

EE413  
Lab 005  
the Operational Amplifier

Jonas Sjöberg  
Högskolan i Gävle,  
Elektronikingenjörsprogrammet,  
[tel12jsg@student.hig.se](mailto:tel12jsg@student.hig.se)

Esther Hedlund  
Högskolan i Gävle,  
Elektronikingenjörsprogrammet,  
[tfk13ehd@student.hig.se](mailto:tfk13ehd@student.hig.se)

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Instructor: Nauman Masud, Shoaib Amin

**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.

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# 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 were used and signal lines were not properly terminated.

## 2 Inverting DC Amplifier

### 2.1 Theory

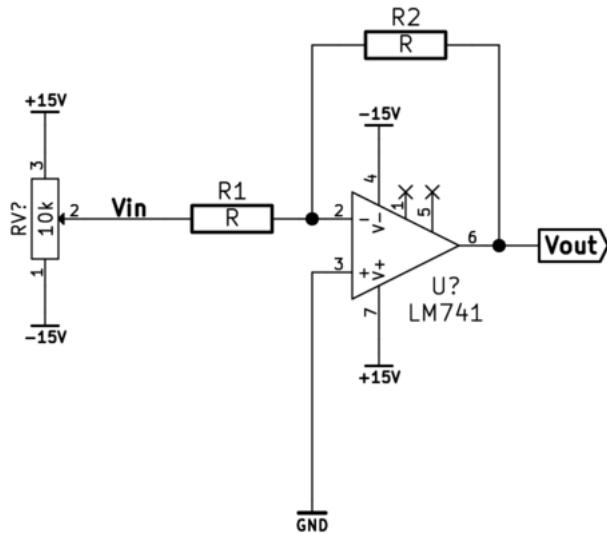


Figure 1: Inverting DC amplifier

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.

$$A_v = \frac{R_2}{R_1} \quad (1)$$

The circuit gain for ideal components is therefore;

For  $R_2 = 100k\Omega$ :

$$A_v = \frac{V_{out}}{V_{in}} = -\frac{R_2}{R_1} \quad (2)$$

$$= \frac{100k\Omega}{10k\Omega} = 10 \times \quad (3)$$

$$= 20 \times \log \frac{10}{1} = 20dB \quad (4)$$

For  $R_2 = 10k\Omega$ :

$$A_v = \frac{V_{out}}{V_{in}} = -\frac{R_2}{R_1} \quad (5)$$

$$= \frac{10k\Omega}{10k\Omega} = 10 \times \quad (6)$$

$$= 20 \times \log \frac{1}{1} = 0dB \quad (7)$$

In both cases, the signal phase is inverted  $180^\circ$ .

## 2.2 Measurements

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

$U_{in}$ (V)	$U_{out}$ (V)	$Av$ ( $\times$ )
-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)	$Av$ ( $\times$ )
-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

$119k\Omega$  and  $11.7k\Omega$ , respectively. Calculated circuit gain for non-ideal, real components;

$$A_v = \frac{V_{out}}{V_{in}} = -\frac{R_2}{R_1} \quad (8)$$

$$= \frac{119k\Omega}{11.7k\Omega} = 10.17 \times \quad (9)$$

$$= 20 \times \log \frac{\frac{119k\Omega}{11.7k\Omega}}{1} = 20.15dB \quad (10)$$

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

$$A_v = \frac{V_{out}}{V_{in}} = -\frac{R_2}{R_1} \quad (11)$$

$$= \frac{12.17k\Omega}{11.7k\Omega} = 1.04 \times \quad (12)$$

$$= 20 \times \log \frac{\frac{12.17k\Omega}{11.7k\Omega}}{1} = 0.34dB \quad (13)$$

### 3 Inverting AC Amplifier

#### 3.1 Theory

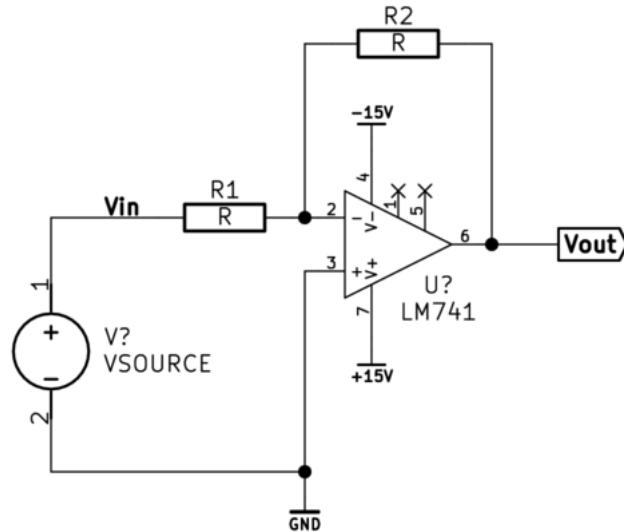


Figure 2: Inverting AC amplifier

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

$$A_v = 1 + \frac{R_2}{R_1} \quad (14)$$

The circuit gain for ideal components is;

For  $R_2 = 100k\Omega$ :

$$A_v = \frac{V_{out}}{V_{in}} = -\frac{R_2}{R_1} \quad (15)$$

$$= \frac{100k\Omega}{10k\Omega} = 10 \times \quad (16)$$

$$= 20 \times \log \frac{10}{1} = 20dB \quad (17)$$

For  $R_2 = 10k\Omega$ :

$$A_v = \frac{V_{out}}{V_{in}} = -\frac{R_2}{R_1} \quad (18)$$

$$= \frac{10k\Omega}{10k\Omega} = 10 \times \quad (19)$$

$$= 20 \times \log \frac{1}{1} = 0dB \quad (20)$$

In both cases, the signal phase is inverted  $180^\circ$ .

### 3.2 Measurements

TODO

### 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.

$$A_v = 1 + \frac{R_2}{R_1} \quad (21)$$

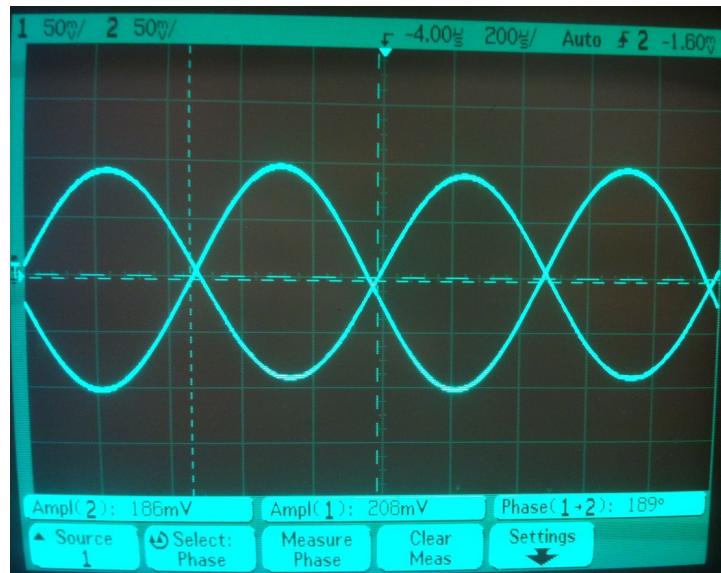


Figure 3: Inverting AC amplifier - 20dB gain

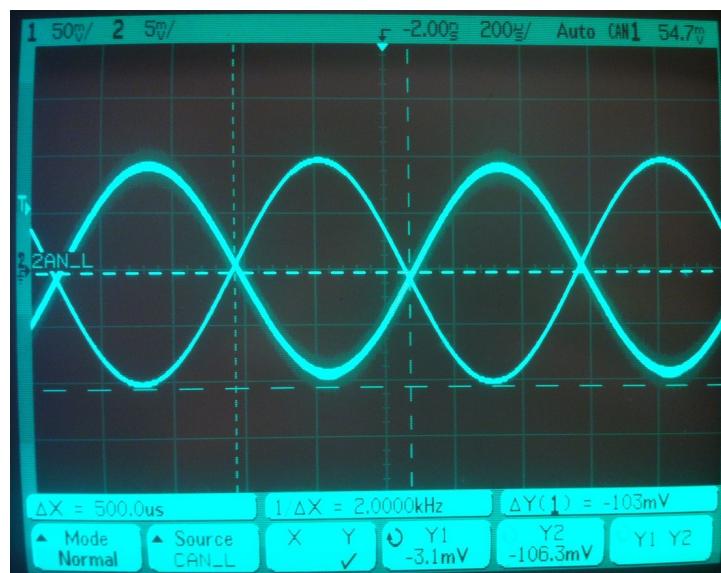


Figure 4: Inverting AC amplifier - unity gain

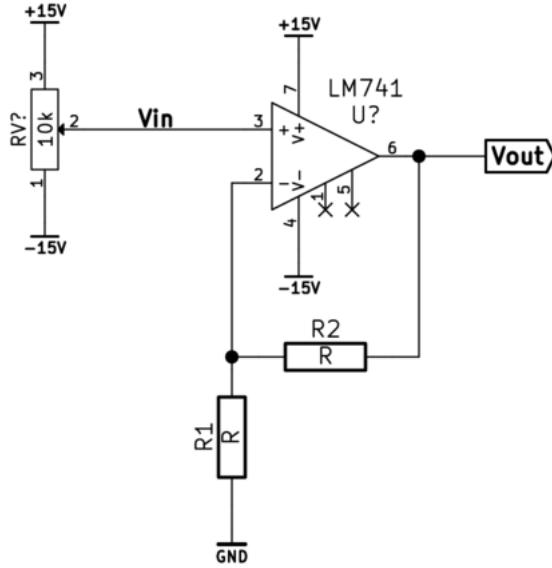


Figure 5: Non-inverting DC amplifier

## 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

TODO

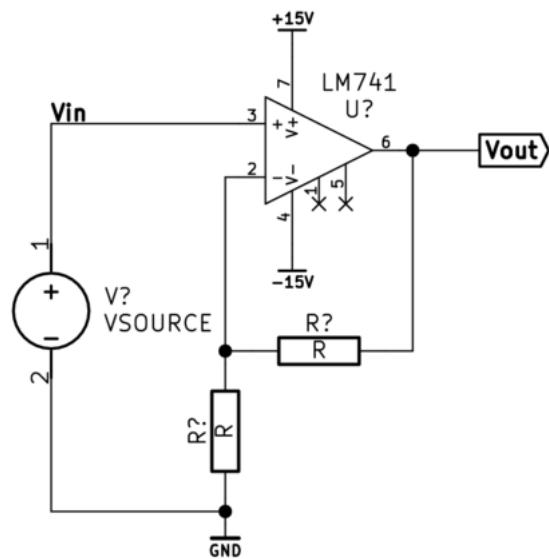


Figure 6: Non-inverting AC amplifier

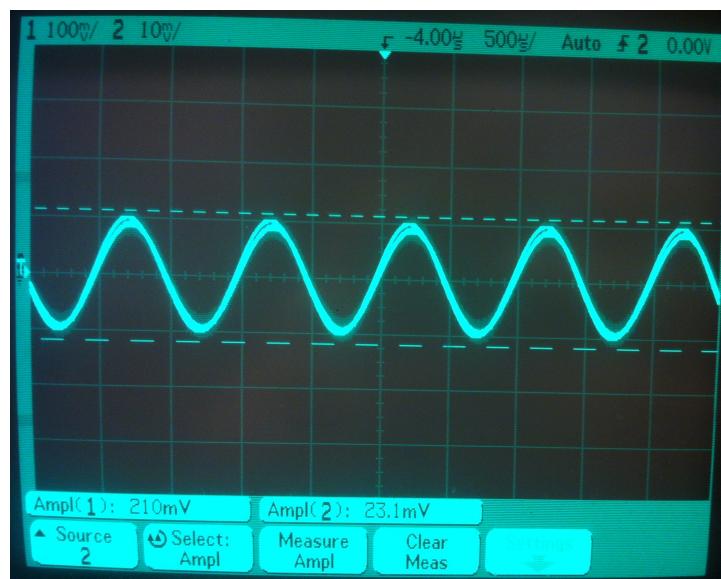


Figure 7: Non-inverting AC amplifier - 6dB gain

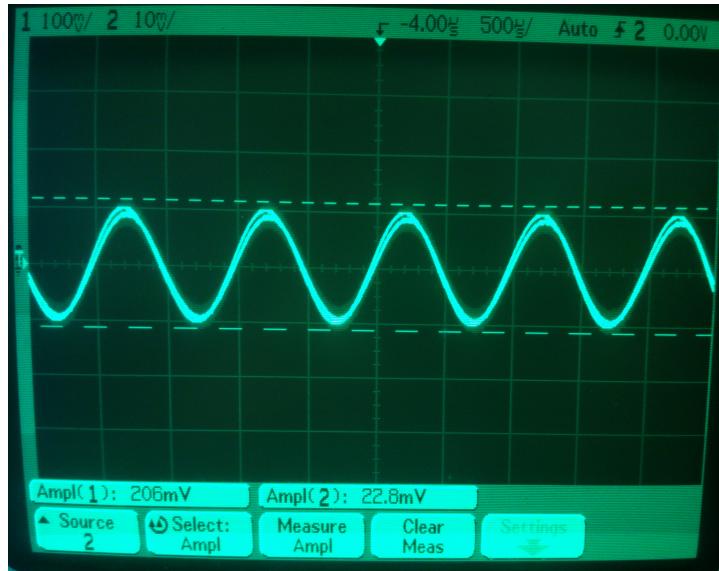


Figure 8: Non-inverting AC amplifier - 20dB gain

## 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 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.

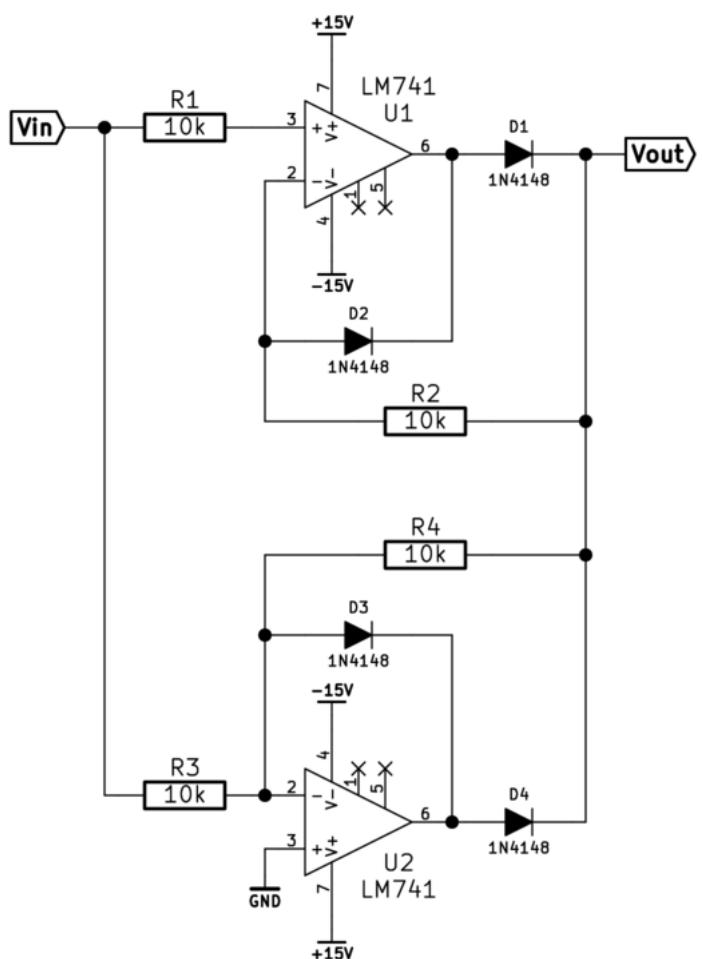


Figure 9: Active full wave rectifier

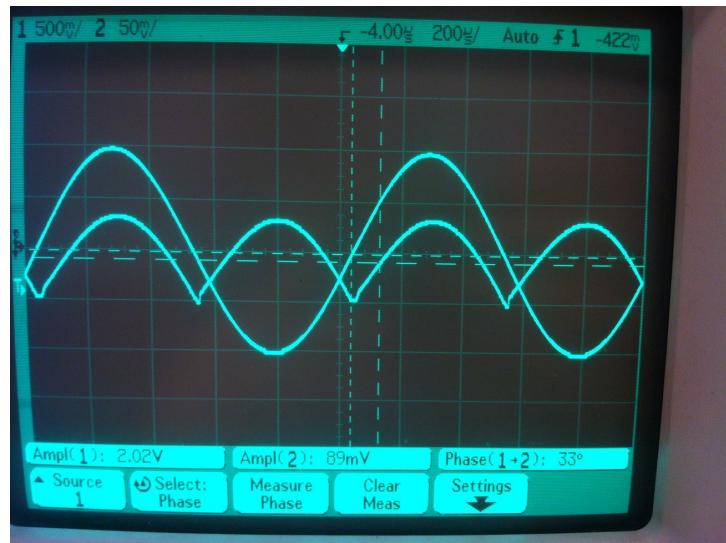


Figure 10: Full wave rectifier - input and rectified output

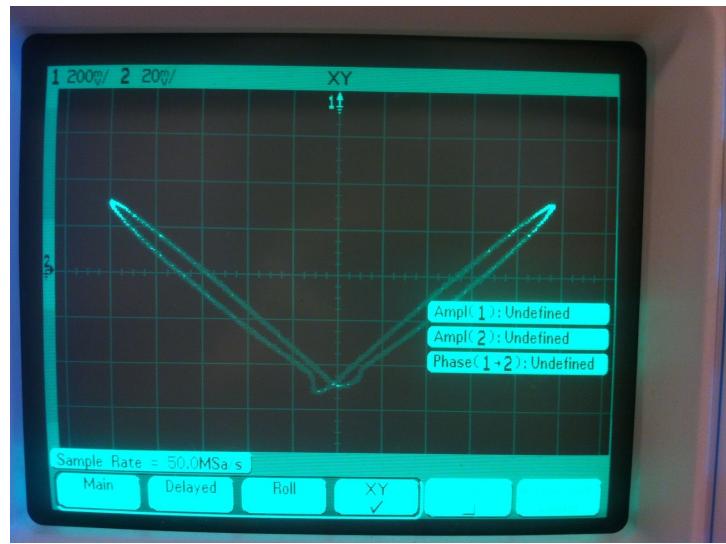


Figure 11: Full wave rectifier - X/Y-view

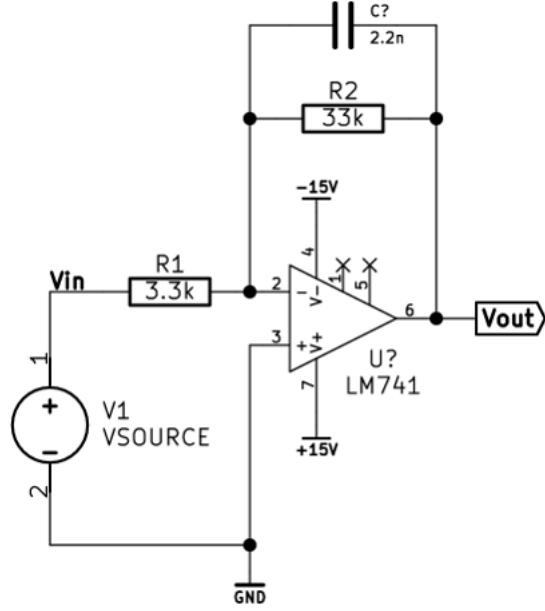


Figure 12: Low pass filter

$$A_v = \frac{Z_f}{Z_i} \quad (22)$$

The circuit transfer function is;

$$A_v = \frac{V_{out}}{V_{in}} = -\frac{Z_f}{Z_i} \quad (23)$$

$$= \frac{R_2}{R_1} \times \frac{1}{\sqrt{1 + (\omega R_2 C)^2}} \quad (24)$$

$$= \frac{33k\Omega}{3.3k\Omega} \times \frac{1}{\sqrt{1 + (\omega \times 33k\Omega \times 2.2nF)^2}} \quad (25)$$

## 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

TODO

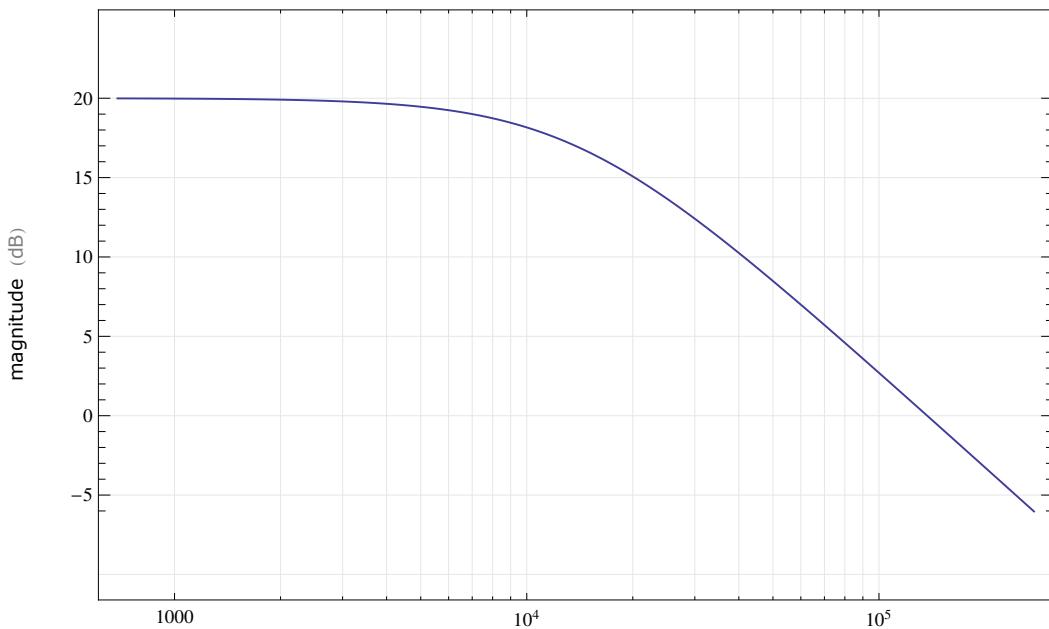


Figure 13: Low pass filter frequency response

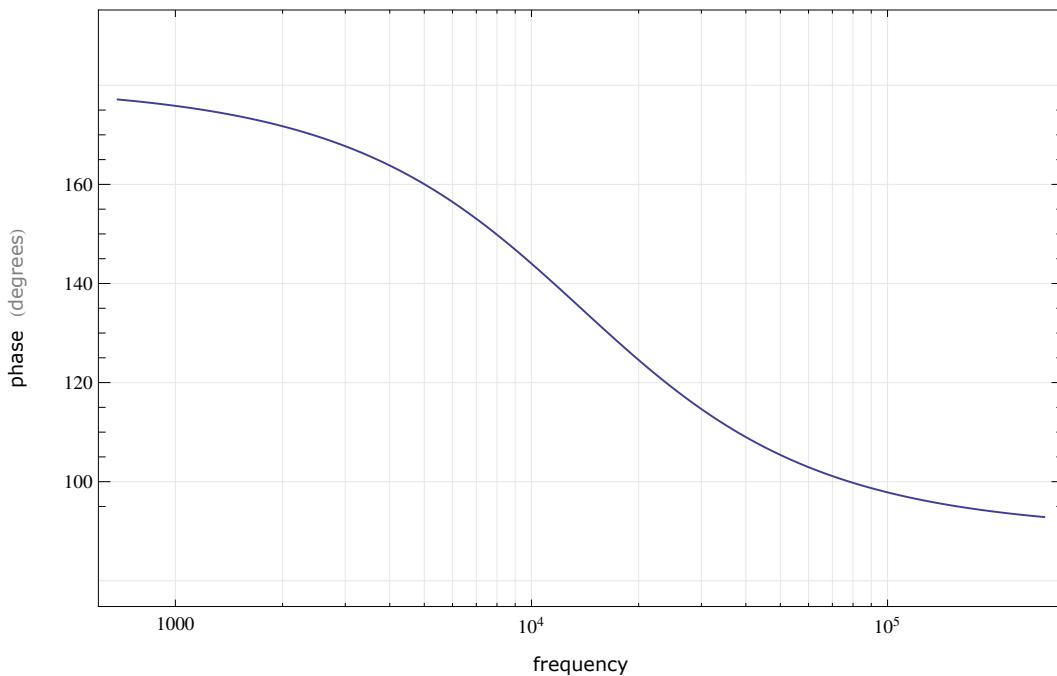


Figure 14: Low pass filter phase response

## 8 Zener diode clipper

### 8.1 Theory

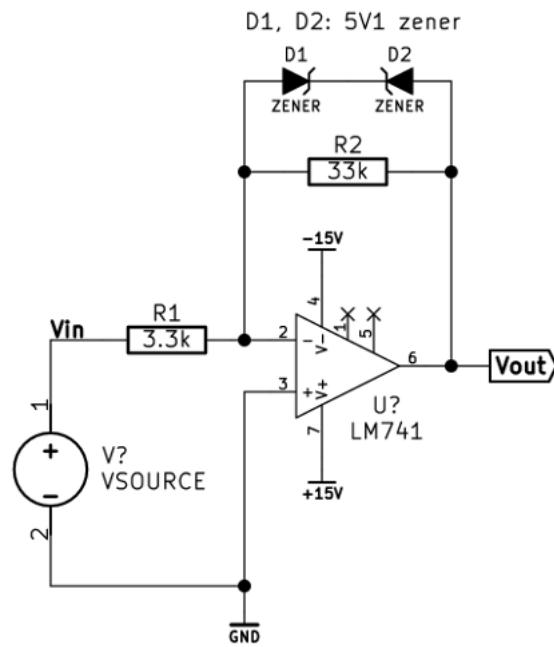


Figure 15: Zener diode clipper

The schematic for a inverting amplifier with a diode amplitude limiting clipper is shown in Figure 15.

### 8.2 Measurements

TODO

### 8.3 Oscilloscope shots

TODO

## 9 Results

TODO

## **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>