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DEPARTMENT OF COMPUTING

Biomedical Instrumentation Lab Report

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1 Part A

Question 1.1 *What function does this circuit perform? Can you identify any possible sub—circuits within it? Write and elaborate on the basic relations needed for deriving the transfer function of this block.*

This circuit performs a band-pass filter action. It is composed of four passive filters, two first order low-pass RC (Resistor and Capacitor) filters with a cut-off frequency of 4.08 Hz on the left-hand side of the circuit and two first-order high-pass RC filters with a cut-off frequency of 80 mHz. The cut-off frequency of those individual filters can be calculated from:

$$f_{c-L} = f_{c-H} = \frac{1}{2\pi RC}$$

To derive the transfer function of any of the band-pass filter we should first state the impedance of the components we are dealing with:

$$Z_{capacitor} = \frac{1}{Cs}$$

$$Z_{resistor} = R$$

We then number the nodes from left to right 1,2 3 and 4. We will take $R_1 = 39\text{k}\Omega$, $R_2 = 2\text{M}\Omega$ and C = 1μF. Applying Kirchoff's Current Law at every node we get:
At node 1:

$$\frac{V_{in} - V_1}{R_1} = V_1 Cs + \frac{V_1 - V_2}{R_1}$$

At node 2:

$$\frac{V_1 - V_2}{R_1} = V_2 Cs + (V_2 - V_3)Cs$$

At node 3:

$$(V_2 - V_3)Cs = \frac{V_3}{R_2} + (V_3 - V_{out})Cs$$

At node 4:

$$(V_3 - V_{out})Cs = \frac{V_{out}}{R_2}$$

Where s is the Laplace variable, for the purpose of our studies s = jω (angular frequency).
By rearring the equation for node 4:

$$V_3 = V_{out} \cdot \left(1 + \frac{1}{R_2 Cs}\right)$$

By plugging this onto the equation for node 3 and with further rearranging we get:

$$V_2 = V_{out} \cdot \left(\frac{1}{(R_2 Cs)^2} + \frac{3}{R_2 Cs} + 1\right)$$

And so on:

$$V_1 = V_{out} \cdot \left(\frac{1}{(R_2 Cs)^2} + \frac{2R_1}{R_2^2 Cs} + \frac{3}{R_2 Cs} + \frac{5R_1}{R_2} + R_1 Cs + 1\right)$$

Finally,

$$\frac{V_{in}}{V_{out}} = (R_1 Cs)^2 + R_1 Cs \cdot \left(3 + \frac{5R_1}{R_2}\right) + \frac{1}{R_2 Cs} \cdot (5R_1 + 3) + \frac{1}{(R_2 Cs)^2} + \frac{R_1}{R_2} \cdot \left(\frac{2R_1}{R_2} + 13\right) + 1$$

If we were to plot $20log_{10}$ of the inverse of this function against the log_10 of frequency (Hz) we would obtain a close match to the band pass filter obtain in figure 3 in part B.

Question 1.2-a *Plot the response from the two measurements (one and two) on the same graph, where the y—axis is the dB drop and the x—axis is the frequency. Comment on these results and explain the difference between the two graphs.*

The plot and tables of the respective measurements can be seen in Part B - Section 2.1.1.
The blue plot shows us the action of the first low-pass filter, which is of first order. For such a circuit theoretically we would expect a roll-off of -20 dB/decade, although we are getting a roll-off of approximately -9 dB/decade in practice. Measurement 2 correspond to the operation of the 2^{nd} order low-pass filter which is simply produced by placing both first order low-pass filters in series. Again, the roll-off does not match the theoretical expectations. The expected roll-off of a 2^{nd} order low-pass filter is of 40 dB/decade but we are getting a roll-off of 17 dB/decade. Finally, it is important to note that at frequencies lower than 2 Hz ($10^{0.3}$ Hz) the operation of both filters is similar.

Question 1.2-b *If the circuit was extended as shown in the diagram below how many dBs/Oct attenuation would you expect between the frequencies of 12Hz and24Hz?*

In the scenario where we are considering frequencies of 12 Hz and 24 Hz, it is safe to assume that the dB drop of the high-pass filter will be 0 (i.e. there will be no signal attenuation by the high-pass filter). The circuit then simplifies to a 3^{rd} order low-pass filter with an expected roll-off of -60dB/decade which is equivalent to -18dB/octave, as 1 dB/decade is equal to $\left(\frac{ln(2)}{ln(10)}\right) \approx 0.3$ dB/octave.
Although this will not be the case. In the previous section we have seen the the roll-off was approximately half the theoretical expectation. This is due to the fact that we cannot take the filter formed by several of these RC filters we are connecting together as isolated filters, where we simply multiply the transfer function of every sub-unit to obtain to transfer function of the main body like in signals theory. The cause of this is that current flows out of every sub-circuit so we cannot apply the voltage divider principle to every sub-unit.

The expected roll-off is hence not -60dB/decade but more or less -30 dB/decade so roughly -9 dB/octave.

Question 1.3 *Plot the response from the two measurements (three and four) on the same graph, where the y—axis is the dB drop and the x—axis is the frequency. Com-*

ment on these results and explain the difference between the two graphs.

The plot and tables of the respective measurements can be seen in Part B - Section 2.1.2
The blue plot shows us the action of the first low-pass filter, which is of first order. Measurement 2 correspond to the operation of the 2^{nd} order high-pass filter. Again, the roll-off does not match the theoretical expectations. In this case, for frequencies higher than $10^{-0.5}$ ($\approx$ 0.3Hz) both measurements are similar until they both reach 0 dB drop.

Question 1.4 *If you were to measure the response across the entire circuit as shown in the above diagram, how would you expect the dB drop to be as frequency of the input sinusoid changed and why? Think of appropriate frequencies to use to make the measurement and prove your point by making your own measurements and show a resulting plot.*

As we are combining a low-pass filter and a high-pass filter we can expect the output to be a band-pass filter. When testing the whole filter if the frequency of the input sinusoid is too low or too high the amplitude of the signal will be attenuated. To be more precise we can expect a null dB drop between the frequencies $10^{-0.5}$ and $10^{0.2}$ Hz, corresponding to the bandwidth of our filter [0.3Hz,1.6Hz]. Outside of these range of frequencies we can expect a slope of ∓18 dB/decade respectively.
The plot and table for this last measurement can be found in Part B - Section 2.1.3.

Question 2.1 *What function does this circuit perform? Can you derive the transfer function?*

Assuming virtual short circuit between the input terminals of the op-amp we have the same structure as in a voltage divider where:

$$V_{in} - 1.5 = \frac{120}{120k + 120} \cdot (V_{out} - 1.5)$$

$$\Leftrightarrow V_{out} - 1.5 = \frac{120k + 120}{120} \cdot (V_{in} - 1.5)$$

$$\Leftrightarrow V_{out} = 1001 \cdot (V_{in} - 1.5) + 1.5$$

$$\Leftrightarrow \text{TF: } V_{out} = 1001 \cdot V_{in} - 1500$$

V_{out} is contained between 0 volts and 3 volts as determined by the power supply of the op-amp. The following gives the range of V_{in} in which the signal is amplified linearly.

$$0 < V_{out} < 3$$

$$\Leftrightarrow 0 < 1001 V_{in} - 1500 < 3$$

$$\Leftrightarrow 1500 < 1001 V_{in} < 1503$$

$$\Leftrightarrow 1.498 \text{ volts} < V_{in} < 1.501 \text{ volts}$$

For values of V_{in} lower than the lower bound of this inequality V_{out} will be 0 volts(Ground) and for values of V_{in} greater than the upper bound of the inequality V_{out} will be 3 volts. This circuit performs the function of a *non-inverting amplifier* in its linear operating region.

Question 2.2 *Show the outputs of the above measurements. Why do we observe this? Why is the DC offset so important?*

The outputs of the above mentioned measurement can be seen on Part B - Section 2.2.1.

The DC offset is important in this situation because if the voltage at the input is lower than 1.5 Volts (1.498 in the theory) the output voltage will be 0 (negative saturation) and if the voltage at the input is greater than 1.501 Volts then the output voltage will be 3 Volts (positive saturation). If the input voltage was between 1.498 and 1.501 Volts the output voltage would follow the Transfer function calculated previously. Saturation can be perceived more clearly in measurement 2, where when sinusoidal input reaches 1.5 Volts, we get a peak of 3 volts at that same time. In measurement 4 we can also see that the output stays at 3 volts as the input voltage is in the range [1.5,2.5], if the input voltage were to drop just below 1.5 Volts we would observe a sudden drop to 0 volts at that time. It is important to note that the input voltage range required for the linear operation of the op-amp is so small that the signal increasing from 0 to 3 volts seems almost instantaneous.

Question 2.3 a) *Show the outputs of the above measurements.*

The outputs of the above mentioned measurement can be seen on Part B - Section 2.2.2.

I want to stress that my measurements 5 (the 2^{nd} one), 6 and 7 are all wrong, as it was too tedious to get a 50 mV peak-to-peak voltage in the first lab to calculate the attenuation frequency. Instead I used a 500 mV peak-to-peak voltage for both finding the attenuating frequency and these three last measurements.
Although, I know what I should have gotten as the output for these measurements as I will explain in the following questions.

Question 2.3 b) *For measurement 5, can you explain the output?*

For this measurement we have a voltage of 50 mV peak-to-peak going into the band-pass filter which attenuates to a sinusoid of 3mV peak-to-peak at a frequency of 16 Hz. Because the positive terminal of the op-amp is connected at the output of the band-pass filter and at the 1.5 Volts power supply, we do not need to worry about adding a 1.5 DC offset as this is already provided by the power supply. The combination of that already sorted DC offset and the very small voltage from the attenuated input by the band-pass filter locates the input signal to the op-amp exactly within the linear operating region of the op-amp. Hence the input signal is linearly amplified by the op-amp in accordance with the transfer function derived in question 2.1. The input voltage into the op-amp should be 1500 ± 1.5 mV. In theory, the output voltage from this measurement is a 3 volts peak-to-peak voltage with a mean value of 1.5 Volts with the same frequency as the input signal (16 Hz). In practice this will be harder to get as we do not get a measurement of what goes into the op-amp input, and slight tweaks in the frequency either at the input or through the filtering will affect the input signal to the op-amp.

Question 2.3 c) *For measurement 6 is the DC offset important in this case? If it is different from before why is this? Why do we need to wait before we measure anything?*

All the graphs will look the same in these measurements as the DC offset will be blocked by the capacitors in the band-pass filters.

In this case we use the capacitors in the filters as coupling capacitor or DC blocking capacitors so whatever DC offset is set at the input will be blocked by the capacitors and only the AC signal will flow through the band-pass filter. The DC offset is hence not important in this case. The capacitors are connected to the 1.5 volts power supply, therefore we need to wait for the capacitor to reach their steady-state operation (i.e. reach the 1.5 V from the power supply). The charging time of the capacitor is also known as the capacitor transient response.

Question 2.3 d) *For measurement 7, can you show the different sub—systems that make up the full circuit and hence can you explain the output?*

The circuit is composed of the band-pass filter that we analysed in question 1. The circuit is also composed by the non-inverting amplifier that we have analysed in this section. The frequency of 16 Hz at which a 50 mV peak-to-peak voltage attenuates to a 3 mV signal is found on the decaying part of the band-pass filter.

When we first increase the frequency by 10 Hz, our signal is found further right on our band-pass filter spectrum, therefore the amplitude of our signal will be decreased further more. The upper and lower boundaries of this sinusoid are included in the linear operating range of the op-amp. Hence, we get a fully amplified version of this smaller amplitude signal at the output of the op-amp.

On the other hand, when we decrease the frequency of the input signal by 10 Hz our signal is found further left on our band pass filter spectrum but not further than the peak of the band-pass filter. Therefore this input signal will be less attenuated and the signal going into to op-amp will have a greater peak-to-peak voltage than 3 mV. Hence the op-amp will either be in positive or negative saturation and the output will be either 3 Volts or 0 volts respectively.

Question 3.1 a) *What are the outputs of the above measurements?*

The outputs of the above mentioned measurement can be seen on Part B - Section 2.3

Question 3.1 b) *For measurement 1 how is the DC offset important in the operation of the diode?*

When the input of the diode has no DC offset, the diode would be either forward biased when the input is greater than 0 volts or reverse biased when the input is less than 0 volts. When the input is forward biased current will flow trough the diode, and the output will be an attenuated version of the input signal as there will still be some resistance in the diode that will draw impede the flow of some of the current. We obtain a peak to peak to voltage at the output of the diode of 680 mV. The rest of the time, when the input is below 0 volts and the diode is reverse biased we should theoretically obtain 0 volts but in practice a parasitic current flows through the diode and we obtain an output voltage of about 100 mV.
When a DC offset of -1 V is applied at the input of the diode is always reverse biased thus no current flows through the diode and the output voltage is 0 V.
When a DC offset of +1 V is applied at the input of the diode, the diode should act as a short circuit allowing all the current to flow, hence the output should be equal to the input signal. In practice even though the depletion region of the diode will expand when forward biasing occurs there is still some resistance in the diode that will cap the output at the lower bound of the sinusoid.

Question 3.1 c) *For measurement 2 what is the effect of changing the signal frequency?Can you estimate a time constant?*

The circuit in question performs the function of a half wave rectification Envelope detector, giving the outline of the positive extremes of the input signal. The circuit does this by storing charge in the capacitor while the diode is forward biased and releasing that charge through the resistor when the diode is reverse biased or off. As we increase the frequency the capacitor gets less time to charge up and less time to charge down therefore at every iteration we increase the frequency the peak-to-peak voltage of our output signal decreases, as the capacitor does not get enough time to operate properly. At a frequency of 10 kHz, the changes in the input voltage happen to quickly and the charging and de-charging of the capacitor is of the order of a ± 10 mV. The output voltage sets at approximately the maximum voltage the capacitor takes at the first measurements with low frequencies. This may not be a coincidence, we initially charge the capacitor up and down and gradually increase the frequency of the signal without disconnecting anything. I we had connect an input signal with a frequency of 10 kHz straight away we would probably get a constant line at 0 volts as the capacitor would not have time to charge nor de-charge.

The resistor and the capacitor operating in parallel work as a low-pass filter and we can derive a time constant from it.

$$\tau = RC; \tau = 47 \cdot 10^3 \cdot 100 \cdot 10^{-9}$$
$$\tau = 4.7 \cdot 10^{-3} s = 4.7 ms$$
$$f_\tau = \frac{1}{\tau} = 213 \text{ Hz}$$

The time constant cannot be too low as then the envelope detector would detect too much noise and ripples and it cannot be too large as it could miss some important information.

Submission of the personal unguided design
See section 2.4 in Part B.

Question 3.2 a) *What is the purpose of the two 220pF capacitors in the circuit in page 27?*

The purpose of the 220 pF capacitors is to smooth the voltage between the skin electrodes and remove any DC offset from it.

Question 3.2 b) *If a square wave from zero to one volt and of frequency 32 kHz is given as input as shown in the above diagram how does this affect the current flow through the wires that attach to the electrodes?*

The part of the circuit containing a resistor of 100kΩ and 1μF capacitor connecting to the positive terminal of the op-amp is a high-pass filter with a DC offset of 1.5V and a cut-off frequency of 1.6 Hz. In this situation the input is not affected by the filtering as it frequency is 32 kHz. The rest of the circuit is a non-inverting amplifier with a DC offset of 1.5V and with a gain of $\frac{R_2+R_1}{R_1}$ where $R_1 = 6.6k\Omega$ and $R_2 = R_{skin}||R_3$ where R_{skin} is the impedance through the skin of the impedance respirometric system user and R_3 is the resistor with a resistance of 1 kΩ. The transfer function of this circuit is:

$$\frac{V_{out} - 1.5}{V_{in} - 1.5} = \frac{R_2 + R_1}{R_1}$$

$$\text{where, } R_2 = R_{skin}||R_3 \ ; R_2 = \frac{R_{skin} \cdot R_3}{R_{skin} + R_3}$$

In this question we consider R_{skin} to be equal to 1 kΩ but in the real case this will vary with the expansion and contraction of the user's tissues.
Hence,

$$R_2 = \frac{1}{2} k\Omega$$

$$\Leftrightarrow \frac{R_2 + R_1}{R_1} = \frac{6.6 + 0.5}{6.6} = 1.08$$

$$\text{TF: } V_{out} = 1.08 \cdot (V_{in} - 1.5) + 1.5$$

The input signal being a square wave from zero to one volt, the output signal will be a square wave from -0.12 to 0.96 volts.
The current trough the skin electrodes can easily be calculated from Ohm's law:

$$i = \frac{V_{in} - V_{out}}{R_{skin}}$$

If $V_{in} = 0$ volts:

$$i_0 = \frac{0.12}{1} = 0.12mA = 120\mu A$$

If $V_{in} = 1$ volt:

$$i_1 = \frac{0.04}{1} = 0.04mA = 40\mu A$$

If the impedance from the expansion and compression of the user's tissue is lower than 1kΩ then more current will flow through the skin electrodes, if the impedance is greater than 1kΩ then less current will flow through the skin electrodes.

Question 3.2 c) *Hence can you explain what function does the circuit in the below diagram perform? How is it useful in the impedance respirometric system?*

The input voltage of this circuit is what is known as the carrier frequency for amplitude modulation. The gain of this circuit will be modulated by the varying resistance of the user's elastic tissues, the frequency at which the resistance will vary is the modulating frequency. The modulating frequency is more simply the breathing rate, this is a very low frequency of about 0.25 Hz (average resting respiratory rate for a healthy adult[1]). The carrier frequency 'carries' the information from the modulating frequency signal which is too low standing alone for electronics. The greater the carrier frequency the better we can perceive the modulating as stated in the report's notebook.

Question 3.3 a) *Derive the transfer function of the following circuit:*

In this circuit we take R = 220kΩ, C_1 = 220 pF, C_2 = 33 pF. We are also taking: $V_{in} = E^+ - E^-$ where E^+ is the voltage at the top and E^- at the bottom. V^+ and V^- state for the positive and negative terminal of the op-amp respectively. All through out the derivation we will consider the 1.5V to be virtual ground.
The impedance Z of the parallel combination of C_2 and R is:

$$Z = \frac{R}{RC_2 s + 1}$$

The part of circuit connected to the positive terminal of the op-amp is a potential divider where:

$$V^+ = \frac{Z}{Z + \frac{1}{C_1 s}} \cdot E^-$$

$$V^+ = \frac{\frac{R}{RC_2s+1}}{\frac{R}{RC_2s+1} + \frac{1}{C_1s}} \cdot E^-$$

$$V^+ = \frac{\frac{R}{RC_2s+1}}{\frac{RC_1s+RC_2s+1}{(RC_2s+1)C_1s}} \cdot E^-$$

$$V^+ = \frac{RC_1s}{R(C_1+C_2)s+1} \cdot E^-$$

The same current flows between V_{out} and V_- and between V_- and E^+. We assume virtual short circuit between the terminals of the op-amp, hence $V_- = V_+$. The current is equal to:

$$i = \frac{E^+ - V^-}{\frac{1}{C_1s}} = \frac{V^- - V_{out}}{Z}$$

$$[E^- + V_{in} - V^+] \cdot C_1s = \frac{V^+ - V_{out}}{Z}$$

Substituting V+ by the previously found value:

$$\left[V_{in} + E^- \cdot \left(1 - \frac{RC_1s}{R(C_1+C_2)s+1}\right)\right] \cdot C_1s = \frac{RC_1s}{R(C_1+C_2)s+1} \cdot \frac{1}{Z} \cdot E^- - \frac{V_{out}}{Z}$$

Substituting Z for the previously stated value and simplifying some terms that cancel out:

$$\left[V_{in} + E^- \cdot \left(1 - \frac{RC_1s}{R(C_1+C_2)s+1}\right)\right] \cdot C_1s = E^- \cdot \frac{(RC_2s+1) \cdot C_1s}{R(C_1+C_2)s+1} - V_{out} \cdot \frac{RC_2s+1}{R}$$

By further expanding all the expression we get:

$$V_{in}C_1s + E^-C_1s \cdot \left(\frac{RC_1s + RC_2s + 1 - RC_1s}{R(C_1+C_2)s+1}\right) = E^- \cdot \frac{(RC_2s+1) \cdot C_1s}{R(C_1+C_2)s+1} - V_{out} \cdot \frac{RC_2s+1}{R}$$

The terms containing E^- on each side of the equation cancel each other out:

$$V_{in}C_1s = -V_{out} \cdot \frac{RC_2s+1}{R}$$

$$\frac{V_{out}}{V_{in}} = -\frac{RC_1s}{RC_2s+1}$$

The output signal would also have an offset of 1.5V relative to the input signal to the input signal.

Question 3.3 b) *What function does this circuit perform?*

This circuit is a high-pass differential amplifier and adds an offset of 1.5V, it measures the difference between the two ends of V_{in} and then amplifies by a factor of approximately $\frac{C_1}{C_2}$ (≈ 6.7).

Question 3.3 c) *How is it useful in the impedance respirometric system?*

This circuit will amplify the voltage difference between the skin electrodes, which is this amplitude modulated square wave that we have studied in the previous section.Any noise carried in this signal will be present in both skin electrodes, hence as this circuit takes the voltage difference between skin electrodes, noise will be cancelled out and we will get our clean amplitude modulated signal at the output. The fact that this differential amplifier also performs the function of a high-pass filter is also very useful as noise from the AC mains signal with frequency of 50-60 Hz will be attenuated and will not go trough this circuit.

Question 3.4.a) *Measure the common mode attenuation of the above circuit.*

The measurements and results for the common-mode attenuation can be found in the appendix - Section 3.1. To measure the common mode attenuation gain I put a voltage of 21 volts trough both V_{in}^{+} and V_{in}^{-}. I could not observe a powerful enough common mode attenuation signal with low input voltages. For the carrier frequency of 32 kHz we are working with the common mode gain is found to be $1.02 \cdot 10^{-}3$.

Question 3.4.b) *Measure the differential gain of the above circuit.*

The measurements and results for the differential gain can be found in the appendix - Section 3.2. To measure the common mode attenuation gain I put a voltage of 1.5 volts in V_{in}^{-} and an oscillating voltage with a DC offset of 1.5V and a peak-to-peak voltage 600 mV in V_{in}^{+}. For the carrier frequency of 32 kHz we are working with the common mode gain is found to be 4.8.

Question 3.4.c) *Hence find the common mode rejection ratio. Look up in the datasheet and compare the value given for the CMRR of the op-amp with the measured. Why is it so different?*

Our operating frequency is 32 kHz, hence we will calculate the CMRR for that frequency. The CMRR can be calculated from:

$$CMRR = 20log_{10}\Big(\frac{A_d}{A_{cm}}\Big)$$

Where A_d stands for the differential gain and A_{cm} stands for the common-mode gain. Plugging in the values found we obtain:

$$CMRR(@32kHz) = 20log_{10}\Big(\frac{4.8}{1.02 \cdot 10^{-3}}\Big)$$

$$CMRR(@32kHz) = 73.5dB$$

The CMRR on the datasheet of the op-amp for the values of voltage we are testing is 84. The difference between the data sheet and our experimental value may generally be due to noise, resistance and/or capacitance fro the copper strips, attenuation from all the filtering action that is undertaken in our circuit.

Question 4) *Using this electrical analogue model of the electrode—skin interface, can you explain why the impedance decreases as injected frequency increases?*

To find the impedance of the whole electrical analogue model of the electrode-skin interface we will calculate the Thevenin resistance r of the circuit by making all voltage sources into short-circuits. r can be calculated by the following derivations:

$$r = Z_d + R_s + Z_e || Z_p + R_u$$

Where,

$$Z_{d,e,p} = C_{d,e,p} || R_{d,e,p} = \frac{R_{d,e,p}}{C_{d,e,p} R_{d,e,p} s + 1}$$

$$Z_e || Z_p = \frac{1}{s(C_p + C_e) + \frac{R_e + R_p}{R_e R_p}}$$

$$r = \frac{R_d}{C_d R_d s + 1} + R_s + \frac{1}{s(C_p + C_e) + \frac{R_e + R_p}{R_e R_p}} + R_u$$

$$r = \frac{R_d}{C_d R_d j\omega + 1} + R_s + \frac{1}{j\omega(C_p + C_e) + \frac{R_e + R_p}{R_e R_p}} + R_u$$

This is enough derivation to prove the the impedance decreases as injected frequency decreases:

$$\lim_{\omega \to 0} r = R_d + R_s + \frac{R_e R_p}{R_e + R_p} + R_u$$

$$\lim_{\omega \to \infty} r = R_s + R_u$$

We see that when we take omega to tend to infinity the value of the impedance r decreases to a minimum of $R_s + R_u$ which is the sum of the resistance of the dermis and the gel.

Question 5) *Looking at this diagram (also on page 5) can you compare it to the electrical circuit that you have built and identify the circuit that performs each function of every box? Based on your lab experience elaborate on the crucial design aspects of each block and how these might affect the system-level performance. How would you improve the specific design?*

The current injecting stage is performed by the skin electrodes in parallel with the 1 kΩ resistor and the very first non-inverting amplifier. A 32 kHz square wave is injected onto the patient's skin, then the output of the non-inverting amplifier is an amplified version of the square wave input where the gain is determined by the patient's tissue electrical impedance. The Signal Reading Stage takes place when the voltage between the electrodes is then amplified by a high-pass differential amplifier to attenuate the noise in the skin electrodes and amplify the signal of interest. This signal goes then trough the Envelope detector which in this circuit is performed by a Schottky diode in series with the parallel combination of a capacitor and a resistor. The DC offset and frequencies that do not interest us are then filtered out by a band-pass filter with its centre frequency at 0.5 Hz and a bandwidth of 2 Hz. Finally the signal is amplified by a non-inverting amplifier with a gain of a 1001.

One thing to improve in this circuit would be increasing the CMRR, this could be achieved by using capacitors and resistors with lower error tolerances so that the Common-mode gain could be reduced. A better op-amp with a greater CMRR could also be of good use as the net attenuation from the filtering action would be less, although this is hard to achieve and would be less cost efficient. The Envelope detector could be implemented by a precision half-wave rectifier[2] which would reduce having to deal with charging and de-charging of the circuit and would provide less resistance to the input voltage. To improve the functioning of the band-pass filter and the non inverting amplifiers better components with lower tolerances would be necessary. In order to reduce noise, shorter wiring would be beneficial as well as making this design in well-designed PCB.

2 Part B

2.1 Lab 1

2.1.1 Measurement 1 and 2

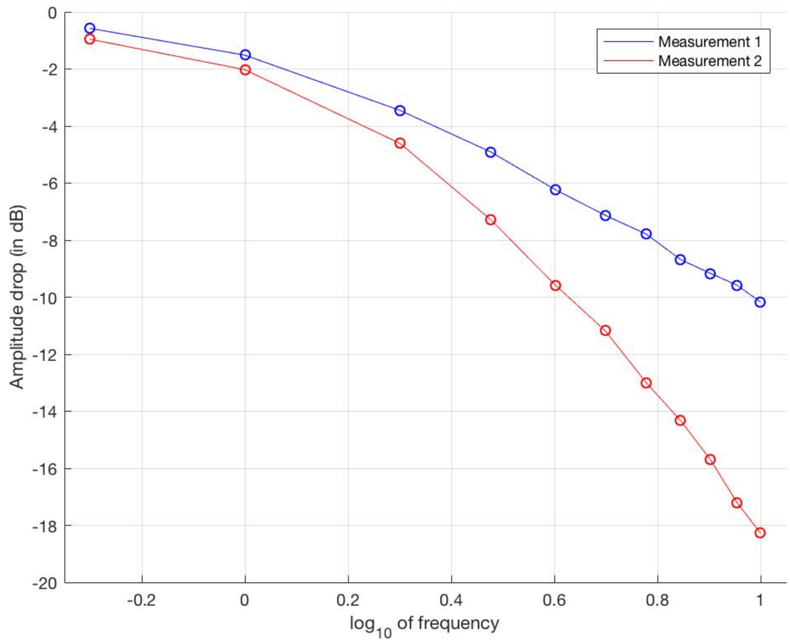

Figure 1: Amplitude drop vs. Frequency for the low-pass filters of the circuit

Table 1: Measurements 1 and 2: Low-pass filters

Frequency [Hz]	Output Voltage (M1)	Output Voltage (M2)	dB drop (M1)	dB drop (M2)
0.5	0.936	0.896	-0.574	-0.954
1	0.84	0.792	-1.514	-2.025
2	0.672	0.588	-3.453	-4.612
3	0.568	0.432	-4.913	-7.290
4	0.488	0.332	-6.232	-9.577
5	0.44	0.276	-7.131	-11.18
6	0.408	0.224	-7.787	-12.99
7	0.368	0.192	-8.683	-14.33
8	0.348	0.138	-9.168	-15.70
9	0.332	0.138	-9.577	-17.20
10	0.31	0.122	-10.17	-18.27

2.1.2 Measurement 3 and 4

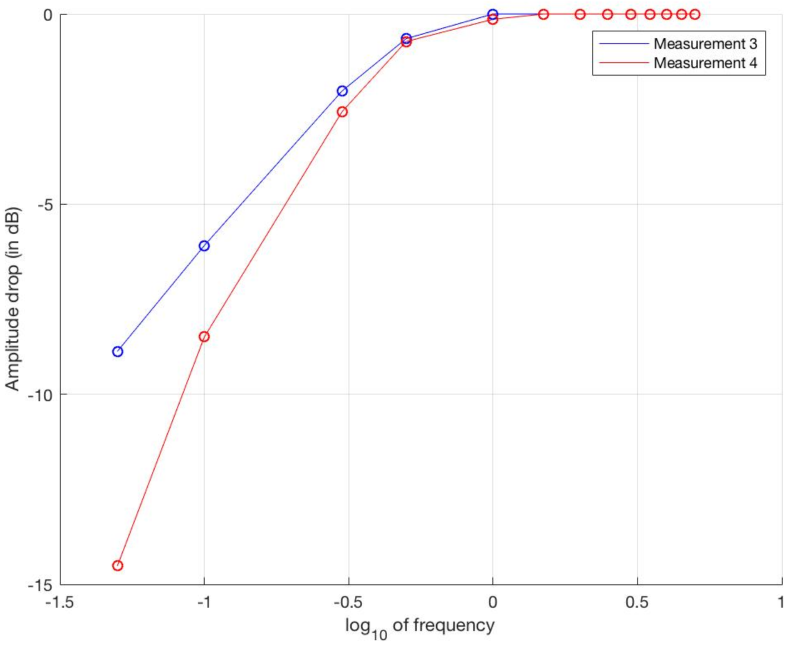

Figure 2: Amplitude drop vs. Frequency for the high-pass filters of the circuit

Table 2: Measurements 3 and 4: High pass filters

Frequency [Hz]	output voltage (M3)	output voltage (M4)	dB drop (M3)	dB drop (M4)
0.05	0.36	0.188	-8.874	-14.517
0.1	0.496	0.376	-6.090	-8.496
0.3	0.792	0.744	-2.025	-2.569
0.5	0.928	0.92	-0.649	-0.724
1	1	0.984	0.000	-0.140
1.5	1	1	0	0
2	1	1	0	0
2.5	1	1	0	0
3	1	1	0	0
3.5	1	1	0	0
4	1	1	0	0
4.5	1	1	0	0
5	1	1	0	0

2.1.3 Measurement 5

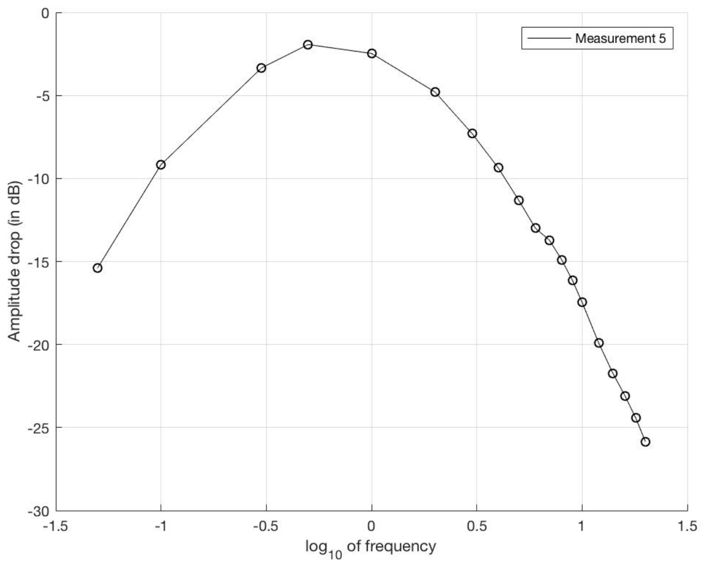

Figure 3: Amplitude drop vs. Frequency for the band-pass filters of the circuit

Table 3: Measurement 5: Band-pass filter

Frequency(Hz)	Output voltage(M5)	dB drop
0.05	0.17	-15.4
0.1	0.348	-9.2
0.3	0.68	-3.3
0.5	0.8	-1.9
1	0.752	-2.5
2	0.576	-4.8
3	0.432	-7.3
4	0.34	-9.4
5	0.272	-11.3
6	0.224	-13.0
7	0.206	-13.7
8	0.18	-14.9
9	0.156	-16.1
10	0.134	-17.5
12	0.101	-19.9
14	0.082	-21.7
16	0.07	-23.1
18	0.06	-24.4
20	0.051	-25.8

2.2 Lab 2

2.2.1 Measurements 1 to 5

Measurement 1

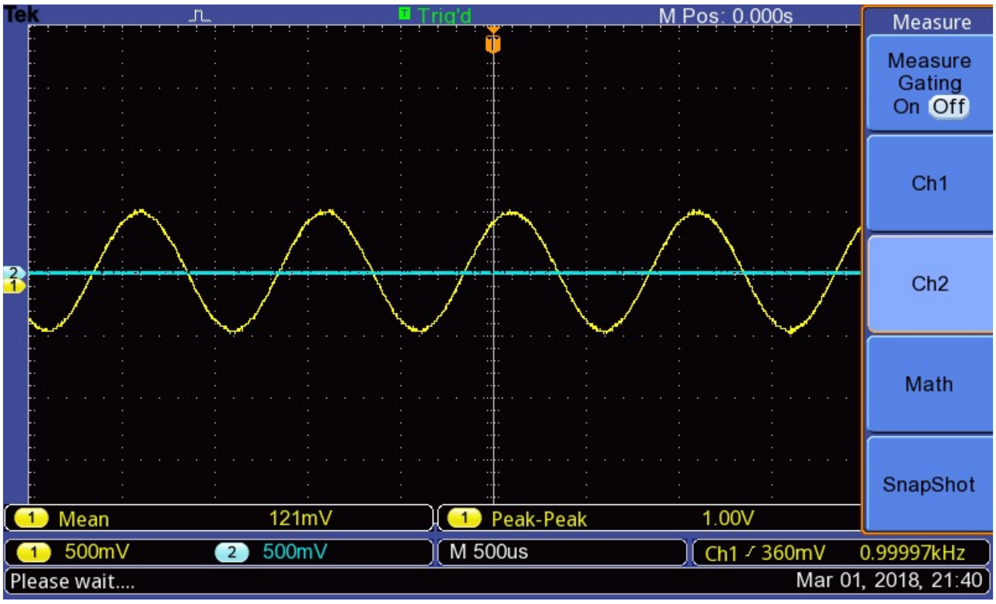

Figure 4: Input signal: 1V p-p voltage sinusoid at 1 kHz with zero DC offset - No output/Negative saturation of the op-amp at 0V

Measurement 2

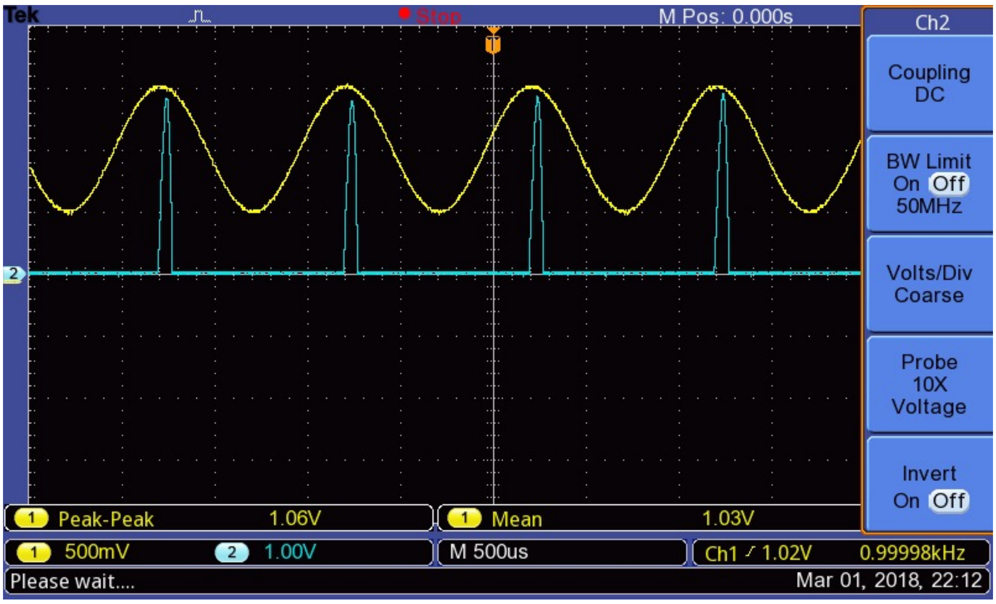

Figure 5: Input signal: 1V p-p voltage sinusoid at 1 kHz with zero DC offset - Output:Peaks at 3V when input signal trespasses 1.5V and negative saturation of the op-amp at 0V

Measurement 3

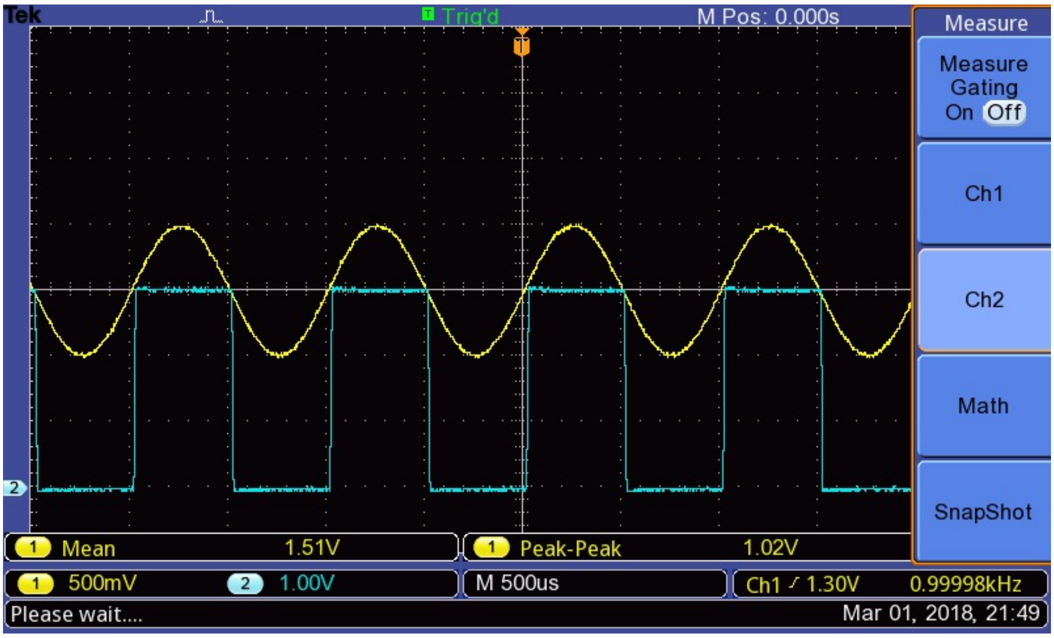

Figure 6: Input signal: 1V p-p voltage sinusoid at 1 kHz with offset of 1.5V - Positive saturation of the op-amp at 3V when input voltage is greater than 1.5V and negative saturation of the op-amp at 0V

Measurement 4

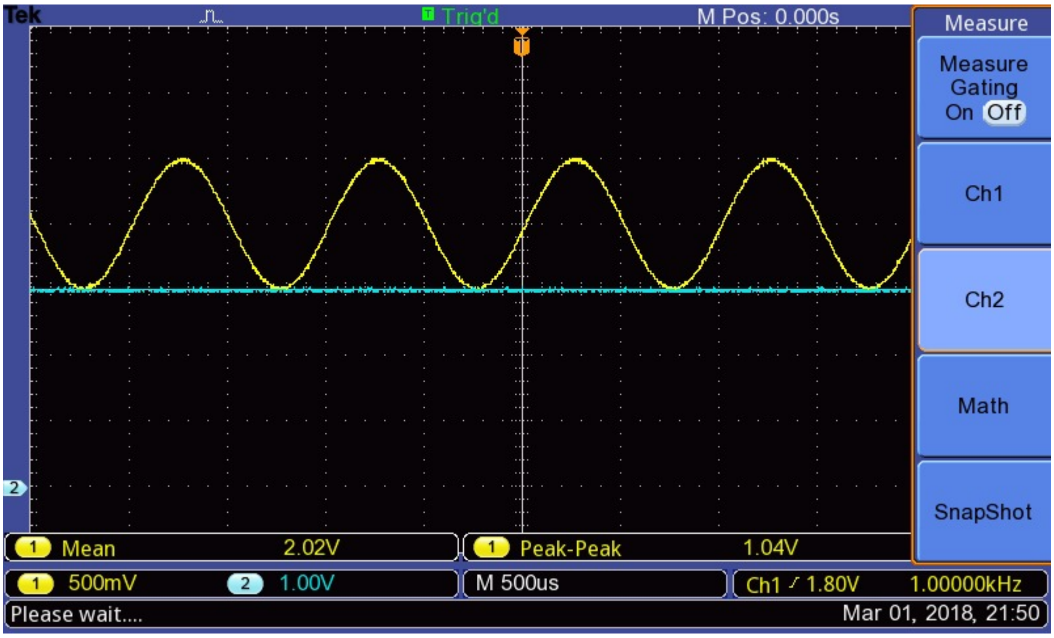

Figure 7: Input signal: 1V p-p voltage sinusoid at 1 kHz with offset of 2V - Positive saturation of the op-amp at 3V

Measurement 5

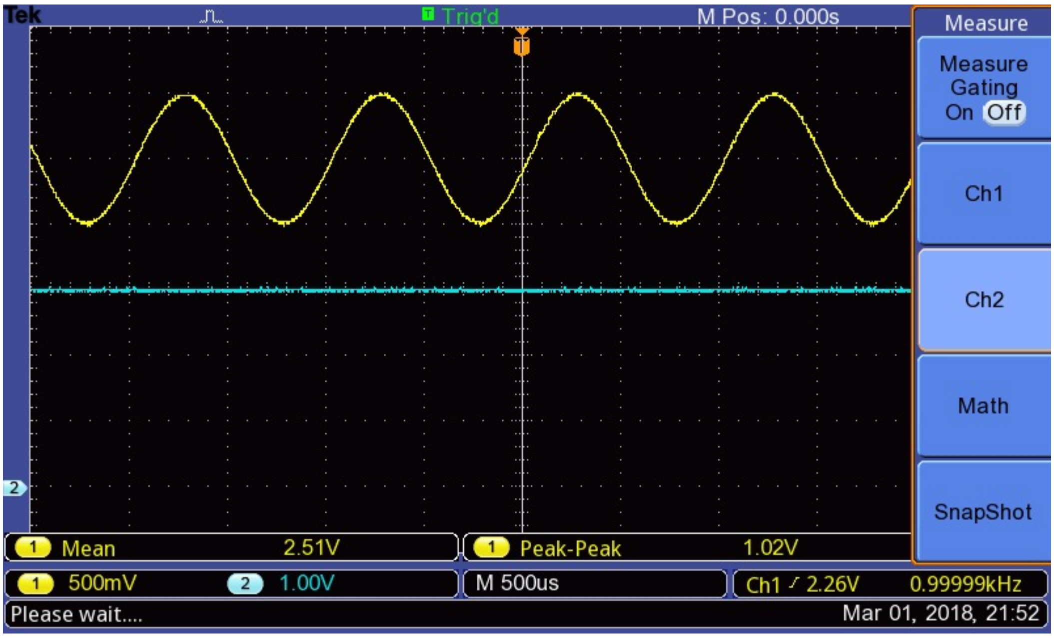

Figure 8: Input signal: 1V p-p voltage sinusoid at 1 kHz with offset of 2.5V - Positive saturation of the op-amp at 3V

2.2.2 Measurements 5' to 7

2^{nd} Measurement 5 [FAILED]

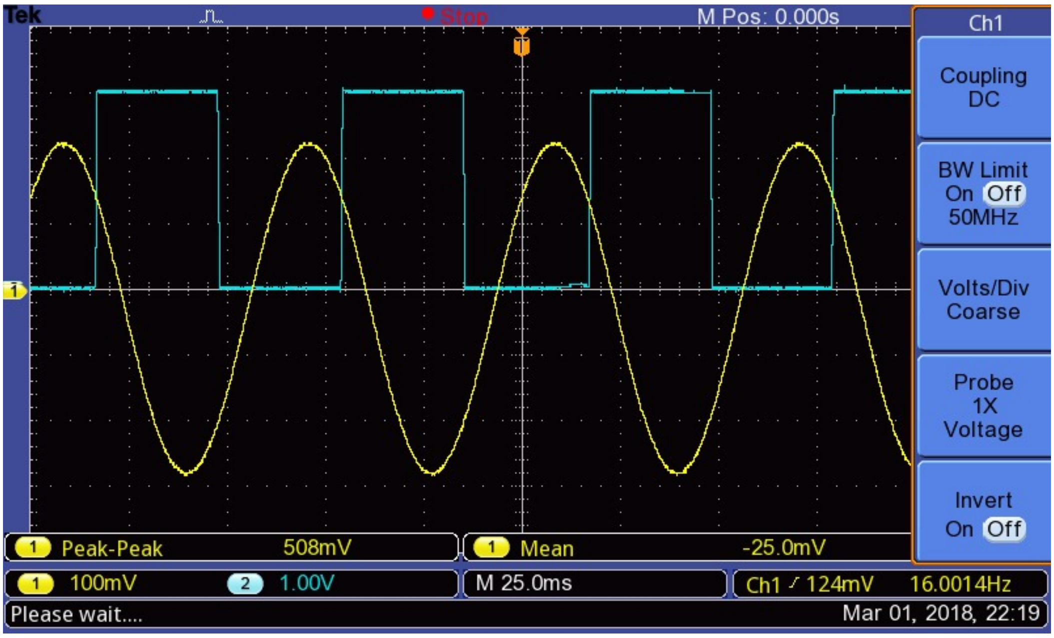

Figure 9: [FAILED] Input signal: 500mV p-p voltage sinusoid at 16 Hz with no offset - Should have obtained amplification of a very small signal

Measurement 6 [FAILED]

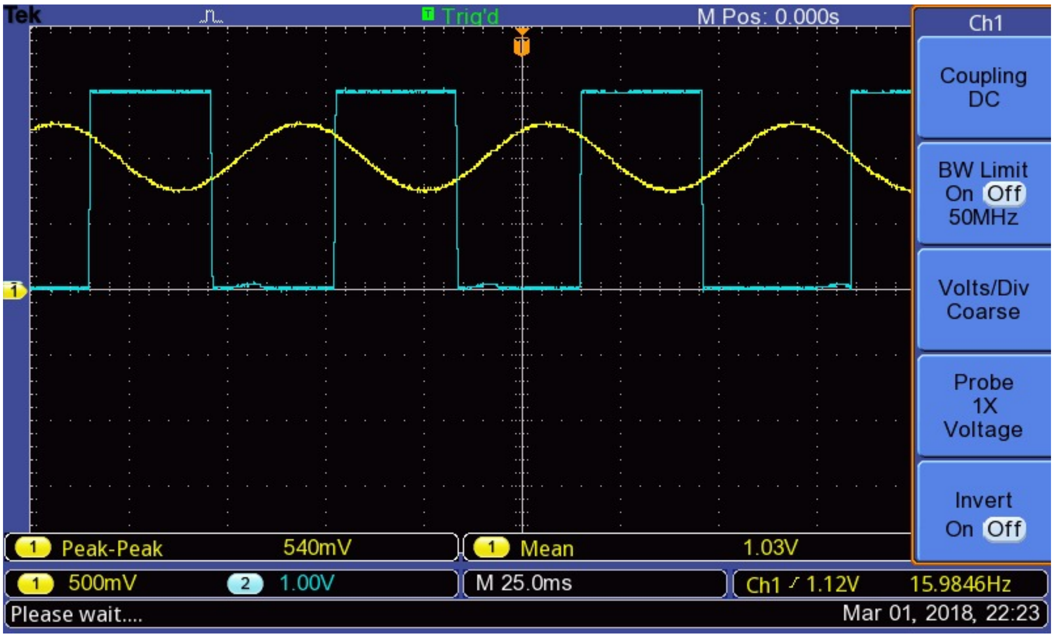

Figure 10: [FAILED] Input signal: 500mV p-p voltage sinusoid at 16 Hz with 1V offset - Should have obtained same results as expected results for 2^{nd} measurement 5

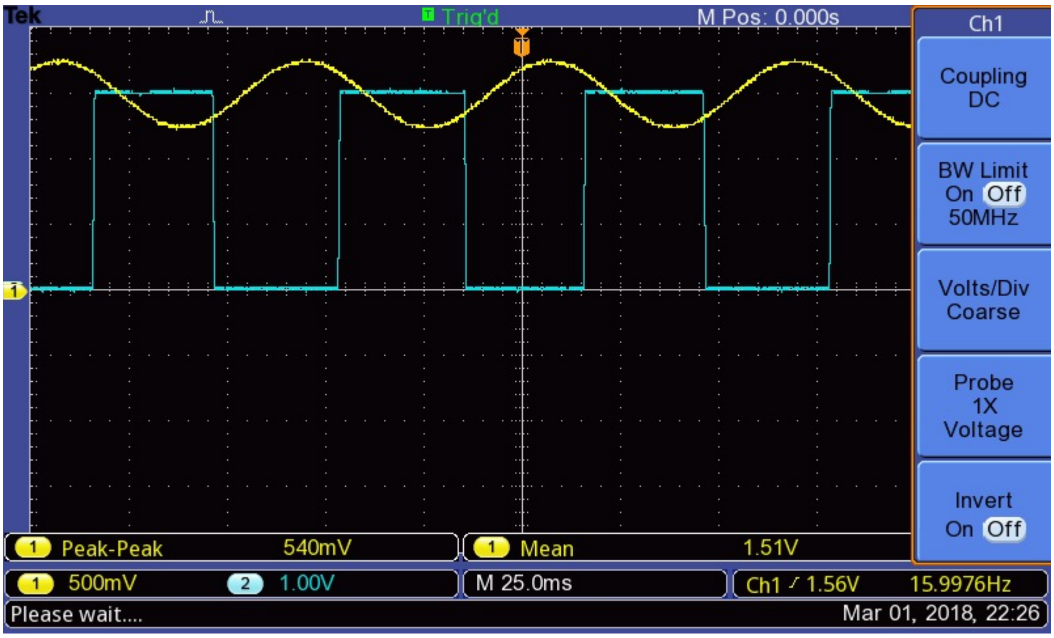

Figure 11: [FAILED] Input signal: 500mV p-p voltage sinusoid at 16 Hz with 1.5V offset - Should have obtained same results as expected results for 2^{nd} measurement 5

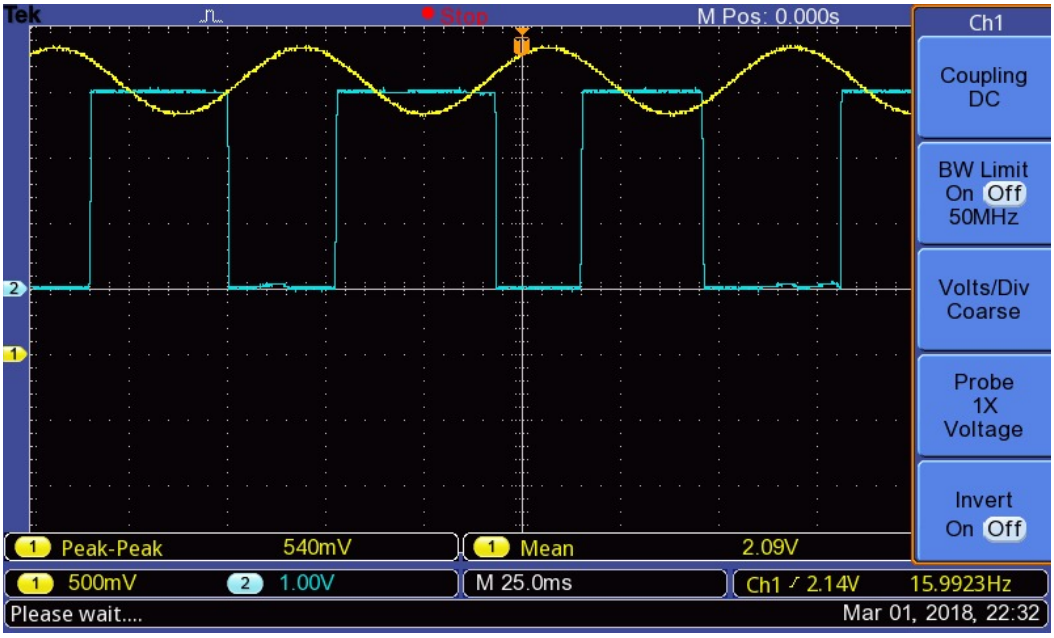

Figure 12: [FAILED] Input signal: 500mV p-p voltage sinusoid at 16 Hz with 2V offset - Should have obtained same results as expected results for 2^{nd} measurement 5

Measurement 7 [FAILED]

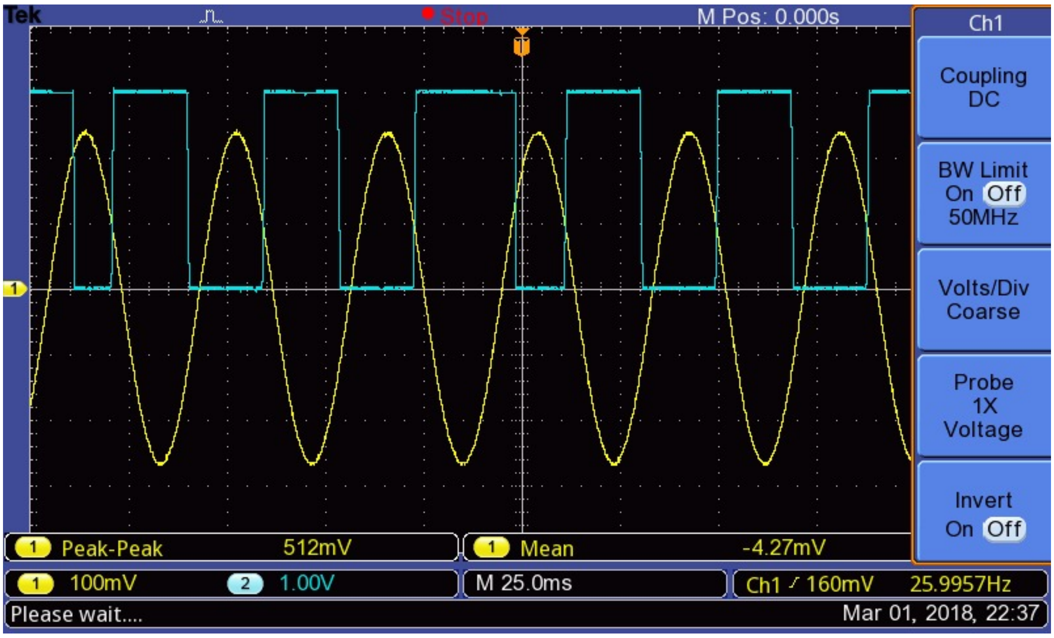

Figure 13: [FAILED] Input signal: 500mV p-p voltage sinusoid at 26 Hz with no offset - Small amplified signal

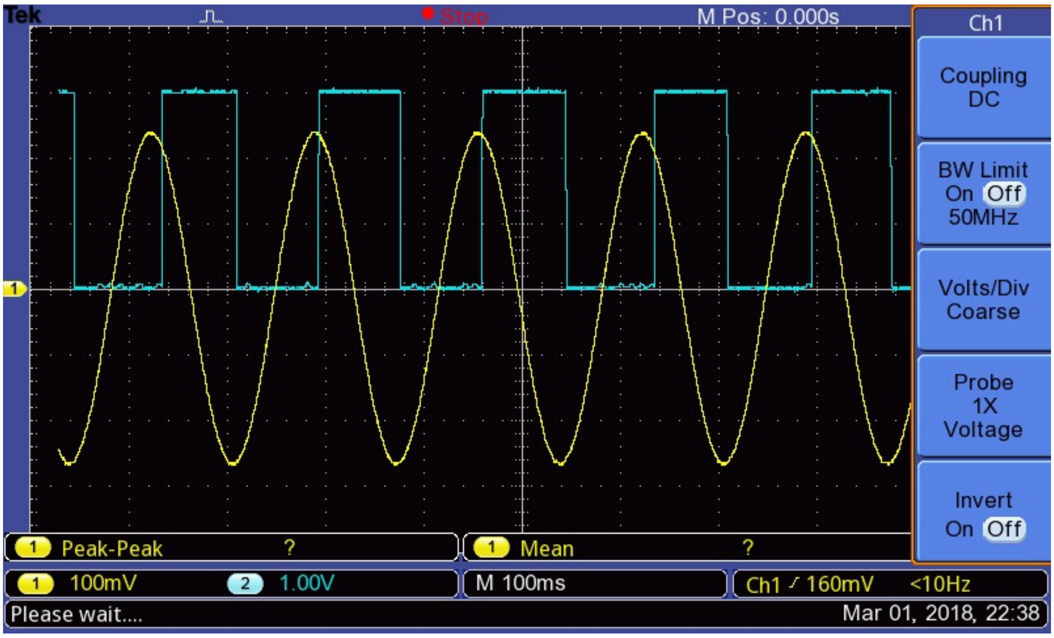

Figure 14: [FAILED] Input signal: 500mV p-p voltage sinusoid at 6 Hz with 1V offset - Positive saturation of the op-amp at 3V when input voltage is greater than 1.5V and negative saturation of the op-amp at 0V

2.3 Lab 3

Measurement 1

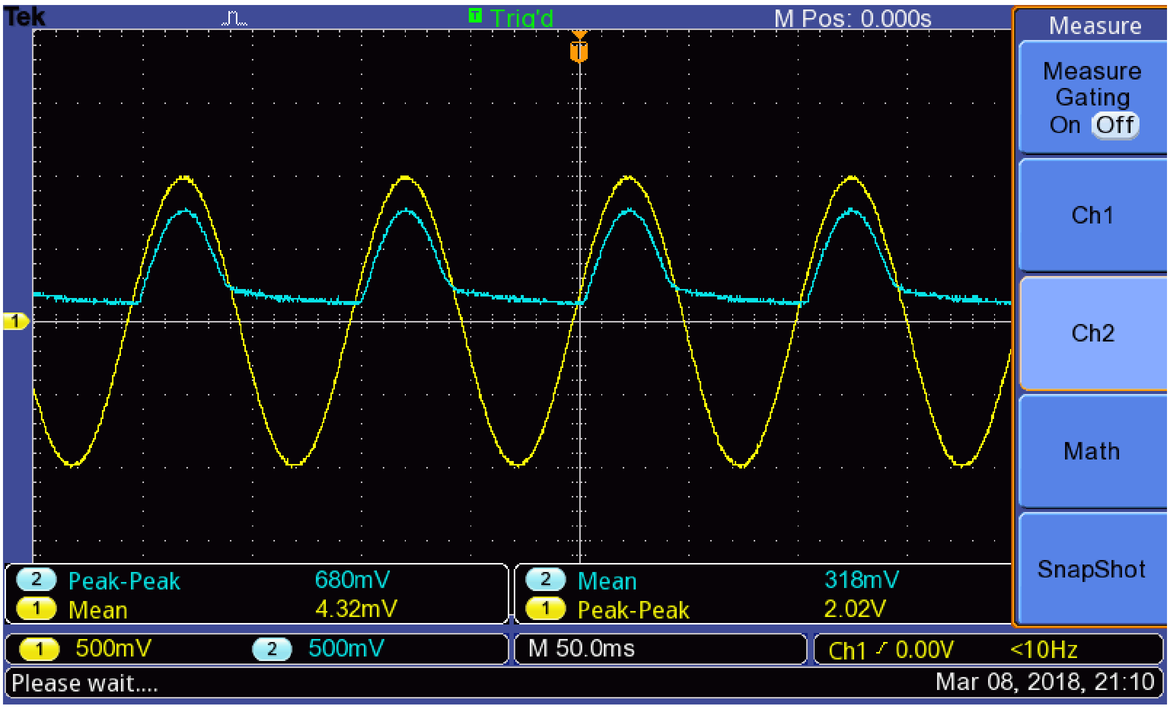

Figure 15: Lab 3 - Measurement 1.1 - No DC offset

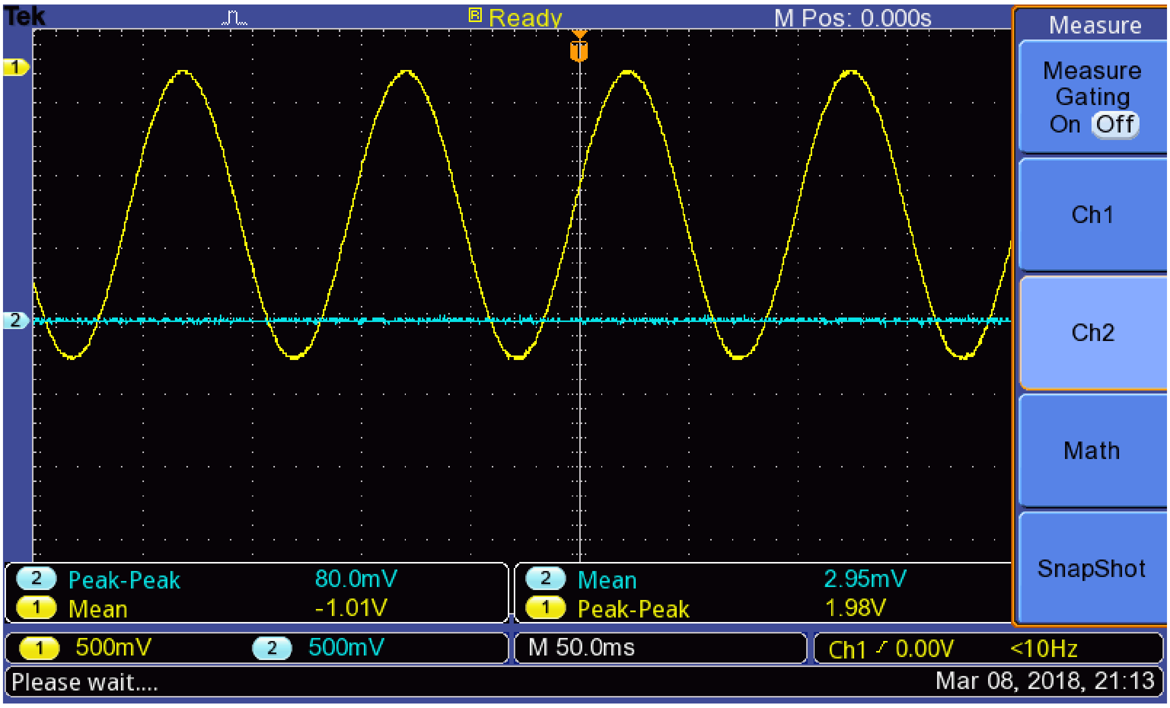

Figure 16: Lab 3 - Measurement 1.2 - -1 V DC offset

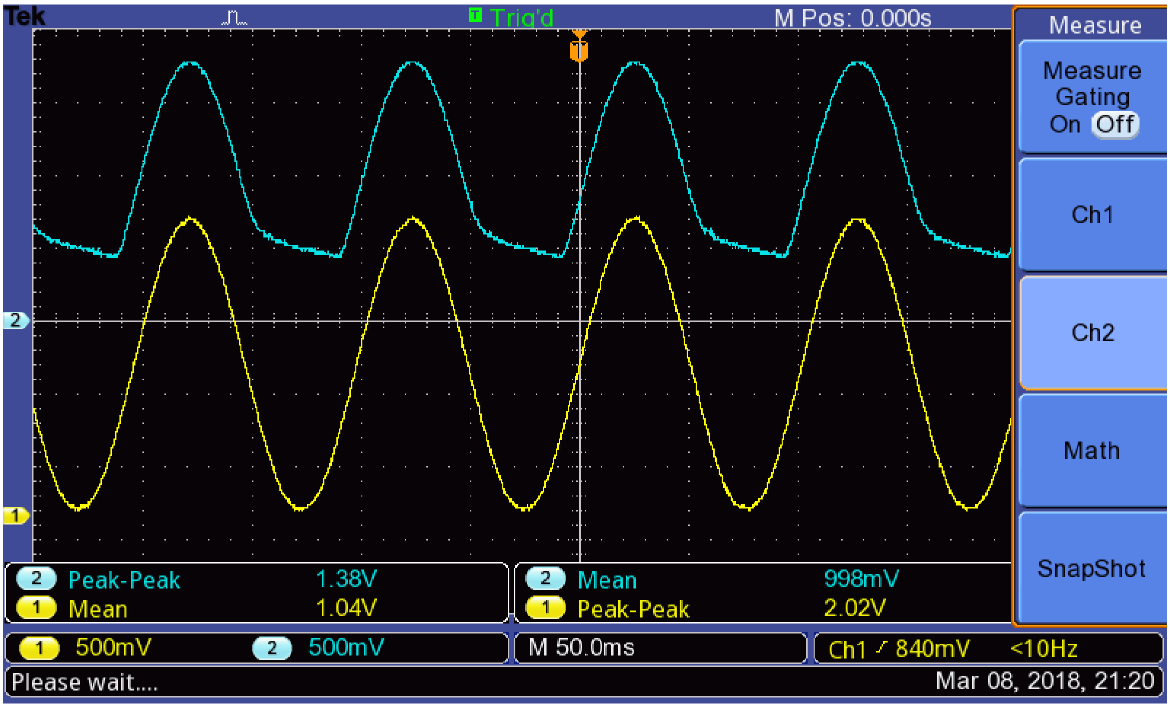

Figure 17: Lab 3 - Measurement 1.2 - +1 V DC offset

Measurement 2

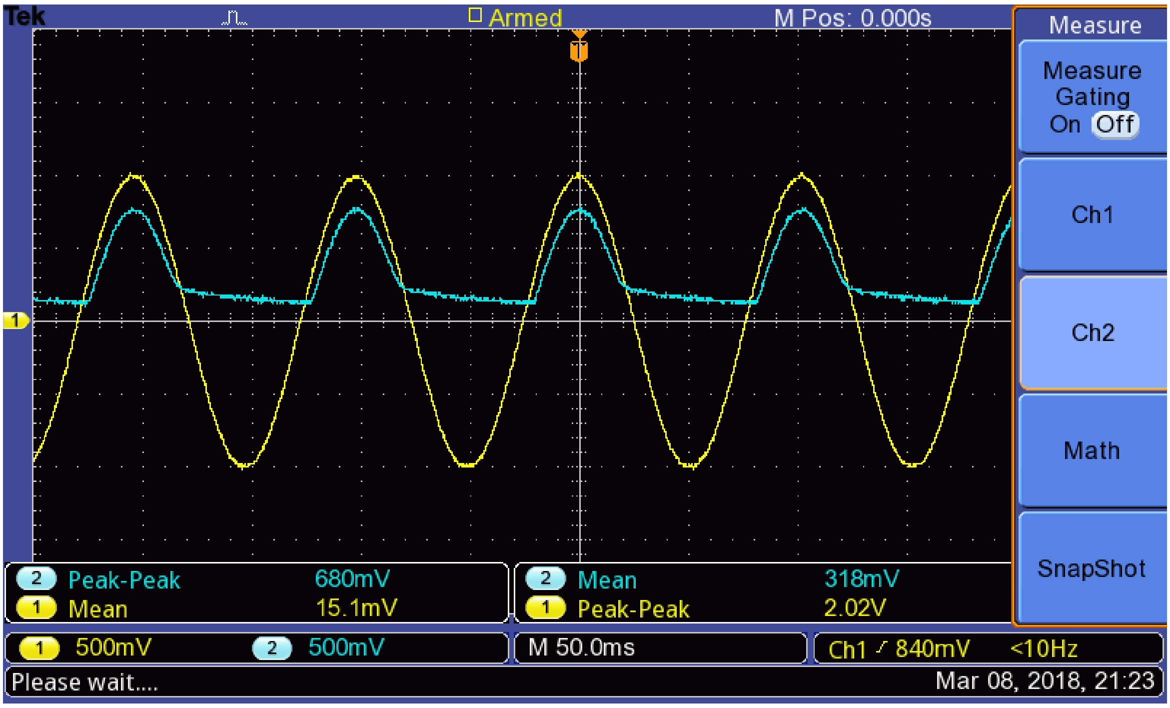

Figure 18: Lab 3 - Measurement 2.1 - frequency = 10 Hz

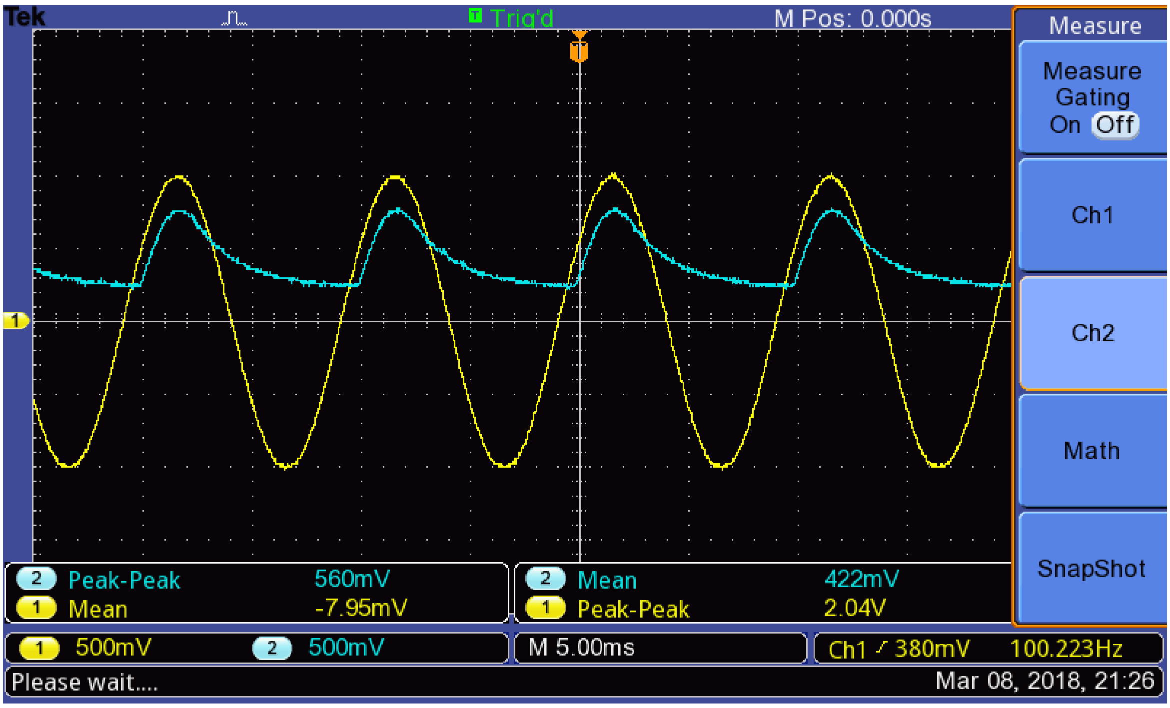

Figure 19: Lab 3 - Measurement 2.2 - frequency = 100 Hz

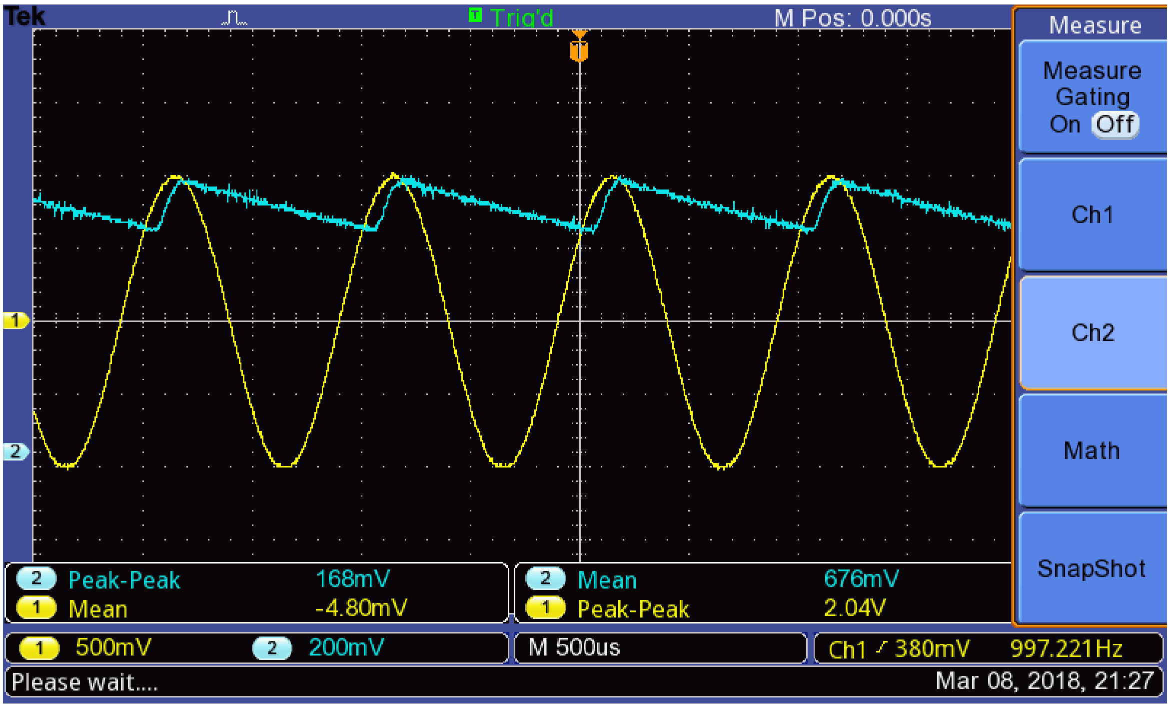

Figure 20: Lab 3 - Measurement 2.3.1 [small zoom] - frequency = 1 kHz

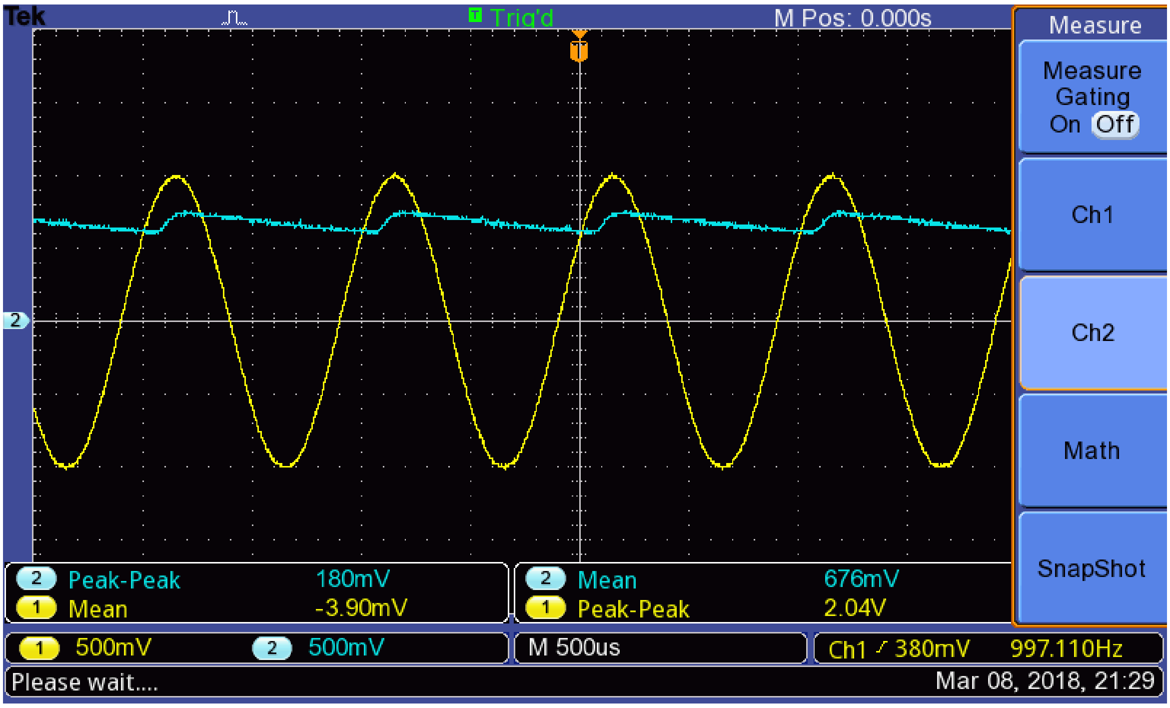

Figure 21: Lab 3 - Measurement 2.3.2 [large zoom] - frequency = 1 kHz

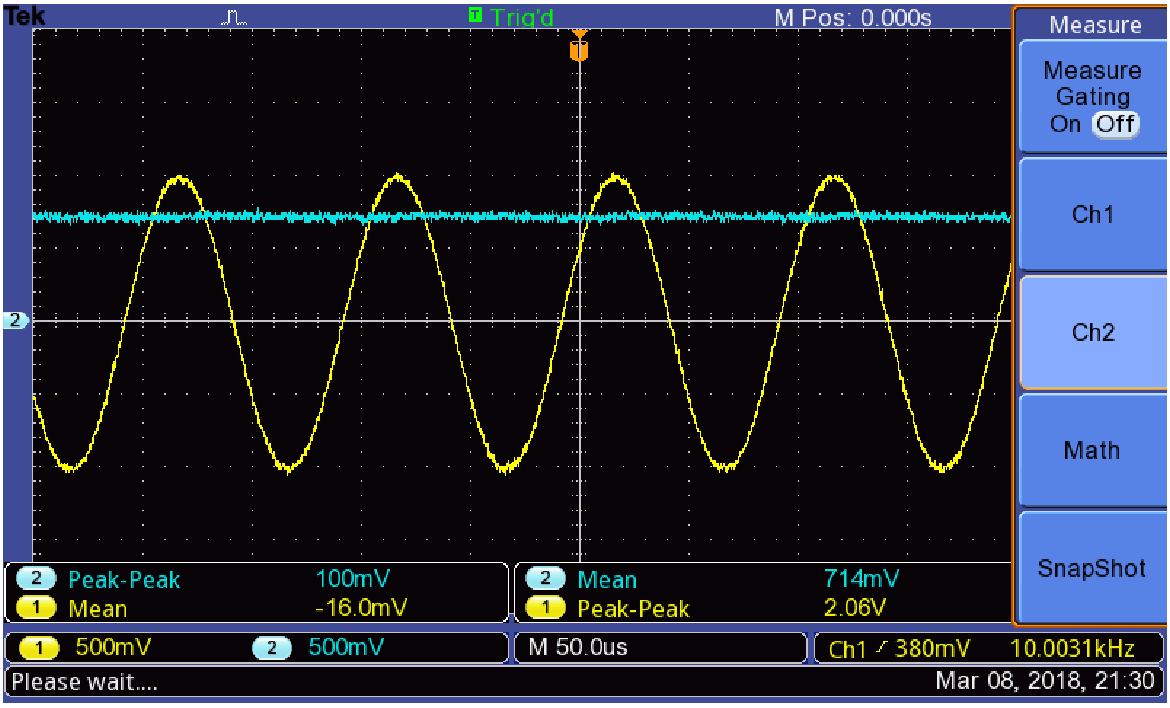

Figure 22: Lab 3 - Measurement 2.4.1 [small zoom] - frequency = 10 kHz

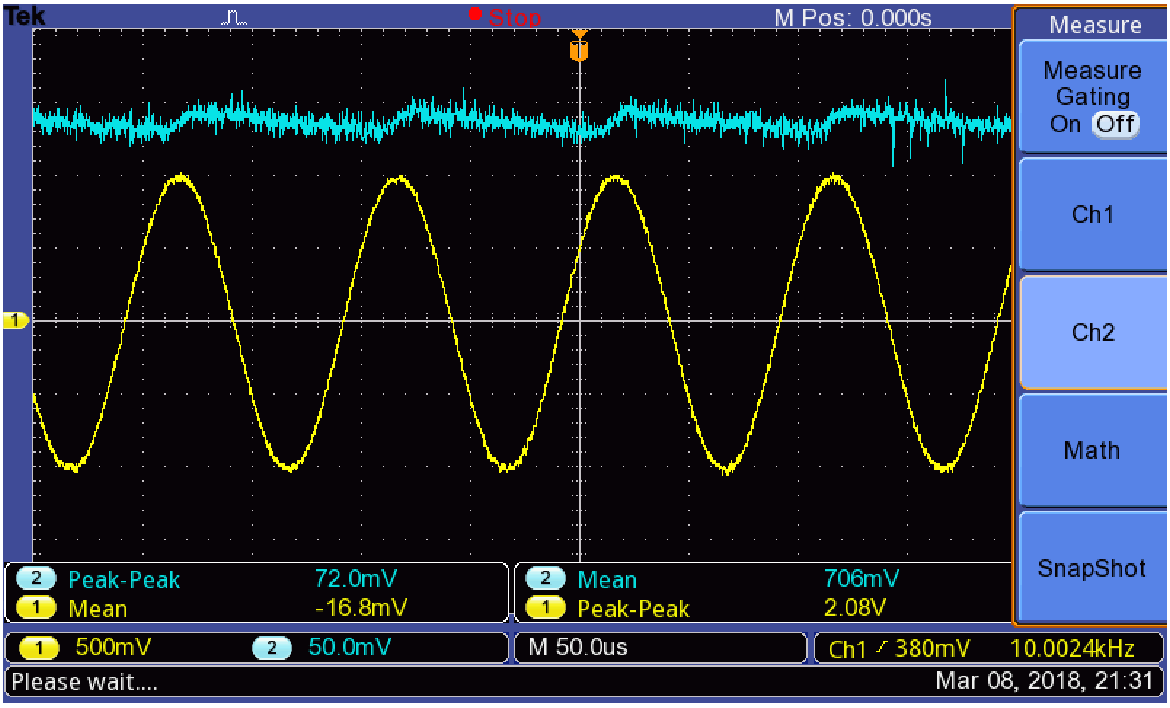

Figure 23: Lab 3 - Measurement 2.4.2 [large zoom] - frequency = 10 kHz

2.4 Unguided design

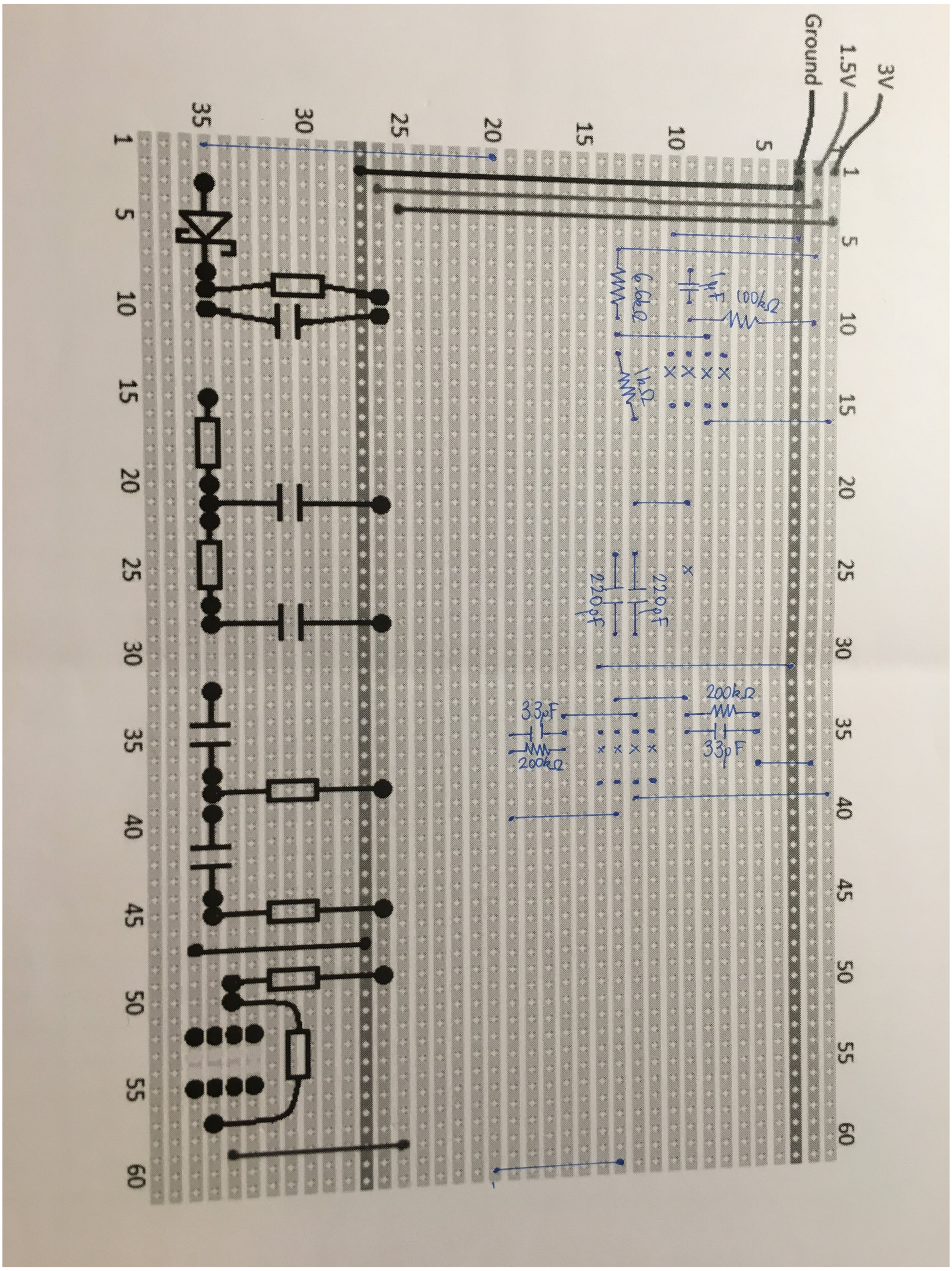

Figure 24: Unguided design

3 Appendix

3.1 Common-mode Attenuation measurements

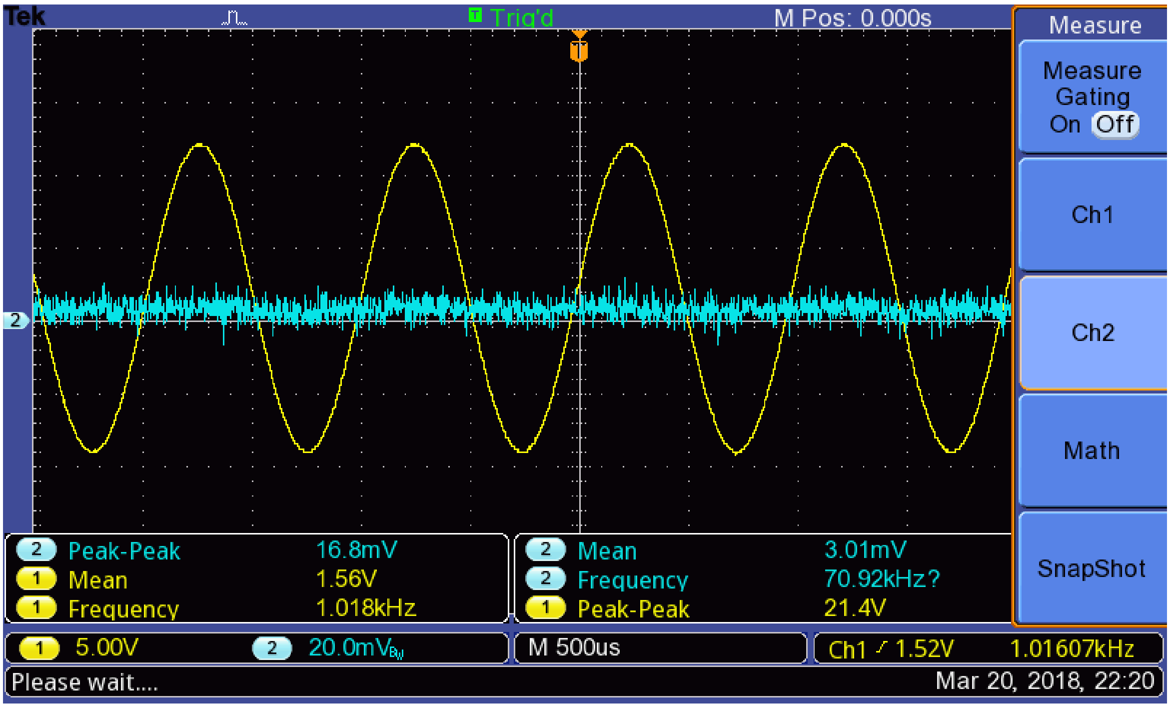

Figure 25: Input signal: p-p voltage = 21.2V - frequency = 1kHz

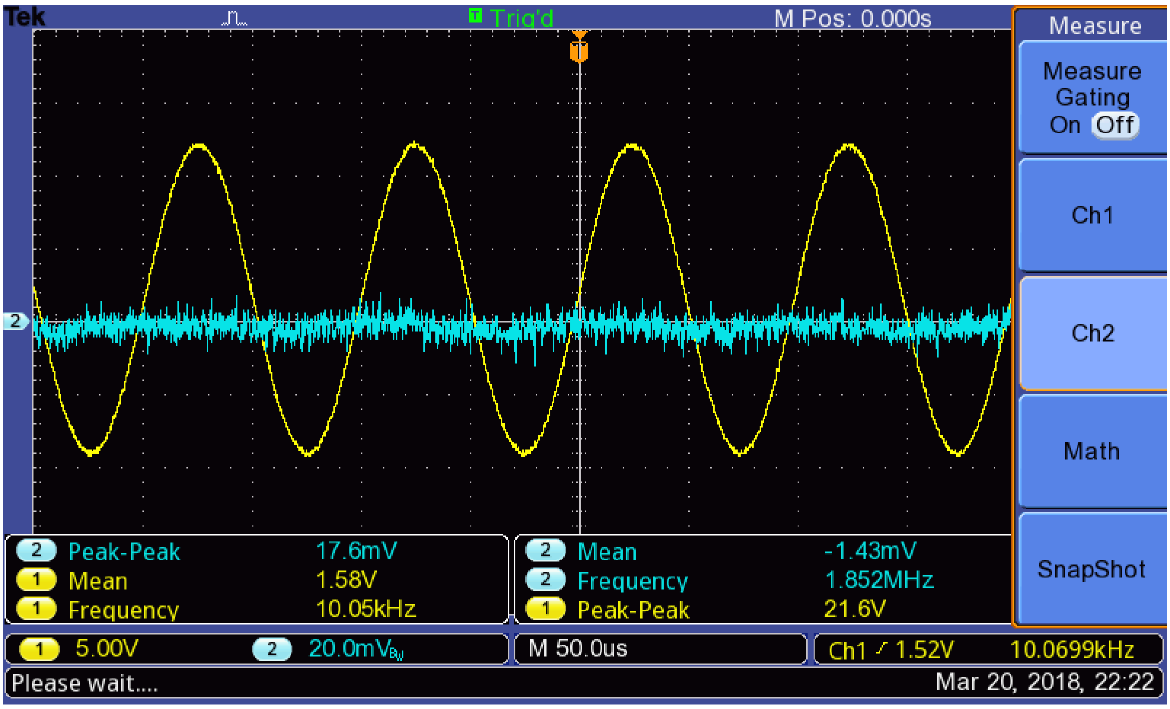

Figure 26: Input signal: p-p voltage = 21.6V - frequency = 10kHz

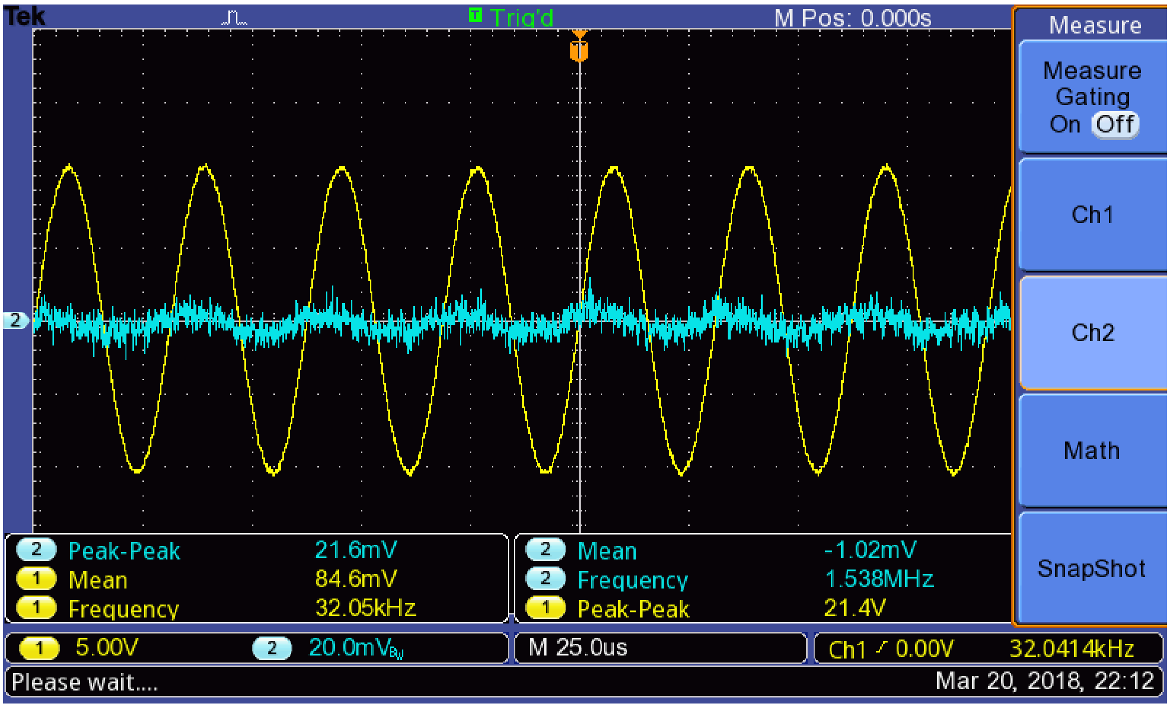

Figure 27: Input signal: p-p voltage = 21.2V - frequency = 32kHz

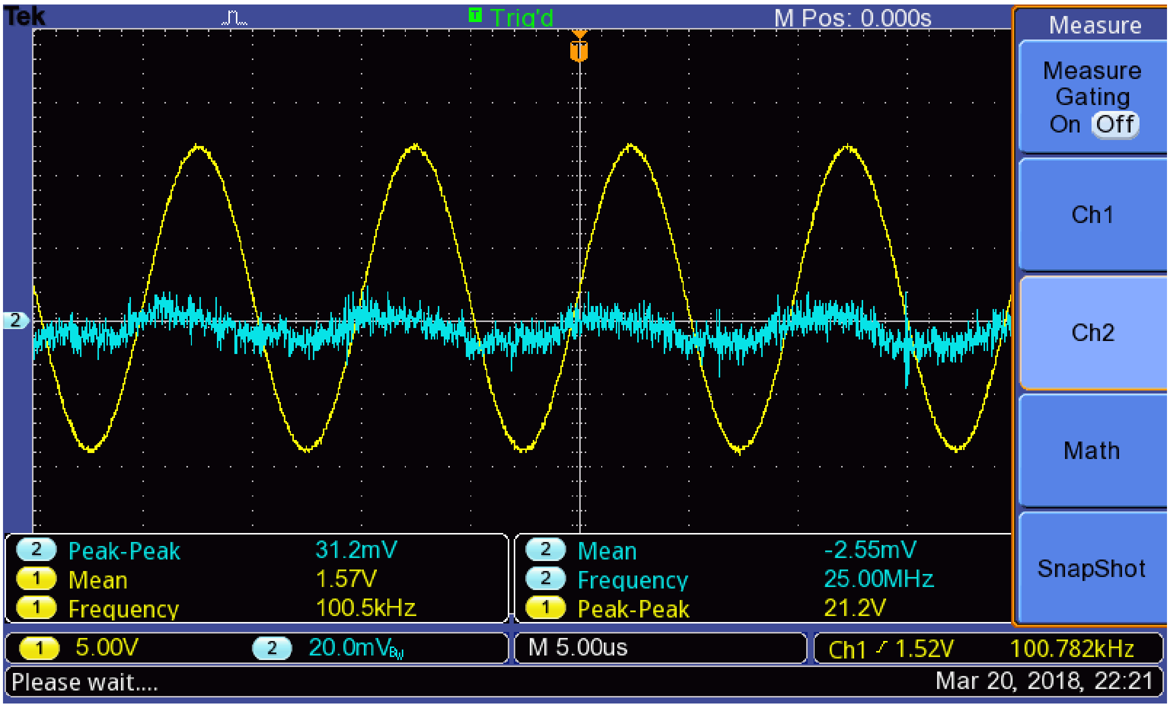

Figure 28: Input signal: p-p voltage = 21.6V - frequency = 100kHz

Table 4: Results for the common mode attenuation

Frequency (kHz)	Output p-p Voltage (mV)	Common-mode Gain
1	16.8	$7.9 \cdot 10^{-}4$
10	17.6	$8.3 \cdot 10^{-}4$
32	21.6	$1.02 \cdot 10^{-}3$
100	31.2	$1.47 \cdot 10^{-}3$

3.2 Differential gain measurements

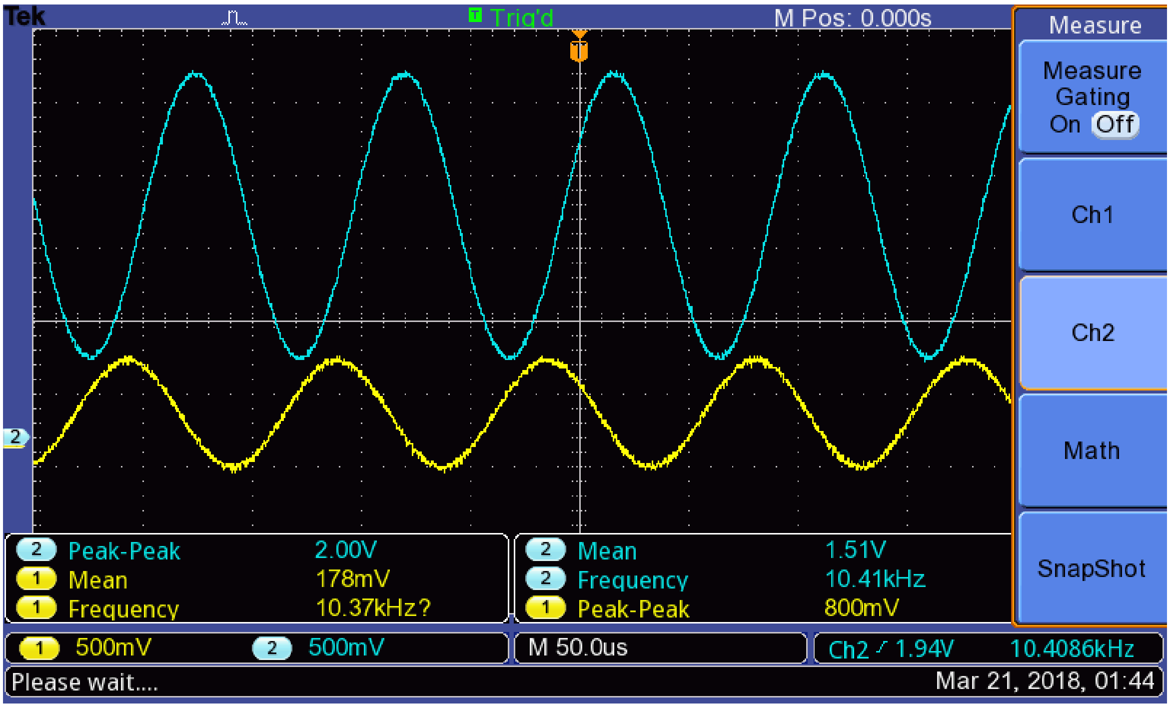

Figure 29: Input signal: p-p voltage = 800mV - DC offset = 178mV - f = 10kHz

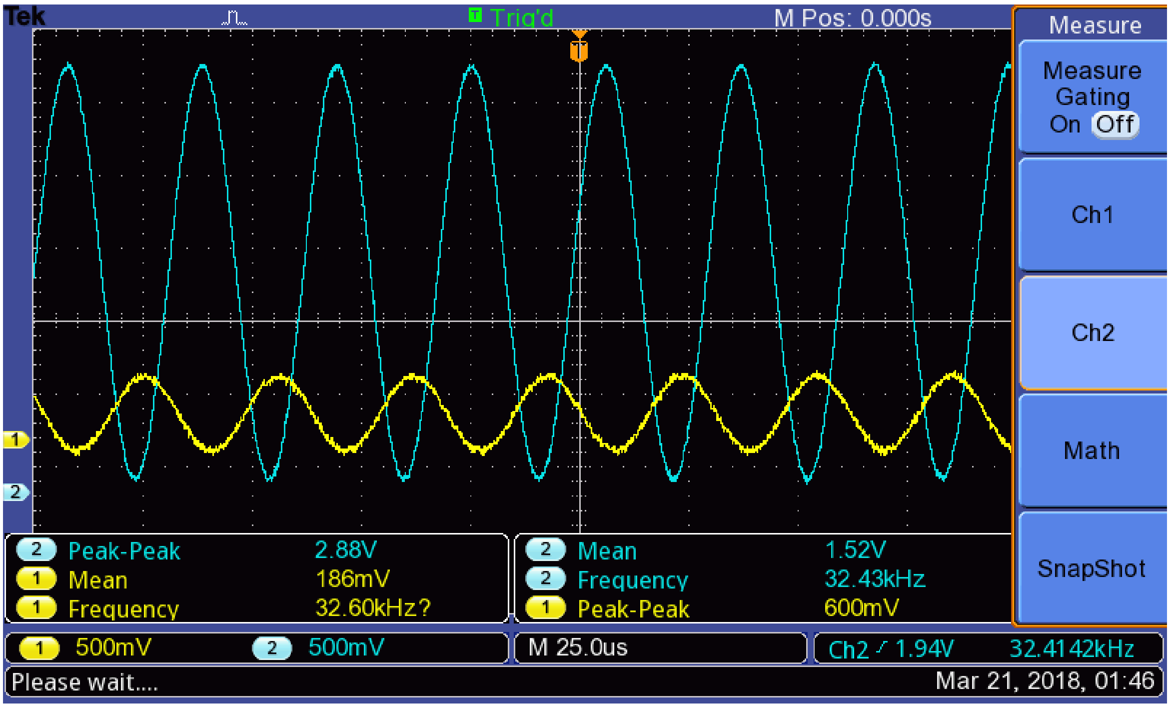

Figure 30: Input signal: p-p voltage = 600mV - DC offset = 186mV - f= 32kHz

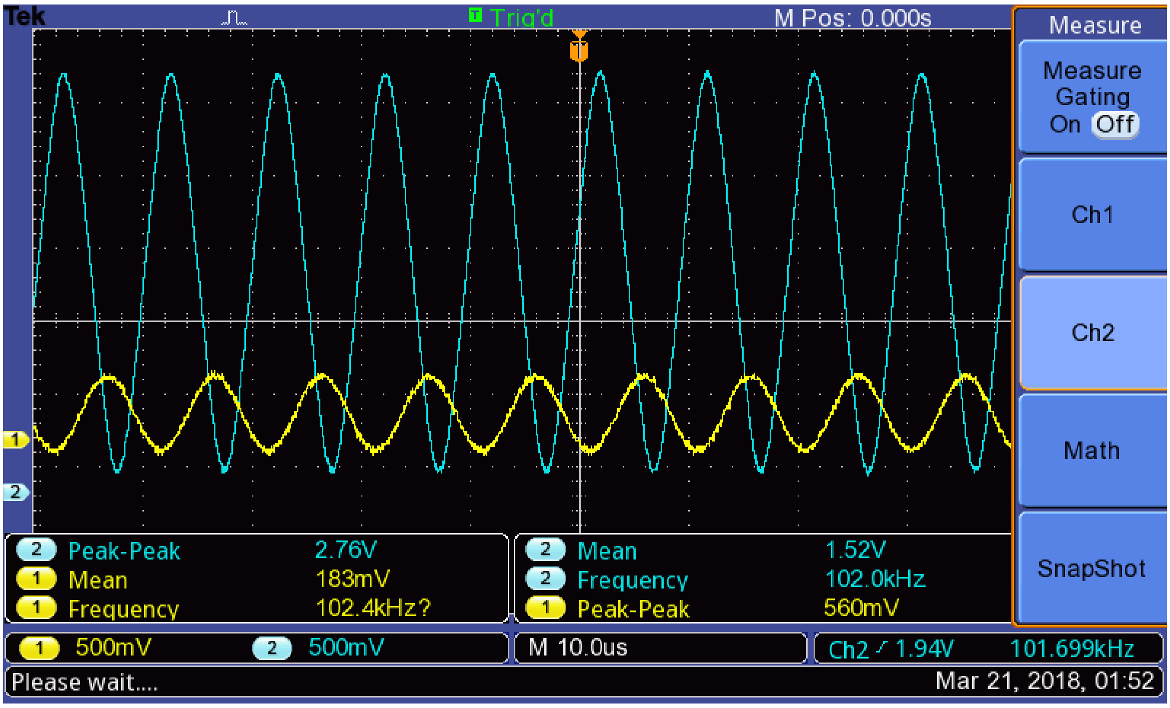

Figure 31: Input signal: p-p voltage = 560mV - DC offset = 183mV - f= 100kHz

Table 5: Results for the differential gain

Frequency (kHz)	Input p-p Voltage (V)	Output p-p Voltage (V)	Differential Gain
10	0.8	2	2.5
32	0.6	2.88	4.8
100	0.56	2.76	4.9

3.3 Final lab measurement

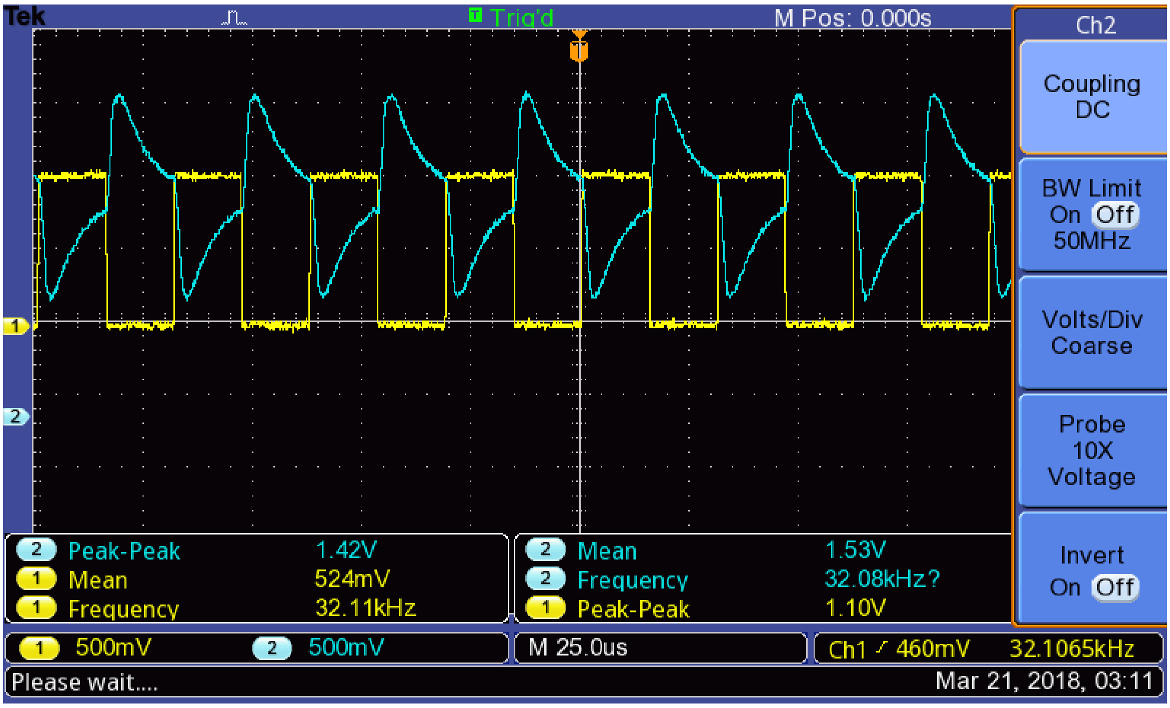

Figure 32: Only complete-circuit measurement where I got an output different than an off-set at the second op-amp output

4 References

1 - BARRETT, K. E. AND GANONG, W. F. Ganong's review of medical physiology [p. 619] Barrett, K. and Ganong, W. (2013). New York: McGraw-Hill. 2 - Horowitz, P. and Hill, W. (2008). The art of electronics. Cambridge: Cambridge University Press.[Accessed through Wikipedia reference]