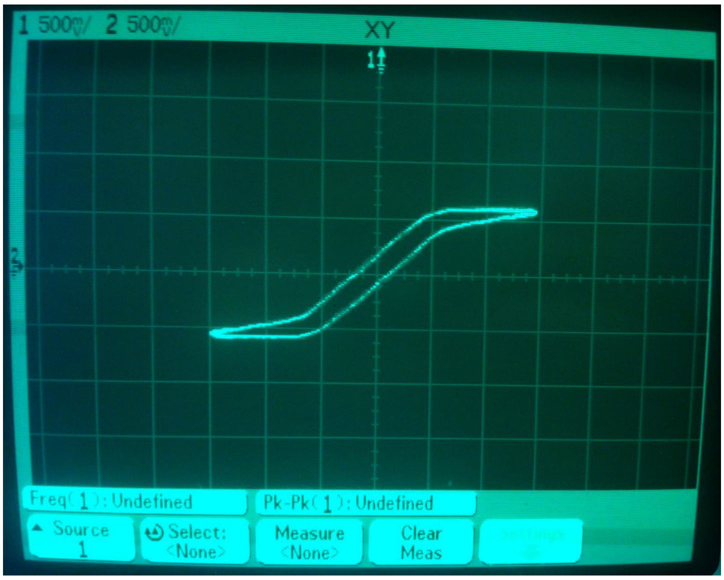

Figure 21: Zener diode clipper photo 4

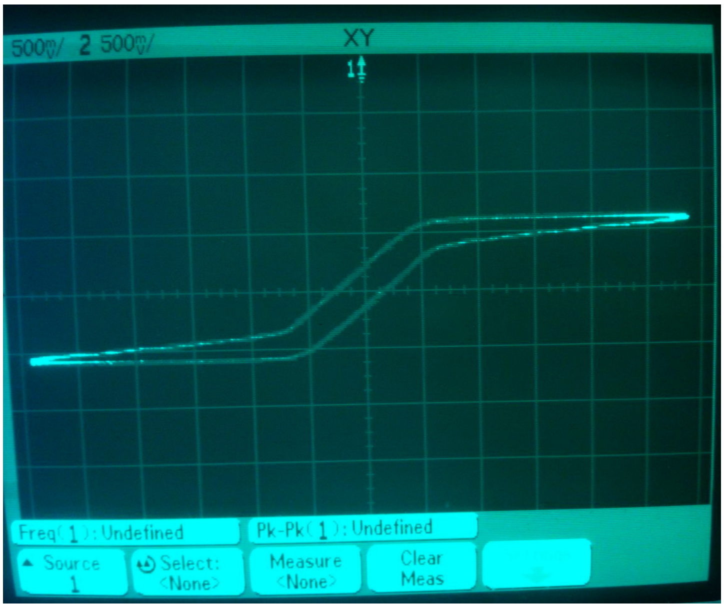

Figure 22: Zener diode clipper photo 5

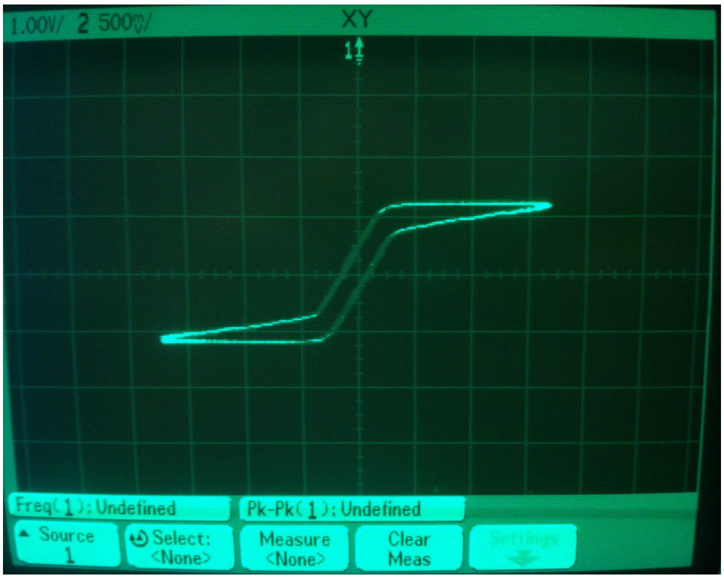

Figure 23: Zener diode clipper photo 6

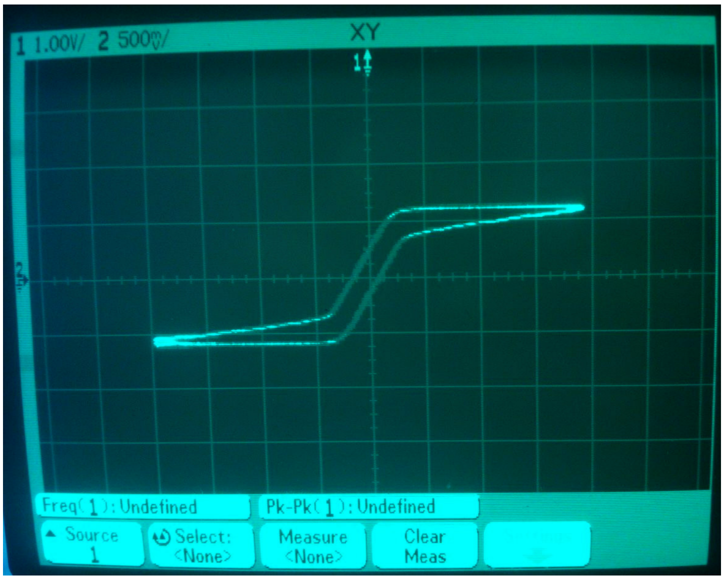

Figure 24: Zener diode clipper photo 7

setup, parasitics play a major role in the behavior of the circuit.

10 References

10.1 Literature

Horowitz and Hill - The Art of Electronics, Cambridge University Press 1989.
Horowitz and Hayes - Student Manual for the Art of Electronics, Cambridge 1989.

10.2 Sources

Full source, including spice simulation files, CSV data, schematics, etc is available at https://github.com/jonasjberg/EE413-lab02