Tel Aviv University
The Iby and Aladar Fleischman Faculty of Engineering

# Electronics - Laboratory B

# Cascode Amplifiers.

# Cascode Amplifiers

## Objectives

Investigation of a MOS differential amplifier and the BiCMOS cascode configuration.
Revisiting the Slew-rate effect and its roots.

Maximum time allotted for this experiment: 6 hours.

### *Recommended sources*

1. Sedra Adel, S. Kenneth, C. Smith. Microelectronic Circuits, 6th Ed., New York, Oxford. Chap 5 (MOSFETs), Chap 7 (mirrors, active loads, and cascode), Chap 12.6 (Slew-rate).
2. Millman, C., C. Halkias. Integrated Electronics Chap 16.
3. Datasheets: 2N3906, 2N2222A, BS170.
4. "VIDEO: Experiment 5: Cascode amplifier" on our Moodle website.

### *Mandatory reading/viewing (files available on our Moodle website)*

A. The Compensated Probe manual (up to page 13)
B. "INFOBIT - Calculating input and output resistances"
C. "INFOBIT - How to measure slew rate"

## Your personal tour guide

- In your preparatory report, you will analyze the circuits used in the experiment.
- The purpose of the purple text is to give you an overview of what you're doing – why are you analyzing this circuit? How does it relate to the other circuits? What is the purpose?

## Preliminary questions

- In some of the following sections you will be required to choose numerical values for hand-calculations or simulations. Use your last six digits, i.e. "ABCDEF".

Use the following data for the calculations regarding the MOSFET BS170 transistors:

| n-channel MOSFET BS170/PLP: $V_T = 2V,\ k = 50.4mA/V^2$ | | |
|---|---|---|
| Cut-off | $I_{DS} \cong 0$ | $V_{GS} < V_T$ |
| Saturation | $I_{DS} \cong k(V_{GS} - V_T)^2$ | $V_{GS} > V_T,\ V_{DS} > V_{GS} - V_T$ |
| Linear | $I_{DS} \cong k\left[2(V_{GS} - V_T)V_{DS} - V_{DS}^2\right]$ | $V_{GS} > V_T,\ V_{DS} < V_{GS} - V_T$ |

Use the following parameters for the BJT transistors:

| BJT transistors | | |
|---|---|---|
| | NPN (Q2222) | PNP (Q3906) |
| $\lvert V_{BE,on} \rvert$ [mV] | ≈715 | ≈656 |
| $\beta$ | 256 | 181 |
| $r_o$ [kΩ] | $\left(100+\dfrac{ABC-500}{10}\right)$ | $\left(100+\dfrac{DEF-500}{10}\right)$ |

All of the following circuits will use supply voltages V+, V- of 15V and -15V, respectively. These voltages are marked using the standard triangle symbol. When simulating a circuit, you must connect grounded DC sources with the right polarity and amplitude in order to receive the proper +/-15V DC signals.

For the simulations in this experiment use the following:

MOSFET: Model MbreakN3 with the parameters: *.model Mbreakn NMOS VTO=2 KP=0.1m W=2.5u L=0.25u* in Breakout

PNP: Q2N3906 in EVAL

NPN: Q2N2222 in EVAL

## 1. A simple formula

For your convenience, pay attention to the following configuration; it should save you many repetitive calculations in the sections that come next:

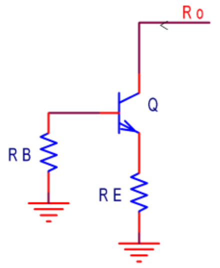



**Figure 1**

- Assume $\boldsymbol{R_B} \to \infty$.

1.1. Prove that in the above circuit, $R_O = r_o + (1 + g_m r_o)(R_E \parallel r_\pi)$.

1.2. Under which assumptions is $R_O \cong g_m r_o (R_E \parallel r_\pi)$?

1.3. Prove that the maximum value for $R_O$ is $R_O\big|_{\max} \cong \beta r_o$.

1.4. How would your answers change if the BJT was replaced with a MOS?

## 2. Current mirrors and active loads

- Text explanations in the following must span NO MORE THAN 3 LINES per answer!

💡 All calculations should remain symbolic (assume R1=R2).

In the following figure, two current sources, or current mirrors, are depicted:

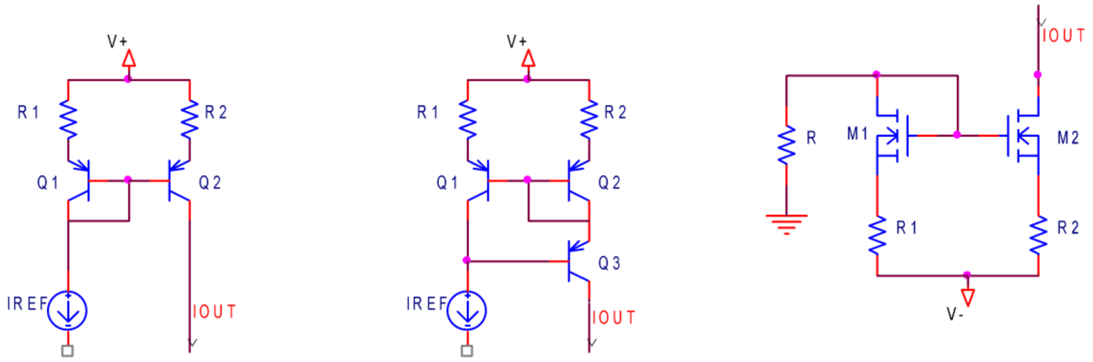



**Figure 2**

💡 You may assume all transistors are conducting in their appropriate regimes.

2.1. Write an expression for the current transfer ratios, $IOUT / IREF$, for the simple current mirror and for the Wilson current mirror. For the MOS mirror, calculate $IOUT$. For this section only, you may also assume $\beta \rightarrow \infty$ and all transistors are identical.

2.2. Write an expression for the output resistance for each. Assume all BJTs have different $r_o$ and $r_\pi$, and the MOS have $r_o$. Appropriate approximations should be justified and made.

2.3. Explain the main differences between these current sources, with respect to the previous sections and in general.

2.4. What is an “active load”?

2.5. Explain the differences in an active load’s DC and AC operation.

2.6. What are the advantages of active loads over passive loads, specifically in differential amplifiers?

2.7. Is there a difference between the resistance of an active load, compared to a current mirror?

## 3. Cascode devices

The following configurations are called “cascode devices”:

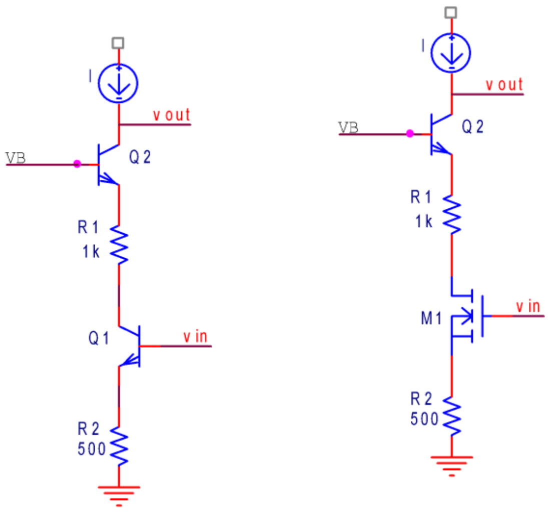



**Figure 3**

- The left circuit is a classic BJT cascode amplifier, and the circuit on the right is called “BiCMOS cascode”, and combines both MOS and BJT transistors.

3.1. Write an expression for the output resistance $R_o$ of each device. R1 and R2 should remain symbolic.

- For simplicity, assume R1=R2=0 in the following derivations.

3.2. Write an expression for the transconductance $G_m$ of the BJT cascode, assuming $g_{m2} \gg \frac{1}{r_{\pi 2}}$. Additional approximations should be made.
3.3. Write an expression for the transconductance $G_m$ of the BiCMOS cascode, making appropriate approximations.
3.4. Write the voltage gain $A_v$ for both devices.
3.5. What could be the advantage of using a MOS transistor rather than a BJT?
3.6. Note that Q2 is connected in a common-base (CB) or “current buffer” configuration. Explain what are its advantages with respect to amplification, “buffering” and frequency response.
3.7. Conclude: what are the advantages of using a cascode device?

## 4. The compensated probe

- In this experiment you will meet a new friend: *the compensated probe*. You must read the manual for it (available on the course website), up until page 13, and answer the following questions (you are limited to 1 page for these answers):

4.1. Explain the term “zero signal source loading”. Why can this state never be reached?
4.2. What are the external causes of noise in our circuits? Why should you use a compensated probe rather than a BNC-pins or BNC-wire connection, like we normally use in other experiments?
4.3. Explain the limitations of the compensated probe, with respect to bandwidth.

4.4. In our lab, we'll use a compensated probe with an attenuation of 1:10. Summarize the sections "dynamic range limitations" and "source loading" from the manual, taking care to mention and explain the definitions "resistive loading" and "capacitive loading".

## Circuits from our experiment

### 5. The cascode amplifier

The following circuit has very interesting features; make sure you can identify each subcircuit:

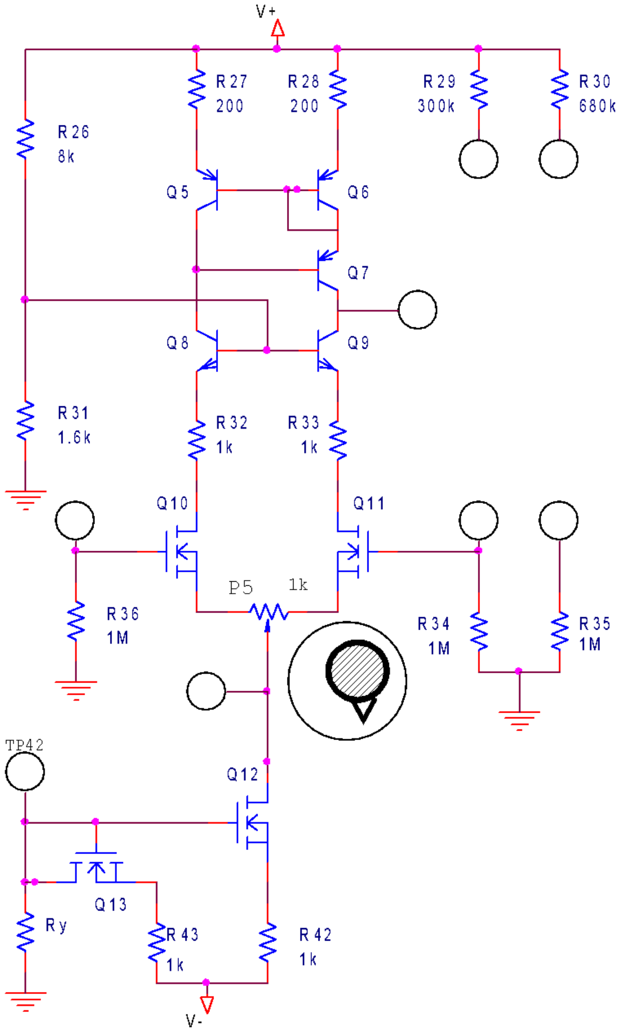



**Figure 4**

Schematically, in the experiment, this circuit will be drawn as follows:

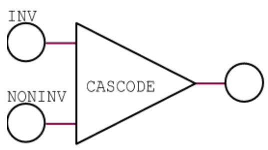



**Figure 5**

To change the bias point of the cascode, you will use its potentiometer: P5.

*The output node*

5.1. Which of the inputs is the *inverting input* and which is the *non-inverting input*? Explain how you decided on this.
5.2. What is the differential input resistance of the circuit in Figure 5?
5.3. Assuming $r_o, \beta \to \infty$, what is the range of voltages possible at the output node such that the circuit is working properly?
5.4. The output resistance of this circuit is estimated to be very high, typically 5MΩ. Explain why, and support your answer by a calculation of $R_{out}$ using the formulas you developed previously (assume the equivalent load on Q9's base resistance is very small).

You should know:

- The scope's "CH1" and "CH2" terminals have a 1MΩ resistance.
- The multimeter's terminal has approximately a 10MΩ resistance.
- The compensated probe has approximately a 10MΩ resistance.
- They also have different capacitance values.

So, every time you measure, you are in fact LOADING the terminal you're measuring!

In simulation, PSPICE assumes an ideal probe – no capacitive effects and infinite resistance. To model the scope or multimeter's loading effect, you could attach to the node you're measuring a grounded 1MΩ or 10MΩ resistor, respectively.

5.5. According to the tips above, and your answers in previous sections, there are two problems in measuring the cascode's output with the scope: (a) the circuit might not work properly when measuring, and (b) even if it works, the measurements are wrong. Explain these two statements.

5.6. In the experiment, you will use potentiometer P5 to offset the output voltage. Suppose that someone attached R29 to the output and ideally set it at 9.3V. Now, you perform two measurements according to the circuits in Figure 6. Use the output resistance you found in section 5.4) $\mathrm{R}_{out}$), and calculate the measured output for both cases. Which is closer to the true value?

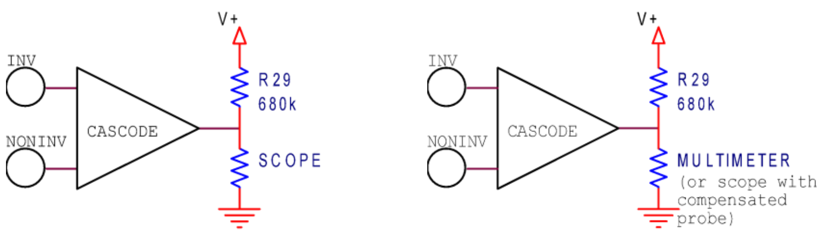



**Figure 6**

6. **<u>Slew rate</u>**

- Review what is the slew-rate effect and its definition.

6.1. Write down the procedure for measuring slew-rate (recall it from the INFOBIT: How to measure slew rate).

6.2. Assume a capacitor $C$ much larger than the parasitic capacitances in the circuits in Figure 7 is connected to each of their outputs (separately). Derive, from first principles, the slew-rate for the actively-loaded differential pair in Figure 7. Show that it is equal to $SR = I_{REF}/C$ assuming $r_o \to \infty$.

- Active loads combined with differential amplifiers are extremely advantageous! In the following sections, you will compare between the two.
  - You may assume Q1+Q2 and Q3+Q4 have (separately) equal small signal parameters and are operating appropriately in these configurations.
  - Note the DC voltage source "VK". Explanations will follow promptly.

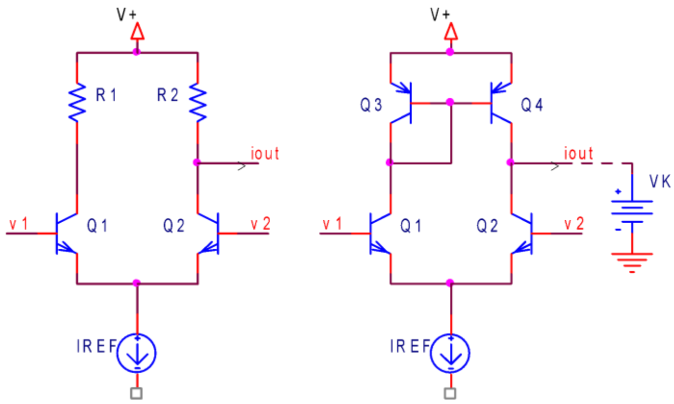



**Figure** 7

- Remember! When we draw a "DC voltage source" - "VK" in Figure 7– in the lab this is not an ideal voltage source! Just as the current source IREF could be realized by a resistor, a transistor, or a current mirror, "VK" could be implemented using something as simple as a resistor to the ground, or resistor to VCC.

- VK could also be implemented as a whole different stage and further down our experiment – the "buffer amplifier" (more on this later).

In the following procedure, you will analyze the slew-rate effect of the cascode circuit. To demonstrate this idea, let us consider the circuit in Figure 8. In this circuit a dominant capacitor is connected to the output, and a potentiometer is connected to the current-source of the cascode:

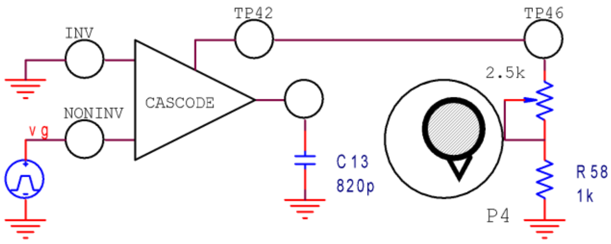



**Figure 8**

6.3. Use PSPICE to simulate the circuit in Figure 8. Set potentiometer P5 to 50% (in Figure 4) and Ry = $(5 + \frac{D}{2})$ kΩ. Assume the potentiometer P4 is set to (ABC/10) percent of its maximal value. Choose Vg (the relevant shape and value) in order to satisfy the following:

6.3.1. Two different cases in which the circuit is not SR-limited.

6.3.2. Two different cases in which the circuit is SR-limited.

Attach simulations of the input and the output for all cases, and make sure your results prove to the reader that you've succeeded in your task by providing important numbers on the simulation graphs.

6.4. According to the simulation results, find the SR value.

## 7. <u>The buffer amplifier</u>

This circuit is built from several recognizable blocks; make sure you understand exactly which is which and how they operate:

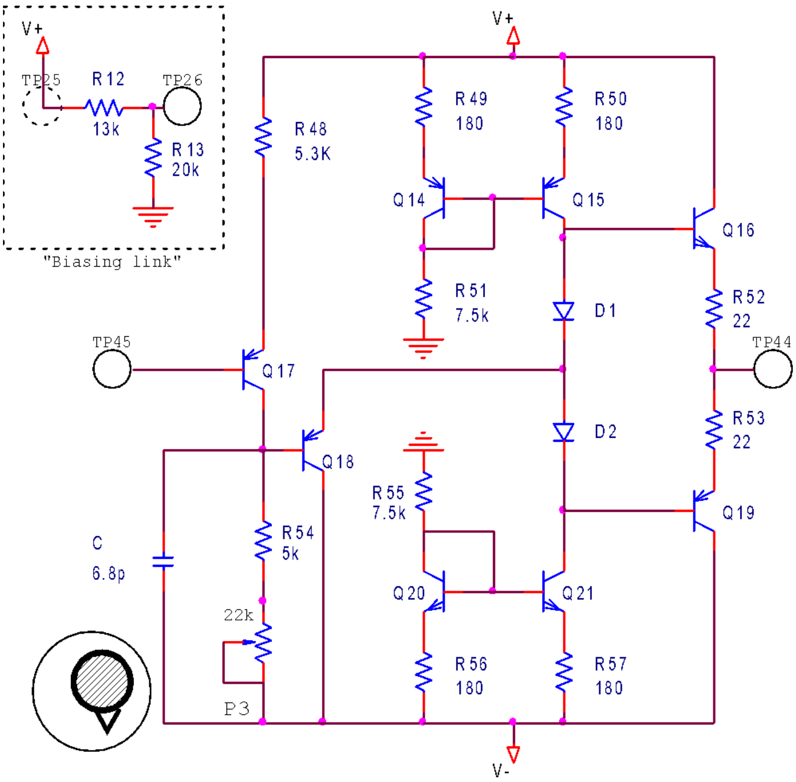



**Figure 9**

Schematically, in the experiment, this circuit will be drawn as follows (here, we explicitly connect the biasing link for the purpose of this section only):

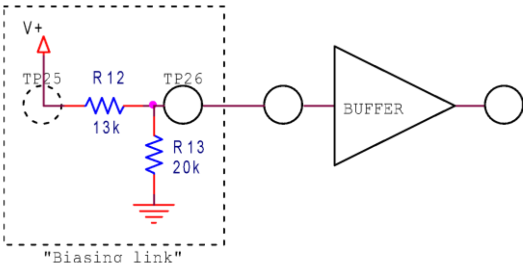



**Figure 10**

7.1. Is the buffer amplifier an *inverting* or *non-inverting* amplifier? Explain why.
7.2. Note TP25 on the biasing link: <u>this terminal is automatically connected to V+</u>. Assuming the buffer's amplifier input resistance is very large, to what voltage does the biasing link force on the buffer's input?

💡 In the following, assume the buffer amplifier's input is biased using the biasing link as in Figure 10 and $r_o \to \infty$.

7.3. What should be the size of the potentiometer P3 (in Ω, out of 22kΩ) such that the buffer amplifier's output is 0V?
7.4. Assuming $\beta_{17} = 100$ and 0V output, calculate the resistance of the buffer amplifier's input.
7.5. Estimate the buffer amplifier's mean output resistance (use realistic numbers for small-signal parameters under mA biasing currents in your calculation).
7.6. Estimate the voltage gain of the buffer amplifier.
7.7. Conclude: why do we call this a "buffer amplifier"?

💡 Okay, so we learned about two stages: the cascode amplifier and the buffer amplifier. Next, we will attempt to combine them to implement an "op-amp"!

## 8. <u>The two-stage op-amp</u>

In the lesson, you will be shown how to build an op-amp using the auxiliary resistors on the circuit board, as follows:

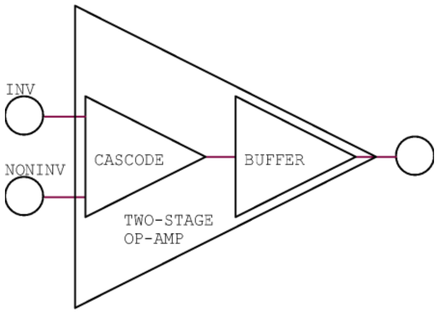



**Figure 11**

8.1. When connecting the cascode to the buffer amplifier as described above (Figure 11), which of the inputs is the *inverting input* and which is the *non-inverting input*? Explain.

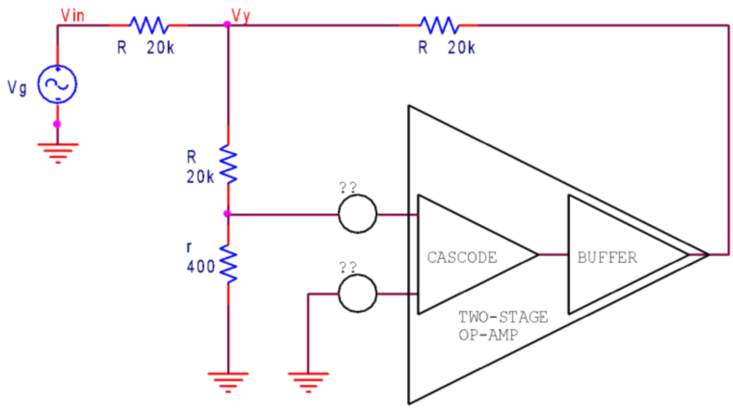



**Figure 12**

8.2. The circuit above (Figure 12) should be very familiar. Write down the formula for the open loop gain as a function of $v_{in}, v_y$.

8.3. What feedback (positive or negative) is expected for this circuit to work properly?

8.4. Calculate the output when the input is 4 Vpp and 20 Vpp, what is the difference? Does the circuit work properly in the lab in both situations?

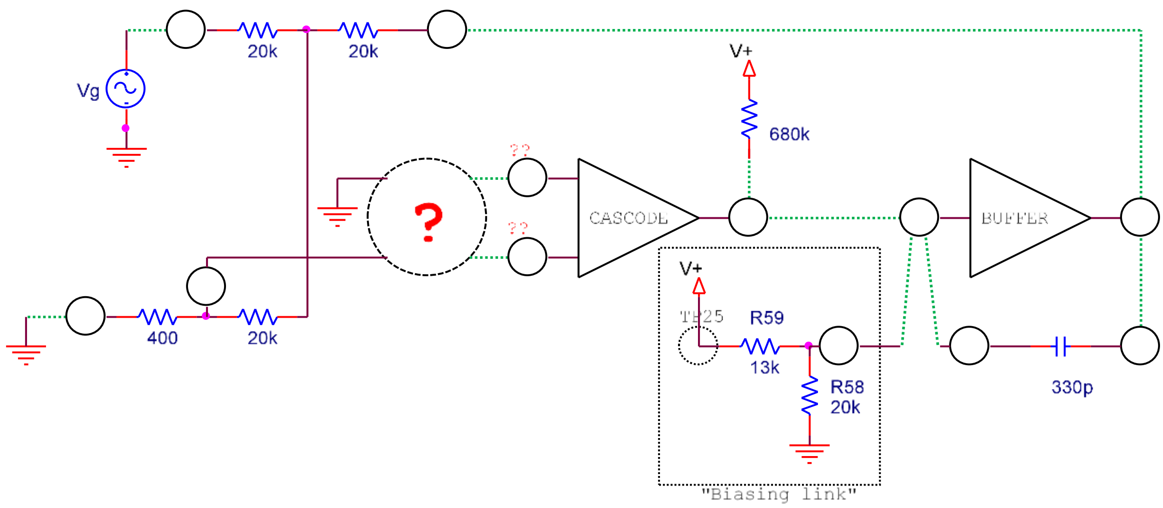



**Figure 13**

In the above figure, the missing connections used during the DC-calibration procedure are marked in green.

- The 330pF capacitor is a "compensating capacitor". You will learn more about it in the next experiment. For now, you should know that it is meant to ensure feedback stability.

- The calibration process in a nutshell: The bias point of the cascode's output must match the bias point of the buffer amplifier's input. Only then you may connect the two stages.

- Calibration for two stage op-amp procedure:

  - Disconnect everything, including the waveform generator.
  - Load the cascode amplifier with a 680 kΩ resistor.
  - Attach the biasing link and compensating capacitor to the buffer.

- Add the feedback network to the output of the buffer and to the input of the cascade, without connecting the cascode to the buffer.
- Ground the input of circuit, instead of the waveform generator.
- Using potentiometer P3, bias the buffer amplifier so its **output** is equal to zero volts (0 V ± 50 mV).
- Using the multimeter, measure the DC voltage at the **input of the buffer**.
- Using P5, bias the cascode so its **output** is equal to the buffer amplifier's **input** voltage within a margin of ±2 V.
- Now, disconnect the biasing link and connect the cascode to the buffer amplifier. Verify that the output of the complete circuit is zero volts (±100mV). If needed, adjust cascode-buffer bias using P5.
- Disconnect the cascode's 680kΩ load and connect the voltage generator to the circuit. If the output bias is still a little off zero volts (>±100mV), you can slightly calibrate it again using P5.

Text explanations in the following must span **NO MORE THAN 2 LINES** per answer!

8.5. Referring to the red question marks in **Error! Reference source not found.**,
   8.5.1. To where would you connect the feedback – the *inverting* or *non-inverting* input?
   8.5.2. To where would you connect the ground – the *inverting* or *non-inverting* input?

8.6. Prior to the final connection of the cascode amplifier to the buffer amplifier, the biasing link must be connected to the buffer amplifier. Also, the cascode must be loaded with the 680kΩ resistor. Why?

8.7. After the final connection, both the biasing link and 680kΩ resistor should be detached. Why are they not needed anymore?

You should review the experimental procedure, now, to ensure you understand what's going to happen in the lab.

# Experimental procedure

| | | | |
|---|---|---|---|
| Or Shaul | | 03 | 15 |
| Ariel Rene | | | |
| **Your names** | **Student IDs** | **Board number** | **Booth number** |

*Reminder:*

a) **All the answers for the practical and theoretical questions shall be written down in this document, during lab hours only.**
b) **Save this file as "reportCascode_XXX_YYY" where XXX, YYY are your student IDs. Please save this document right now as to avoid any future inconvenience.**
c) **At the end of this lab you must upload this file under the right assignment to the course site and click "hand in assignment":**
    - **If you have yet to complete this experiment in its entirety, please upload the file under the "Progress report" assignment.**
    - **If you had completed this experiment and answered all of the questions, please upload the file under the "Post lab (Final)" assignment.**
d) **You cannot "fix" sections that have been answered without a special approval from your lab instructors.**
e) **You should not attempt to upload or send the assignments from your home or after/before lab hours.**

## 1. The cascode amplifier

Refer to the preliminary report, section 5.

Since the output bias changes whenever you change the equivalent load resistance, you **MUST** make sure the output bias voltage remains 9.3±0.5V each time. Not only here, but in any section to come. Recall how to do this from the preliminary report!

Build the following circuit:

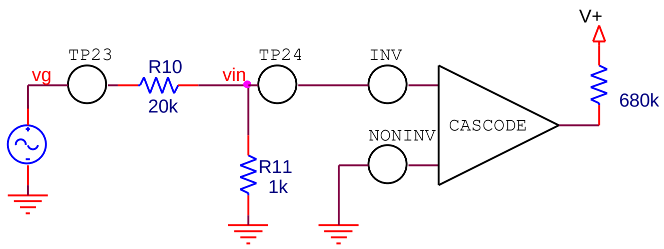
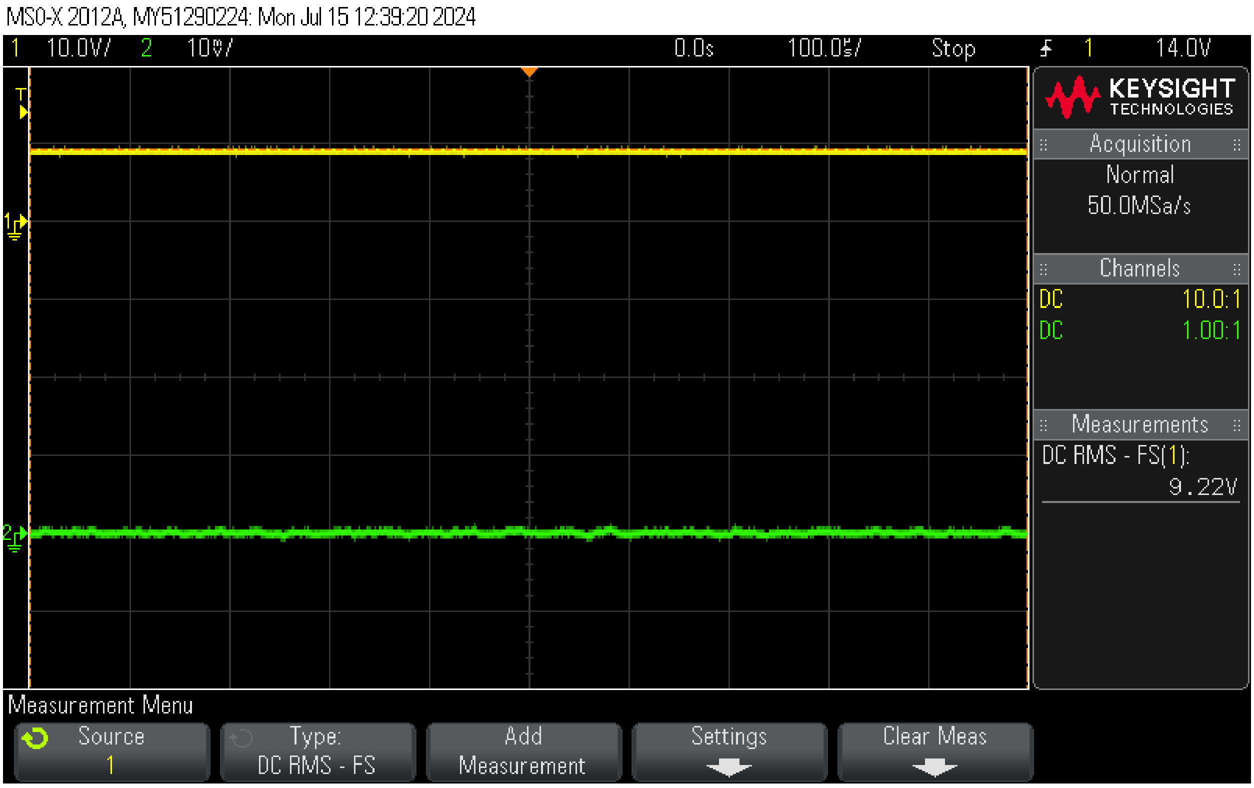



**Figure 13**

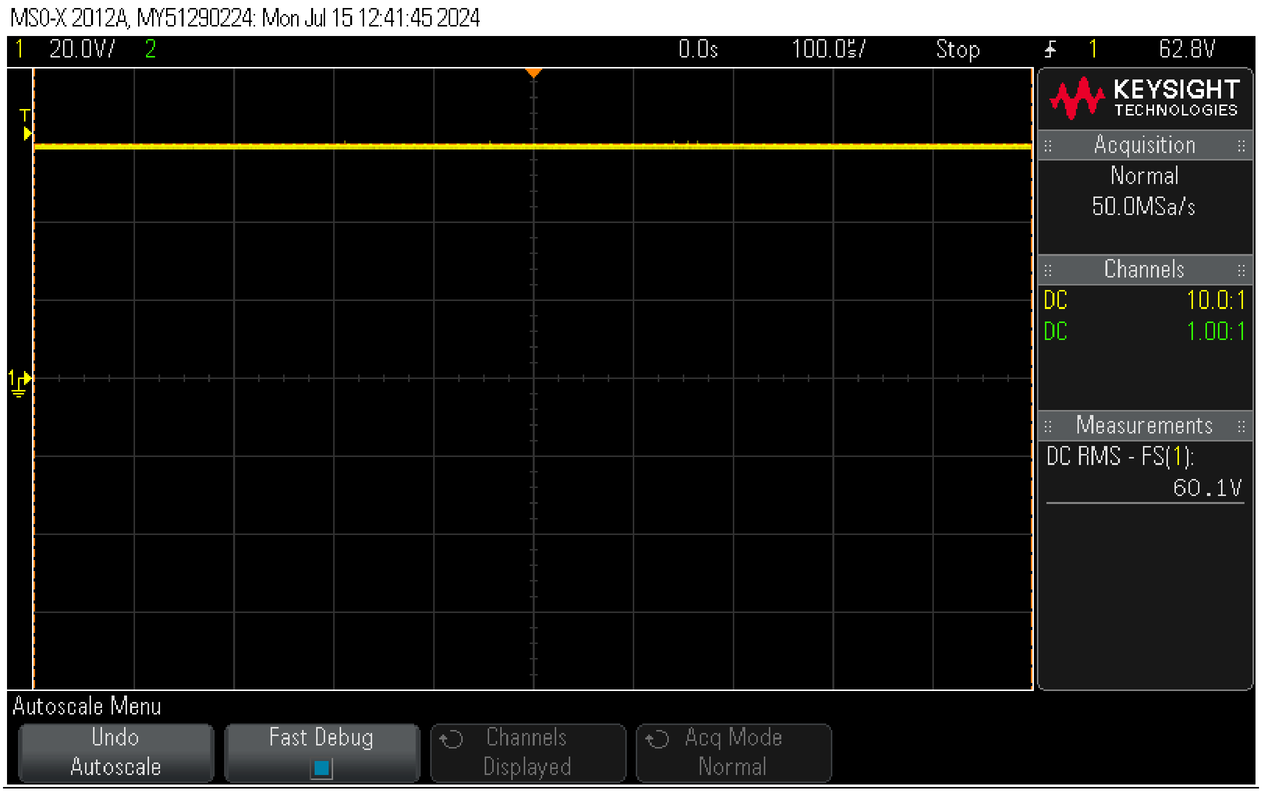
1.1. Use the compensated probe with CH1 and measure the Cascode's output bias voltage. Set it to 9.3±0.5V and attach a print with an Average measurement (total of 1 measurement).

*Print: vout, compensated probe*




1.2. Disconnect the probe and use a regular BNC cable to measure the Cascode's output, without changing anything else. Attach a print with an Average measurement (total of 1 measurement).

*Print: vout, BNC*




1.3. Disconnect the BNC, and measure the Cascode's output using the multimeter. Write down the measurements in the table below:

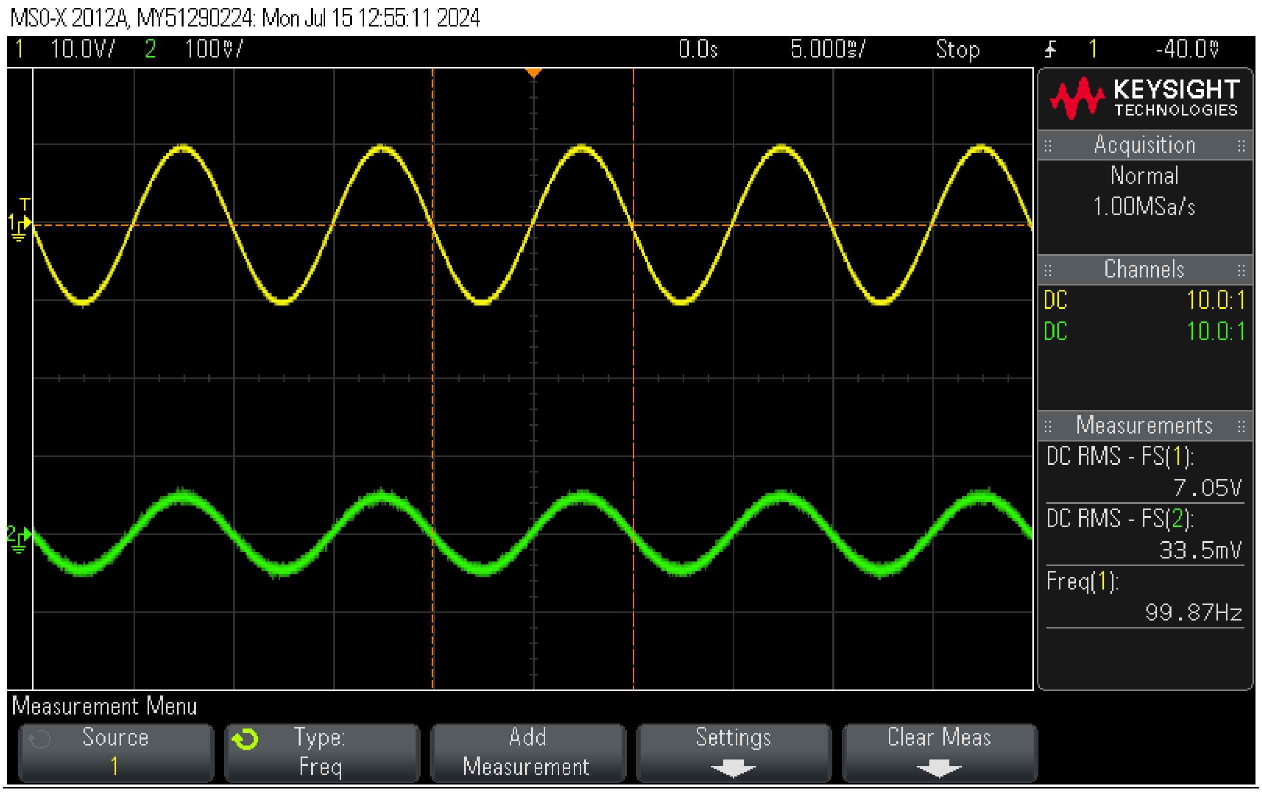
| Device | Measurement [V] |
|---|---|
| Scope with probe | 9.22 |
| Scope with BNC | 60.1 |
| Multimeter | 8.9 |

💡 Discuss amongst yourselves: why is there a difference between these measurements? Is the circuit affecting the measurement, or vice versa? You should figure this out on your own, using your preliminary report, *without the help of the instructor*.

✓ Use your conclusion and choose the best measurement device for the rest of the experiment (unless instructed otherwise).

1.4. Choose an input signal SIN/100Hz with an appropriate amplitude and attach a print showing several cycles of vin (CH2) and vg (CH1), with two RMS measurements and a frequency measurement of the vg (total of 3 measurements).

*Print: vin and vg, 100Hz*



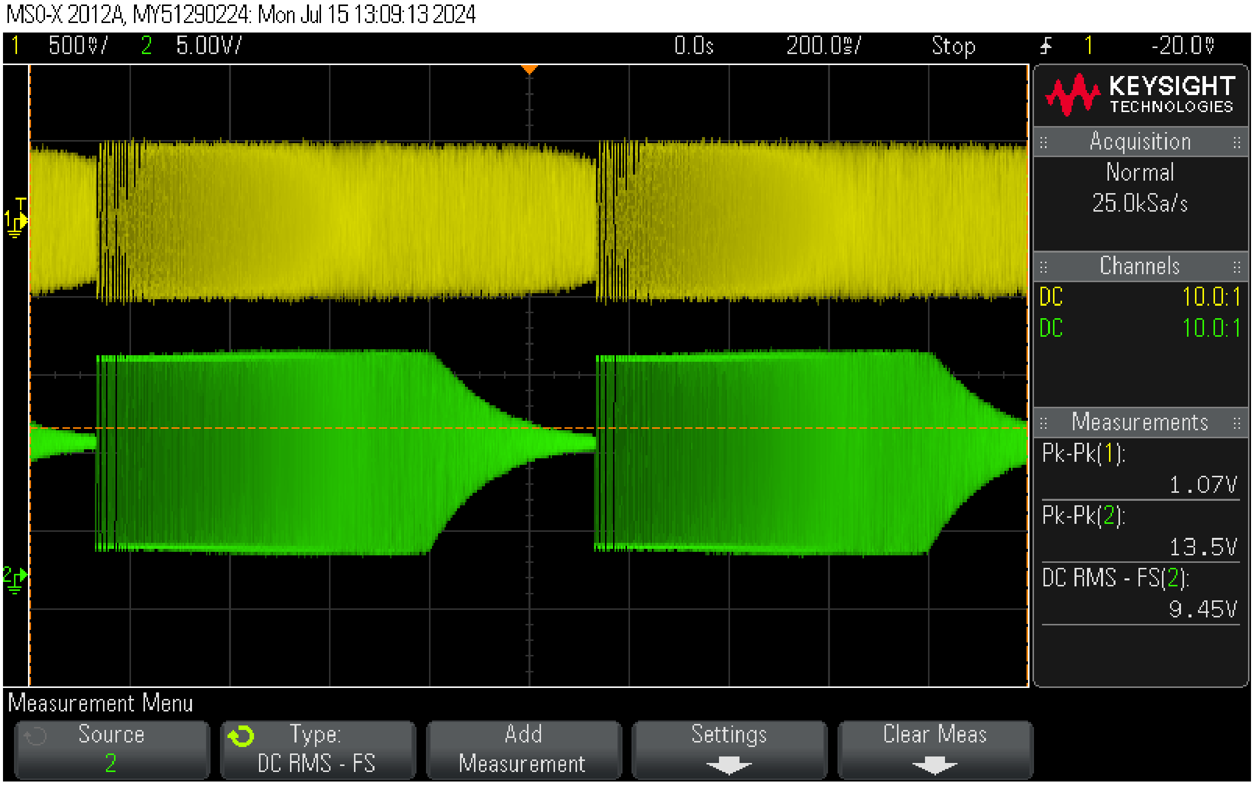

1.5. From the print, calculate the attenuation, vin/vg. Derive the theoretical value for this attenuation and compare the two.

| |
|---|
| 0.0335/7.05 = 0.00475<br>(שמנו לב לקראת הסוף שהרזולוציה של הערוצים הייתה אמורה להיות 1:1 ולא 10:1 ולכן התוצאה<br>שהיינו אמורים לקבל באמת היא 0.0475). |

1.6. Now, attach a print of an AC sweep, with VPP measurements for vin (CH1) and vout (CH2), and DC-RMS measurement for vout (total of 3 measurements). Choose vg appropriately.

| **SWEEP MEASUREMENT** | |
|---|---|
| Frequency range | $100Hz - 1MHz$ |
| Sweep time | $1sec$ |
| Input voltage | $1V_{pp}$ |

*Print: vin and vout sweep*

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*<u>Measuring the output resistance and gain</u>*

1.7. Use DC coupling on both channels. Measure vg (CH1) and vout (CH2). Choose an input signal SIN/100Hz with an appropriate amplitude.

1.8. <u>Attach a print</u> with AC-RMS and DC-RMS measurements (total of 4 measurements). This is the "unloaded" case.

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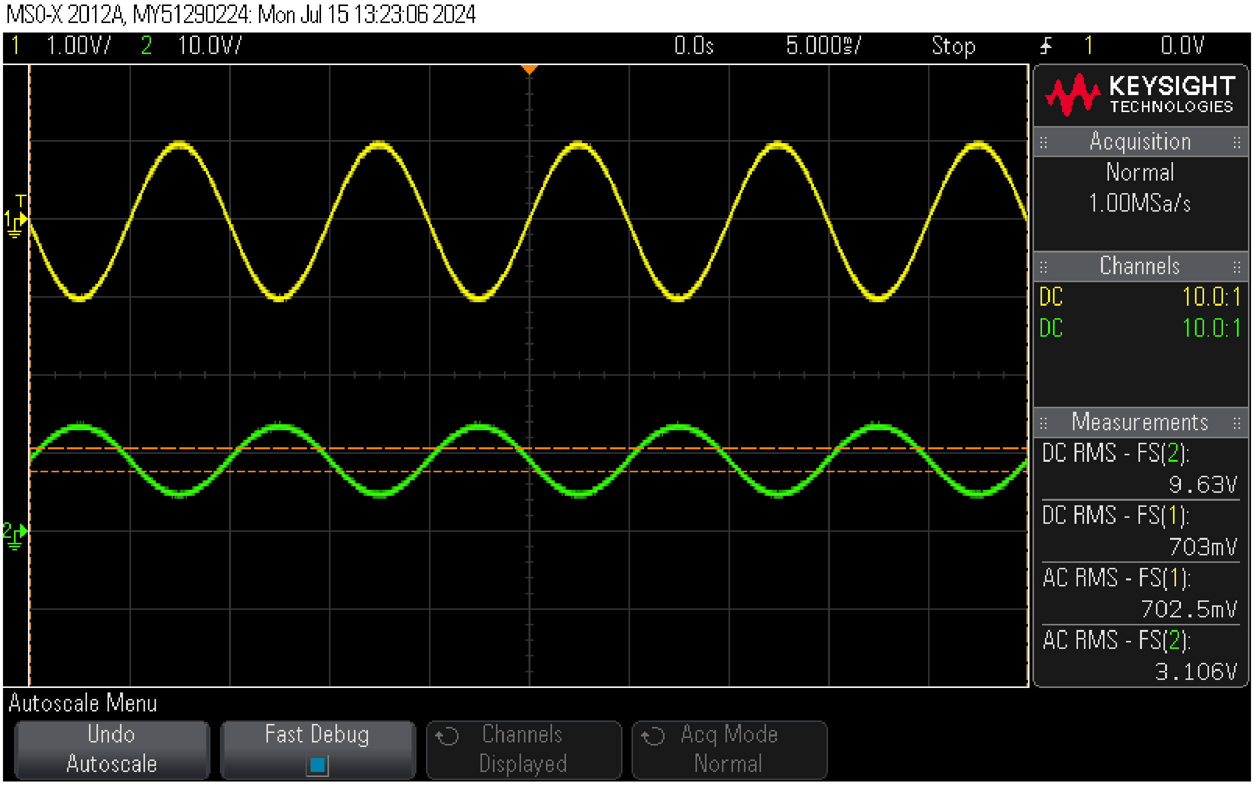
*Print: vout and vg, unloaded case*

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1.9. Using this print and the previous sections, calculate the cascode's gain, vout/vin. Write your full calculation (what you're dividing by what):

| |
|---|
| Vout/Vin=(Vout/Vg)*(Vg/Vin)=(-3.106/0.703)*(1/0.00475)=4.418*210=-930 |
| |
| |

1.10. Now attach a grounded 1MΩ resistor to the output (find it on the board).

1.11. <u>Attach a similar print</u> with AC-RMS and DC-RMS measurements (total of 4 measurements). This is the "loaded" case.

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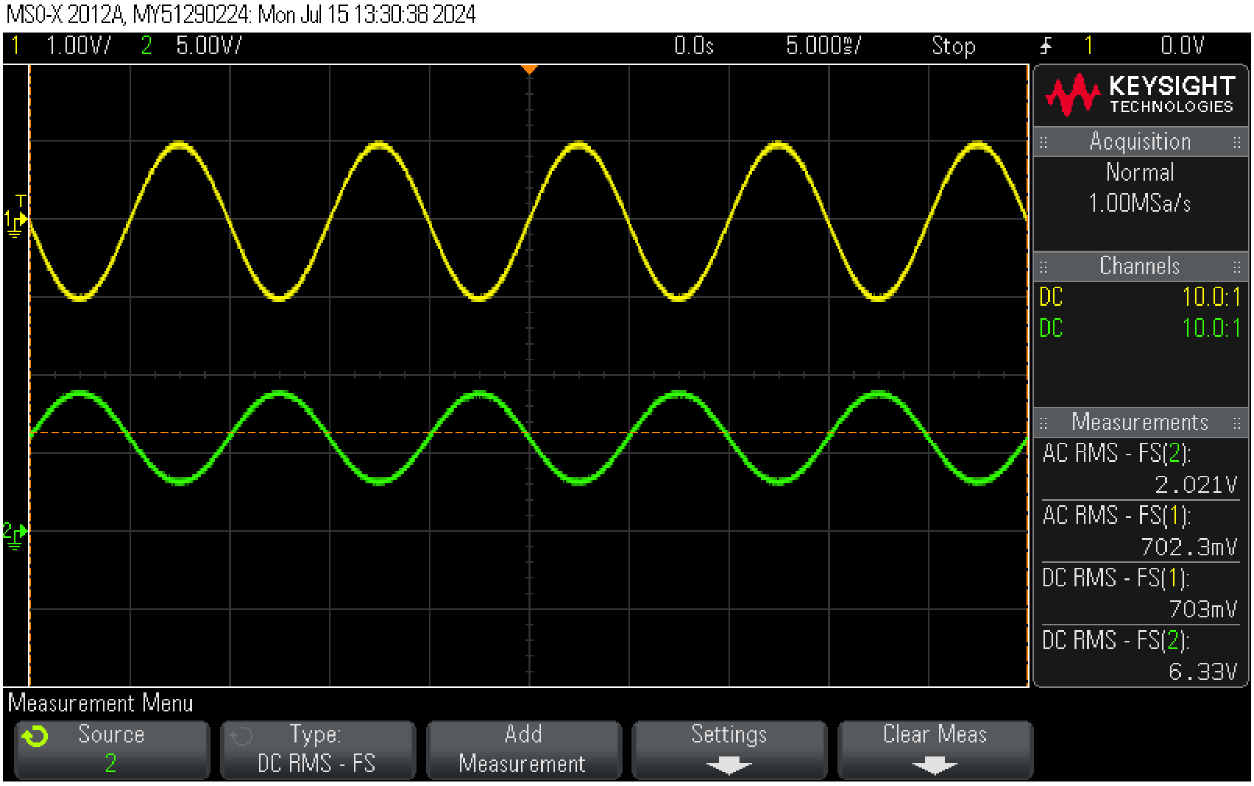
*Print: vout and vg, loaded case*




1.12. Disconnect the 1MΩ resistor.

1.13. Calculate the cascode's output resistance. Show derivation and explain where necessary. Is this what you expected?

| RESISTANCE MEASUREMENT | |
|---|---|
| Vout (unloaded) | 9.23V |
| Vout (loaded) | 6.33V |
| Load resistor | 1M |
| Calculation | $R_{out}$ = 5.907Mohm |
| | |
| Full derivation and explanation: | |
| $$680\ k\Omega \parallel 1\ M\Omega = 404.76\ k\Omega$$ | |
| $$\mathrm{R_{out}} = \frac{\mathrm{V_{out,unloaded}} * \frac{(680k\|\|1Meg)}{\mathrm{V_{out,loaded}}} - (680k\|\|1Meg)}{1 - \frac{\mathrm{V_{out,unloaded}}}{680\mathrm{k}} \cdot \frac{(680k\|\|1Meg)}{\mathrm{V_{out,loaded}}}} = \frac{590195}{0.99913} = 5.907 Mohm$$ | |
| | |

*Measuring slew-rate*

- Refer to the preliminary report, section 6.

1.14. Disconnect everything. Measure the output of the cascode amplifier only, and make sure the output is set to 9±1V. Do not touch the potentiometer in the remaining subsections of the slew-rate measurement.

1.15. Construct the circuit in Figure 8. Set the potentiometer P4 all the way counter-clockwise (we denote this "**P4cc**").

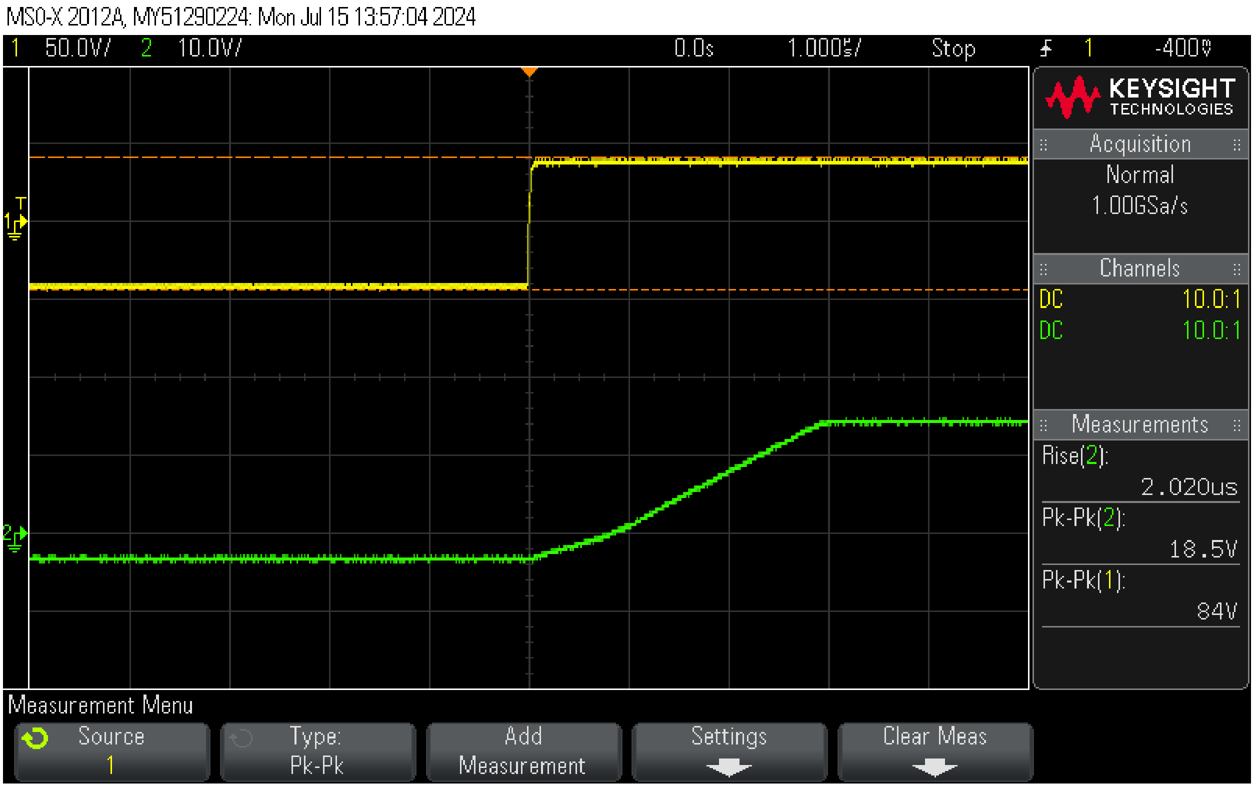
✓ You will now have to prove that you're correctly measuring SR using a number of prints. Review it if you've forgotten how (don't ask the instructors about this!)

1.16. Set the input to 100Hz-square wave with zero offset and 50% duty-cycle. Set the trigger to synchronize on CH2's RISING slope (find this option in the trigger menu).

1.17. Attach two different prints of the input and output signals, showing cases where the output *is not* SR-limited, with VPP measurements for each and a measurement of "t-rise" *or* "t-fall" for the output (use the measurement which is relevant to your calculation, total of 3 measurements).

---

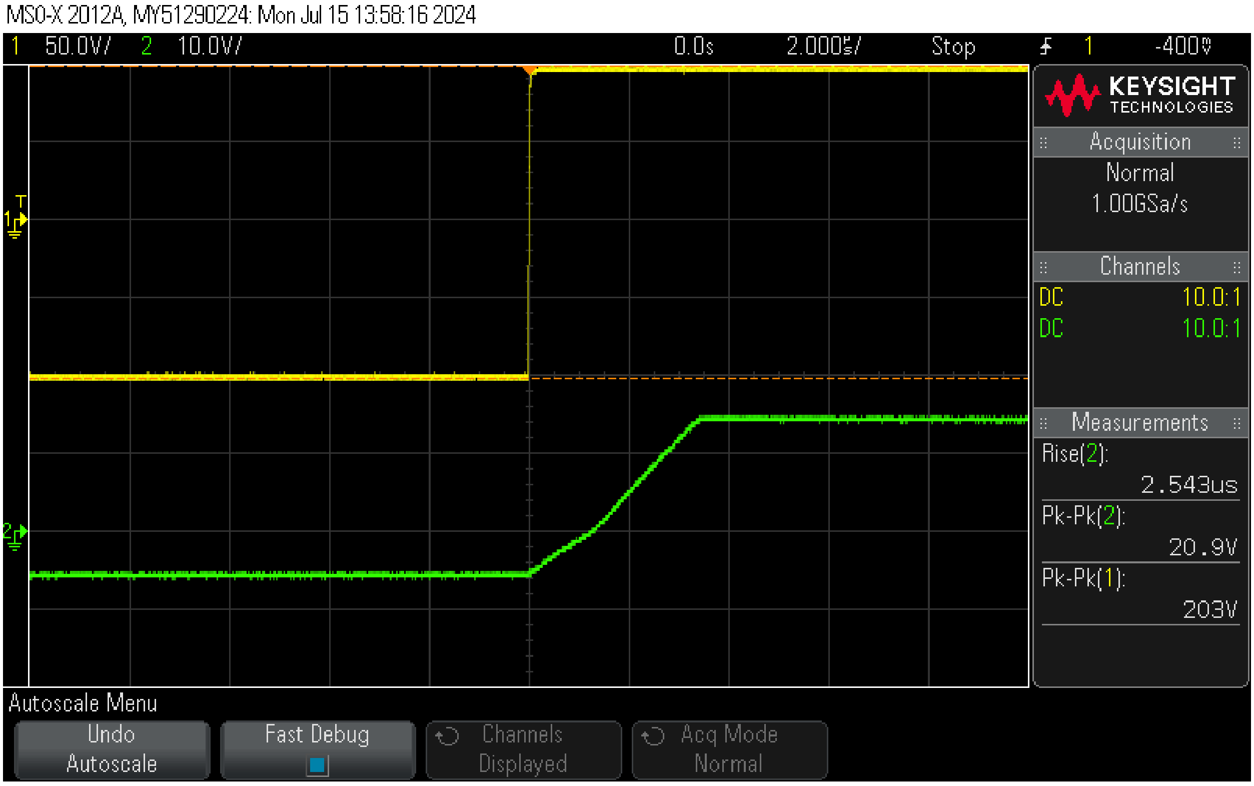
*Print: input and output, #1*




---

---

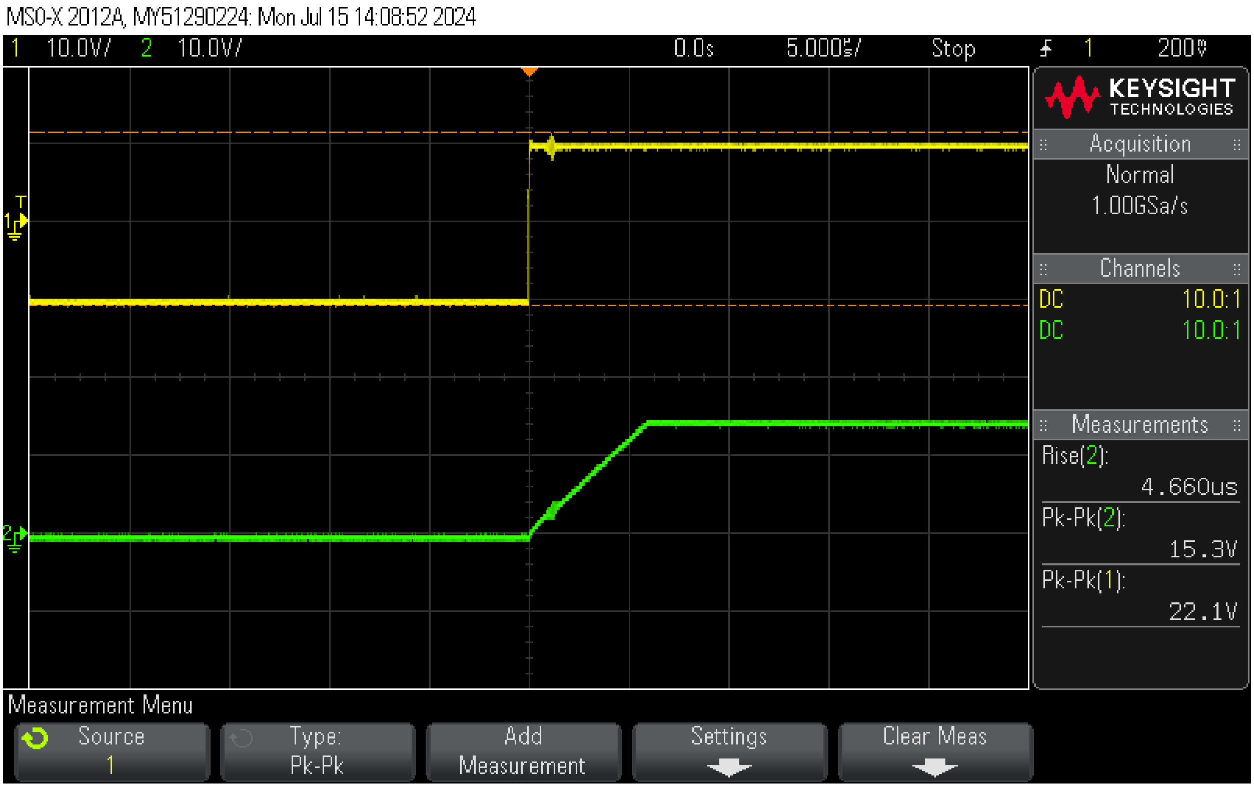
*Print: input and output, #2*



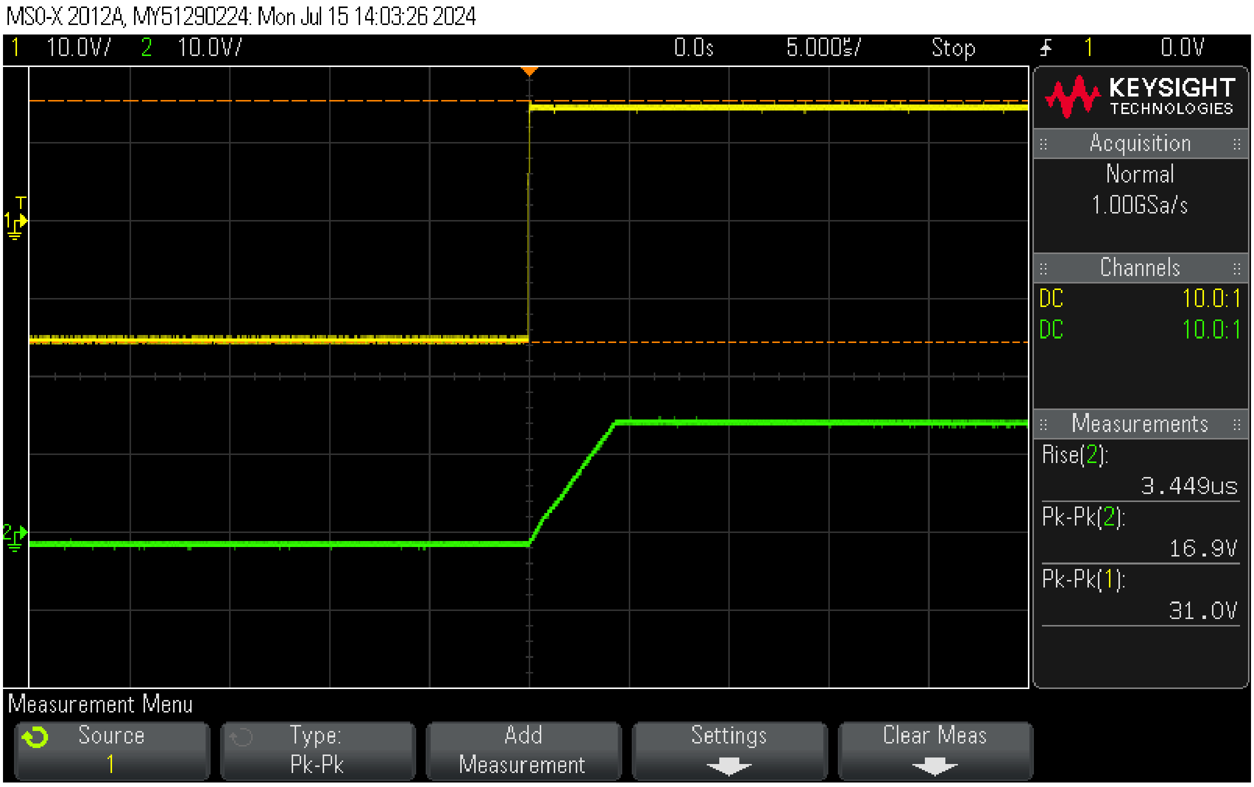

1.18. <u>Attach two different prints</u> of the input and output signals, showing cases where the output *is* SR-limited. Use the cursors to measure SR in both prints.

---

*Print: input and output, #1*



*Print: input and output, #2*



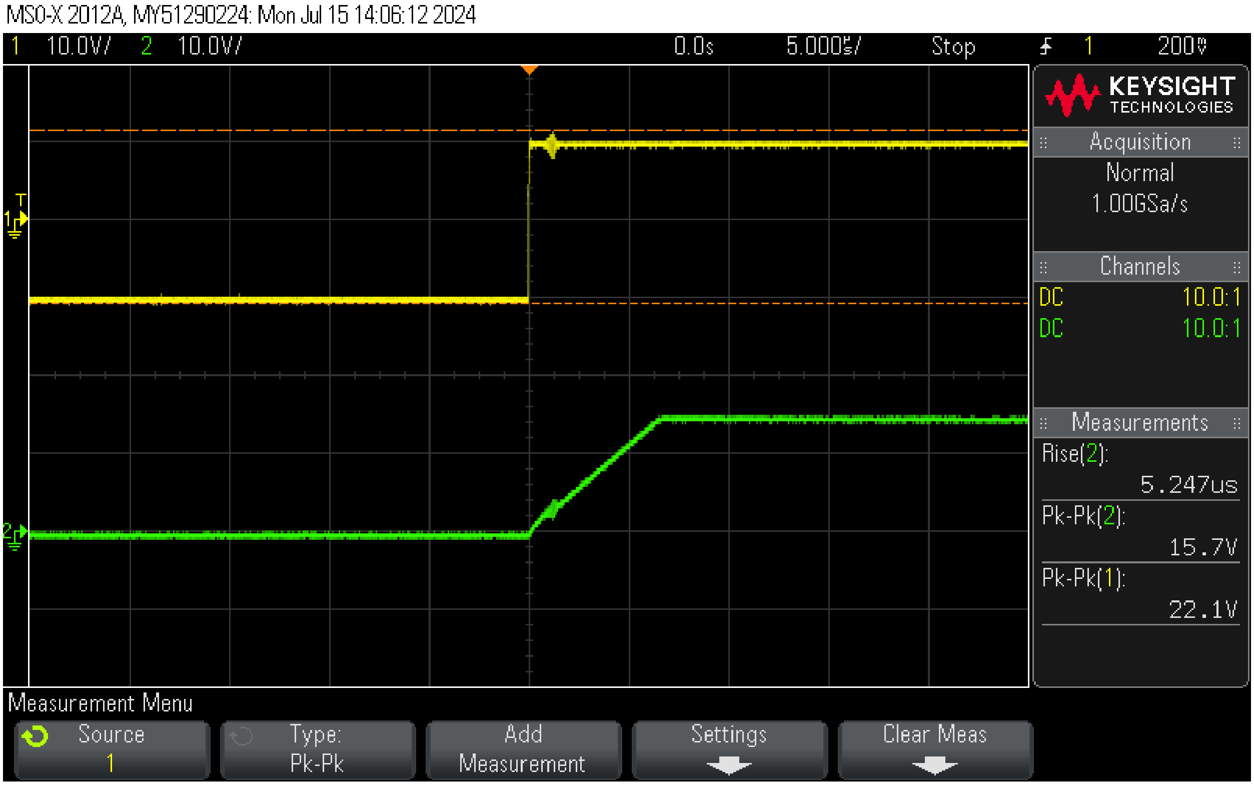

1.19. From your measurements, calculate SR for the case **P4cc**.

$$SR|_{P4cc} = 15.375/6.1 = 2.52[V/\mu s]$$

1.20. Now set the potentiometer P4 all the way clockwise (we denote this "**P4c**").

1.21. Attach a print of the input and output signals where the output *is* SR-limited. Use the cursors to measure SR.

*Print: input and output*




1.22. From the print, calculate SR for the case **P4c**.

$$SR|_{P4c} = 15.125/6.8 = 2.224[V/\mu s]$$

1.23. Finally, calculate the following value:

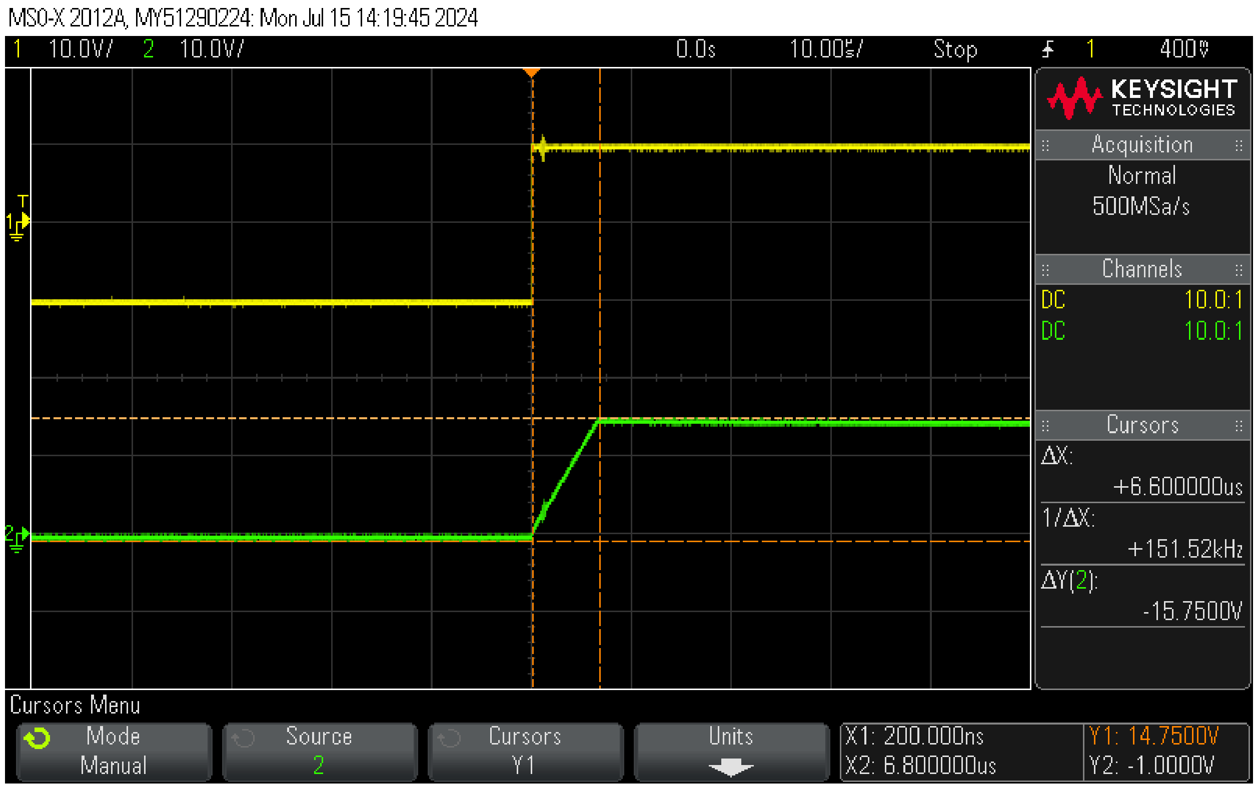
$$SR|_{YOU} = \min\left(SR|_{P4cc}, SR|_{P4c}\right) + abs\left(SR|_{P4cc} - SR|_{P4c}\right) \cdot \left(\frac{ABC + DEF}{2000}\right),$$

where $abs$ is the "absolute value" function and $\min$ is the "minimum" function.

$$SR|_{YOU} = 2.224 + 0.296 * (393 + 662)/2000 = 2.38[V/\mu s]$$

1.24. Set the potentiometer to give this value. Attach a print of the input and output signals at this SR, and measure it with the cursors.

*Print: input and output*




1.25. Prove that the measurements you took from this print give this SR by calculation.

$$\frac{\Delta Y}{\Delta X} = \frac{15.75V}{6.6\mu s} = 2.38\left[\frac{V}{\mu s}\right]$$

1.26. Now use the multimeter to measure the voltage on Ry. Calculate the value of the equivalent resistor driving the current source; explain your derivation (you do NOT need additional measurements. Hint: review section **Error! Reference source not found.** in the preliminary report).

$V_{Ry} = -8.68V$

Calculation of equivalent resistor driving the current source:

KVL: $V_{Ry} - RI_{ref} = 0$

SR= $\frac{I_{ref}}{C}$

-8.68-2.38· $10^6 \cdot 820p \cdot R = 0$

R=4447ohm

Explanations:

| |
|---|
| 6.2 השתמשנו בנוסחה לחישוב slew rate מהדוח מכין בפתרון לשאלה |

1.27. Disconnect everything.

## *2. The buffer amplifier*

Refer to the preliminary report, section 7.

*Sanity check*

2.1. Make sure everything on the board is *disconnected*, especially the biasing link.
2.2. Use the multimeter to measure the voltage given by the biasing link. Is this what you expected?

| |
|---|
| Biasing link voltage: 9.0214<br><br>Is this what you expected? yes |

OTHERWISE, as previously mentioned, on some of the boards the biasing link resistors (R12 and R13) are not 13kΩ and 20kΩ.You can verify this using the resistor color code that should be on the wall in your booth.

2.3. If not, verify the size of the resistors using the color-code table that should be hung on the wall in your booth. **DO NOT ATTEMPT TO MEASURE RESISTANCE USING THE MULTIMETER'S RESISTANCE MEASUREMENT ("Ω2" or "Ω4") UNDER ANY CIRCUMSTANCES! THIS MAY DAMAGE THE MULTIMETER.** Write the values of the resistors down for later use.

| |
|---|
| |

2.4. Construct the circuit in Figure 10.
2.5. Bias the buffer amplifier so its **output** is equal to zero volts (±50mV).

*Measuring the input resistance*

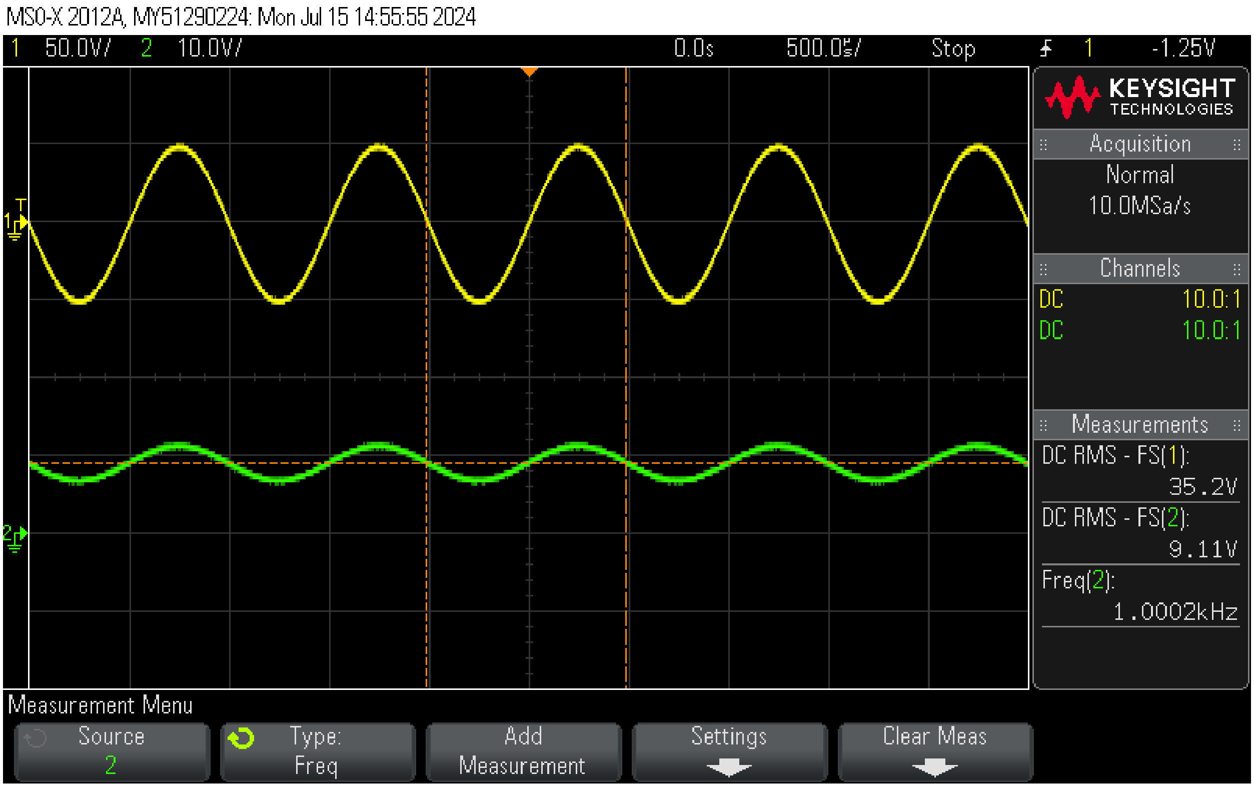
2.6. Connect **TP19** to the buffer amplifier's input.
2.7. Connect a SIN/1kHz/5Vpp to a 10kΩ resistor (find it on the board) and from there to **TP18** (capacitor C15).

You have just *serially* connected the waveform generator through a 10kΩ resistor and an electrolyte capacitor to the buffer amplifier's input.

2.8. Measure vg (CH1) and vin (CH2) and attach a print showing several cycles with two RMS measurements and a frequency measurement (total of 3 measurements).

---

*Print: input and output, 1kHz*




---

2.9. Calculate the input resistance from these measurements. Is this what you expected from your preliminary report?

- NOTE: if you find a negative value for the resistance, you have to take more accurate measurements or calculate with more digits (numerical error).
- OTHERWISE, as previously mentioned, on some of the boards the biasing link resistors (R12 and R13) are not 13kΩ and 20kΩ.

| RESISTANCE MEASUREMENT | |
|---|---|
| Vg | 35.2V |
| Vin | 9.11V |
| Calculation | $R_{in} = 3.491k\Omega$ |
| | |
| Full derivation and explanation: | |
| $$V_{R8} = 35.2 - 9.11 = 26.09\ V = \frac{35.2 \cdot 10^4}{10^4 + R_{in}} \rightarrow R_{in} = 3.491k\Omega$$ | |
| | |

| |
|---|
| |

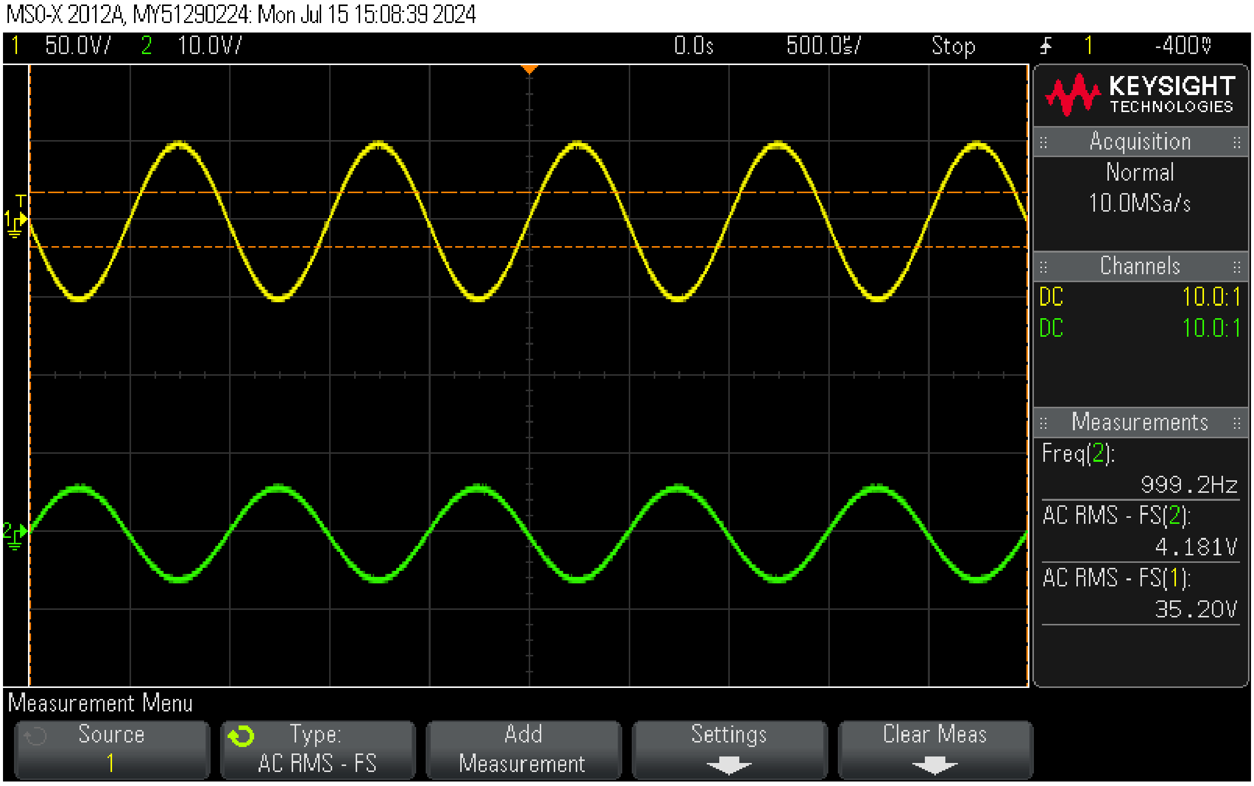
*Measuring the output resistance*

2.10. Measure the output resistance. Explain every step. You may choose any method you'd like, but **DO NOT USE THE MULTIMETER'S RESISTANCE MEASUREMENT ("Ω2" or "Ω4") UNDER ANY CIRCUMSTANCES! THIS MAY DAMAGE THE MULTIMETER.** Be sure to attach prints proving that the numbers you measured are valid. All prints must be in DC coupling.

✓ Assuming you are using an additional resistor to perform the measurement, write down its value and explain why you chose it over other optional resistors.

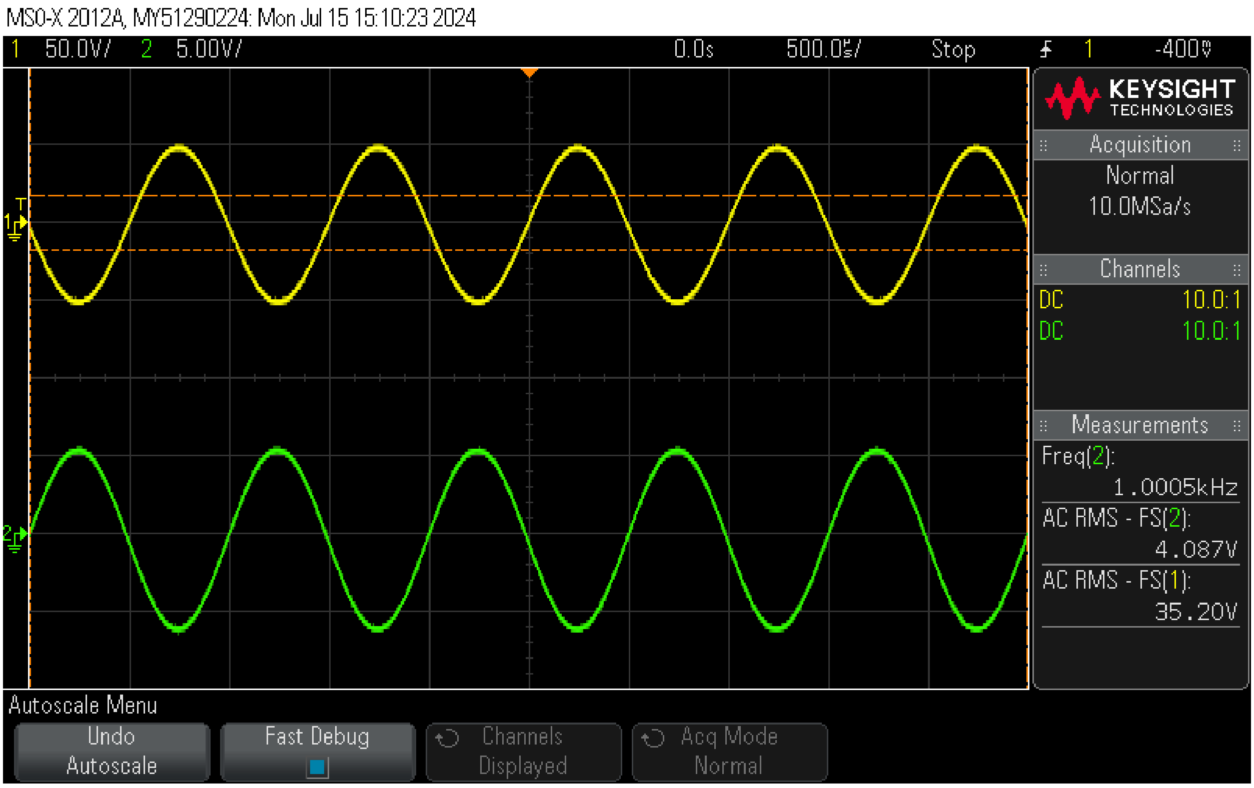
| RESISTANCE MEASUREMENT | |
|---|---|
| Output resistance | $R_{out} =$ |
| | |
| Full derivation and explanation: | |
| $R_{load} = 1k\Omega, v_{tot} = 9.23\text{V}$ | |
| $v_{out} = v_{tot} \cdot \frac{R_{load}}{R_{load} + R_{out}}$ | |
| $6.33\text{V} = 9.23 \cdot \frac{1 \cdot 10^3}{1 \cdot 10^3 + R_{out}} \rightarrow R_{out} = 458.135\ ohm$ | |
| Is this what you expected? | |
| התוצאה אינה תואמת את הדוח המכין ($25[\Omega]$) בערך בסדר גודל. כנראה הייתה שגיאה במדידה. | |
| | |

*Print: #1: (if needed) Ex




plain what you measured here*

*Print: #2: (if needed) Explain what you measured here*




*Print: #3: (if needed) Explain what you measured here*

_Measuring the gain_

2.11. Turn the waveform generator OFF. Construct the following circuit;

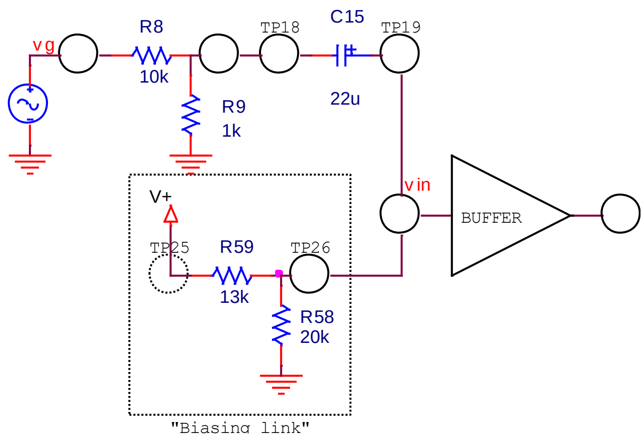



**Figure 14**

**MAKE SURE TP19 IS CONNECTED TO THE BUFFER'S INPUT!**

2.12. Measure as required, then calculate the gain, vout/vin, at 1kHz. Explain. All prints must be in DC coupling.

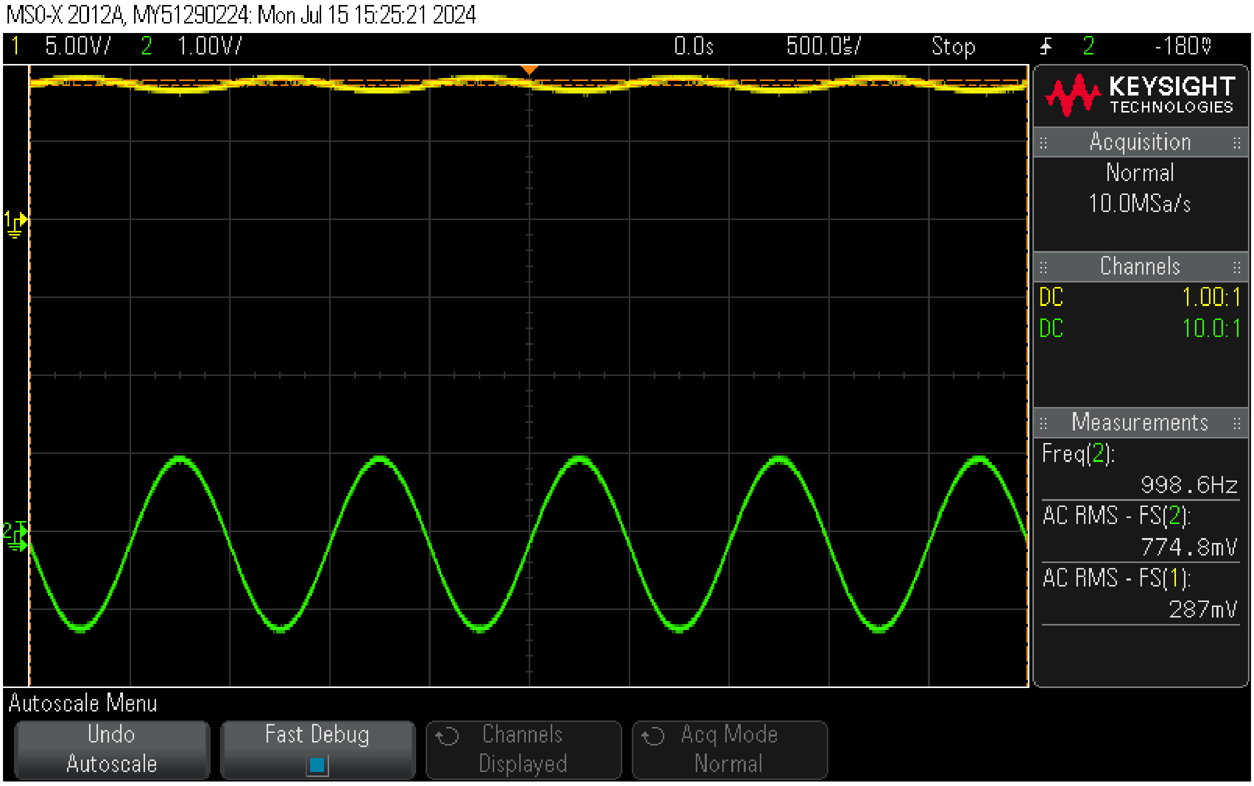
Explanation and calculation:

$$A_v = \frac{V_{out}}{V_{in}} = -2.699$$

ביצענו מדידה של המוצא והכניסה על פי החיבור שתואר לעיל. על מנת לקבל את ההגבר חילקנו בין הערכים שנמדדו. ניתן לראות כי המוצא נמצא בפאזה הפוכה לכניסה, לכן ערך ההגבר שלילי.

---

*Print: #1: Explain what you measured here*

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## *3. <u>The two-stage op-amp</u>*

<u>Refer to the preliminary report, section 8.</u>

✓ You must understand what to connect and how on your own. Do not use the help of your friends or the instructors. Everything is in the preliminary report!

3.1. <u>Disconnect everything.</u>
3.2. Load the cascode amplifier with a 680kΩ resistor.
3.3. Attach the biasing link and compensating capacitor.
3.4. Add the feedback resistors and relevant connections. Make sure the waveform generator is currently <u>disconnected</u> and the circuit's input is grounded instead.
3.5. Bias the buffer amplifier so its **output** is equal to zero volts (±50mV).

- NOTE: in the following critical step you'll notice the circuit is responding like a sensitive antenna: when you move your hands next to it or move the wires, everything changes! Don't worry! This only happens in this stage of the calibration. When the circuit is complete, these kinds of effects should disappear.

3.6. Bias the cascode so its **output** is equal to the buffer amplifier's **input** (±2V).
3.7. Disconnect the biasing link and connect the cascode to the buffer amplifier. Make sure the complete circuit's output is zero volts (±100mV) by slightly changing the bias of the cascode, if needed.
3.8. Disconnect the cascode's 680kΩ load, and connect the voltage generator to the circuit. If the output bias is still a little off zero volts (>±100mV), you can slightly calibrate it again.

- Your two-stage op-amp should be complete, and working!
- ✓ You should decide on the parameters of the input voltage *yourself*.

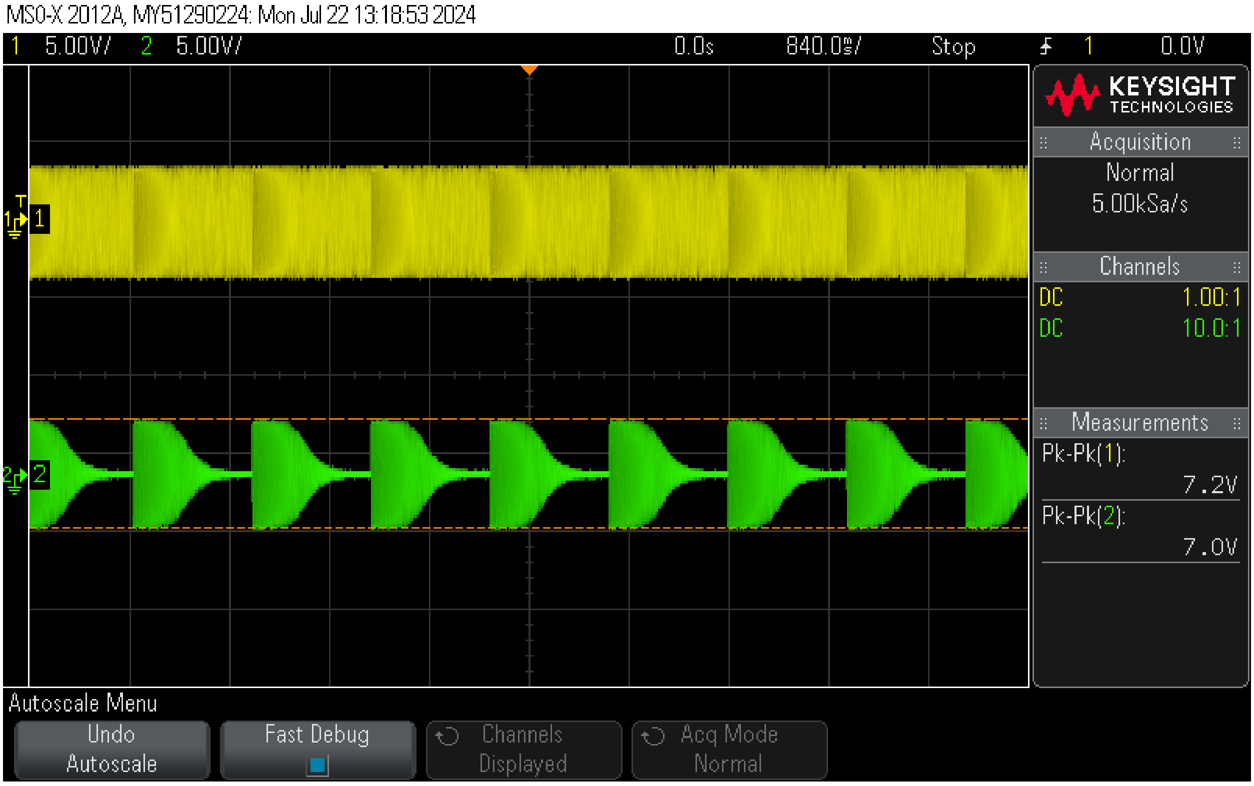
3.9. Now, attach a print of an AC sweep, with VPP measurements for the input and output signals (total of 2 measurements). Choose your input appropriately.

- **NOTE:** If the sweep signal is asymmetric, gently "tinker" with the supply voltages, until the signal is symmetric. The change in the supply voltages shouldn't be more than 1V!
- **ALSO:** If the sweep is symmetric isn't oscillating around zero volts, you can try again slightly adjust the average output voltage to (±100mV).

| SWEEP MEASUREMENT | |
|---|---|
| Frequency range | 100HZ – 1MHZ |
| Sweep time | 1 Sec |
| Input voltage | 3.5Vpp |

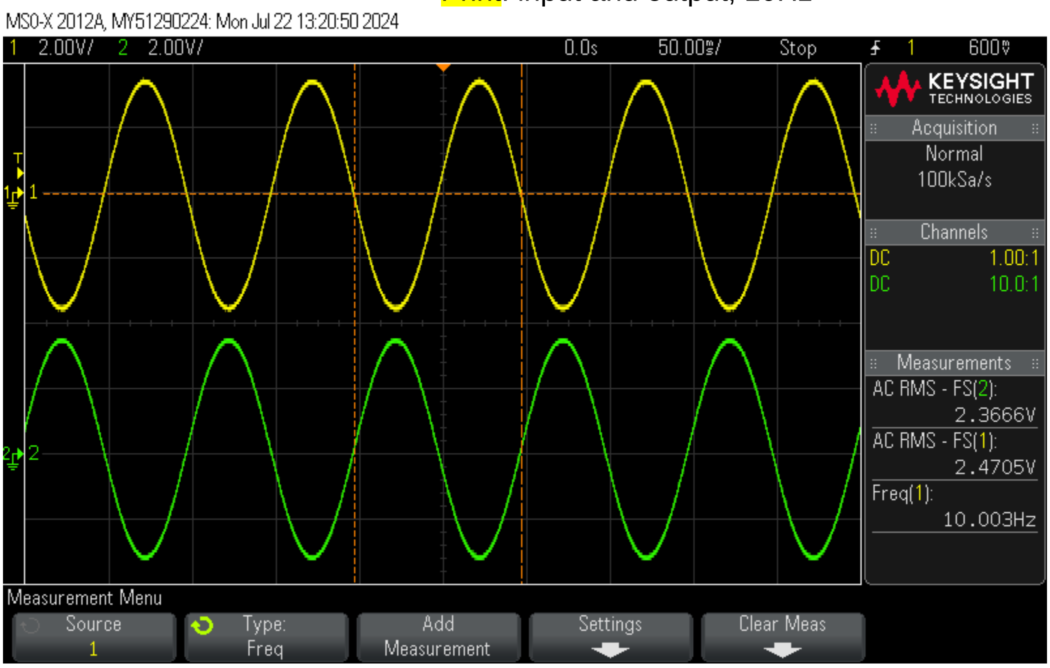
---

*Print: input and output sweep*




3.10. Choose an input frequency of 10Hz, and attach a print showing several cycles of the input and output, with two RMS measurements and a frequency measurement of the input (total of 3 measurements).

*Print: input and output, 10Hz*



3.11. Fill the following table using the scope. Calculate the open-loop gain for each frequency, then answer the questions below.

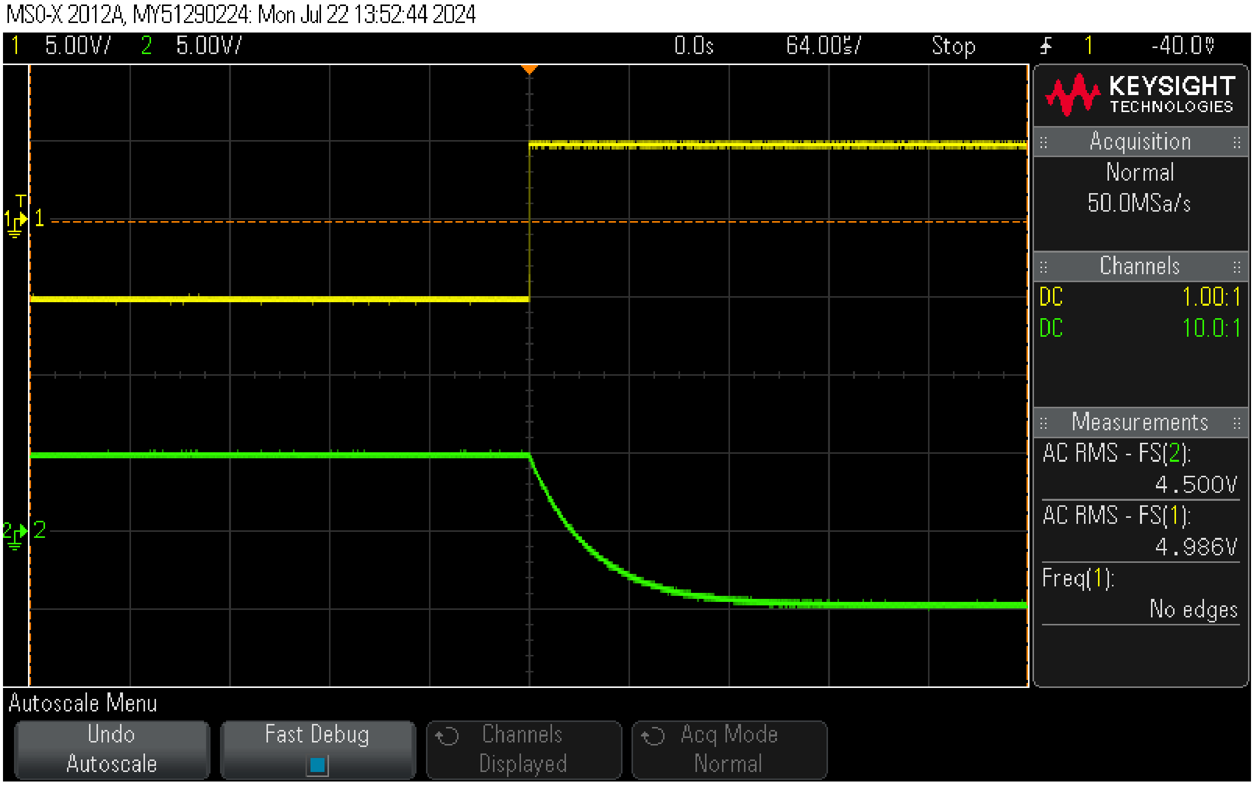
| **TABLE MEASUREMENT** | | | | |
|---|---|---|---|---|
| Transfer Function | $\frac{V_{out}}{Vy}$ | | | |
| $f[Hz]$ | $V_g = V_{in}$ | $V_y$ | $V_{out}$ | $A[dB]$ |
| 1 | 3.428[V] | 95[mV] | 3.316 [V] | 30.857 |
| 2 | 3.517[V] | 89[mV] | 3.405[V] | 31.654 |
| 8 | 3.525[V] | 93[mV] | 3.413[V] | 31.292 |
| 9 | 3.518[V] | 92[mV] | 3.385[V] | 31.315 |
| 10 | 3.517[V] | 90[mV] | 3.406[V] | 31.559 |

| What is the amplifier's open-loop gain, in DC (estimation)? |
|---|
| $A_{OL} = 51 \cdot \left(\frac{V_{out}}{V_y} - 3\right)$ = 1773.666 = 64.97[dB] |
| |

| Compare your calculation to your measurements from earlier sections (sections 1.9 and 2.12). Quote the gains from those sections here and make necessary calculations. |
|---|
| $A_{cascode} = -930, \quad A_{buffer} = -2.699$ |
| $1773.666 = A_{OL} \approx A_{cascode} \cdot A_{buffer} = 2510.07$ |
| התוצאה אינה מדויקת אך קרובה מספיק על מנת לדעת שעמדנו בציפיות. |
| |
| |
| |
| |

*Slew-rate (again)*

3.12. As before, find the circuit's SR-limit and prove it with appropriate prints. If you cannot do it, explain why and support your claim with prints. Add explanations below. No need to connect a special capacitor or the potentiometer P4 this time.




*Print: #1: Vout/Vin for a square input waveform.*

3.13. From your measurements, calculate SR, and/or explain.

| |
|---|
| $SR = XX[V/\mu s]$ |
| Explanation: לא ניתן למדוד את הSR כיוון שהFeedback מנמיך את האות. |

# This concludes the experiment.

**You have reached to end of this experiment: <u>ask the lab guide to write down the time.</u> Hand in the preliminary report, and present the complete preliminary report of the next experiment before starting it.**