

Measurement Lab #3  
EECS 170LC  
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# 1 Objective

A differential amplifier is constructed on a breadboard. The differential outputs are analyzed, and the common-mode and differential-mode gain are calculated. The limits of the output voltages before clamping distortions occur are then determined.

# 2 Descriptions

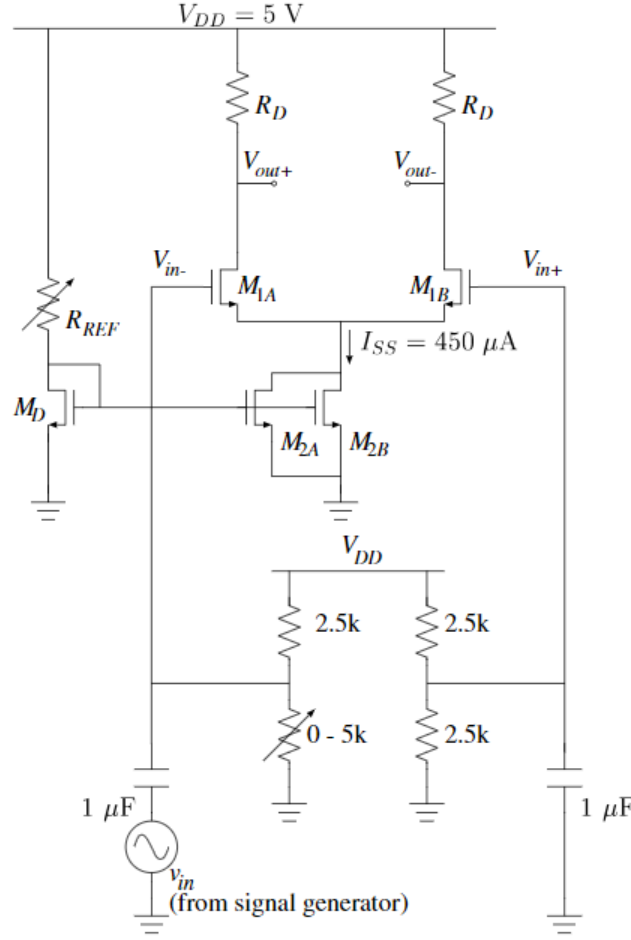


Figure 1: Differential Amplifier

First, the left hand portion of the current source is constructed. The resistor  $R_{REF}$  is tuned to get the proper  $225\mu\text{A}$  current. A  $10\text{k}\Omega$  resistor is used, which yields a  $213\mu\text{A}$  current. The two transistors for the current sources are then attached. Since each current source is expected to produce  $225\mu\text{A}$ , the total current  $I_{SS}$  is expected to be  $450\mu\text{A}$ . Their total current  $I_{SS}$  is measured to be about  $480\mu\text{A}$ , which is quite close. They are tested by setting the drain voltage sufficiently high so that both of the transistors on the right-hand of the current source enter saturation.

The first voltage divider is then constructed and tested with two  $5\text{k}\Omega$  resistors in series. Common source amplifiers are constructed with  $M_{1A}$  and  $M_{1B}$ .  $5\text{k}\Omega$  and  $10\text{k}\Omega$  resistors in parallel ( $3.3\text{k}\Omega$  equivalent resistance) for  $R_D$  turn out to be sufficient to ensure that both transistors at the voltage input are biased in the middle of the saturation region, which corresponds to an output voltage of about  $3.0\text{V}$ .

The current sources and the two halves of the differential pair are then connected to form the final amplifier. The bias current on either half of the differential pair is expected to be about  $225\mu\text{A}$ . On one side,  $240\mu\text{A}$  is measured. On the other side,  $246\mu\text{A}$  is measured. These values are astonishingly close to the design specification.

### 3 Calculations

#### 3.1 Differential-Mode & Common-Mode Gain

A sine wave centered at  $0\text{V}$  with amplitude  $100\text{mV}$  and frequency  $1\text{MHz}$  is applied to  $v_{in}$  as indicated by the differential amplifier circuit schematic. The oscilloscope displayed the following waveforms for  $V_{out+}$  and  $V_{out-}$ .

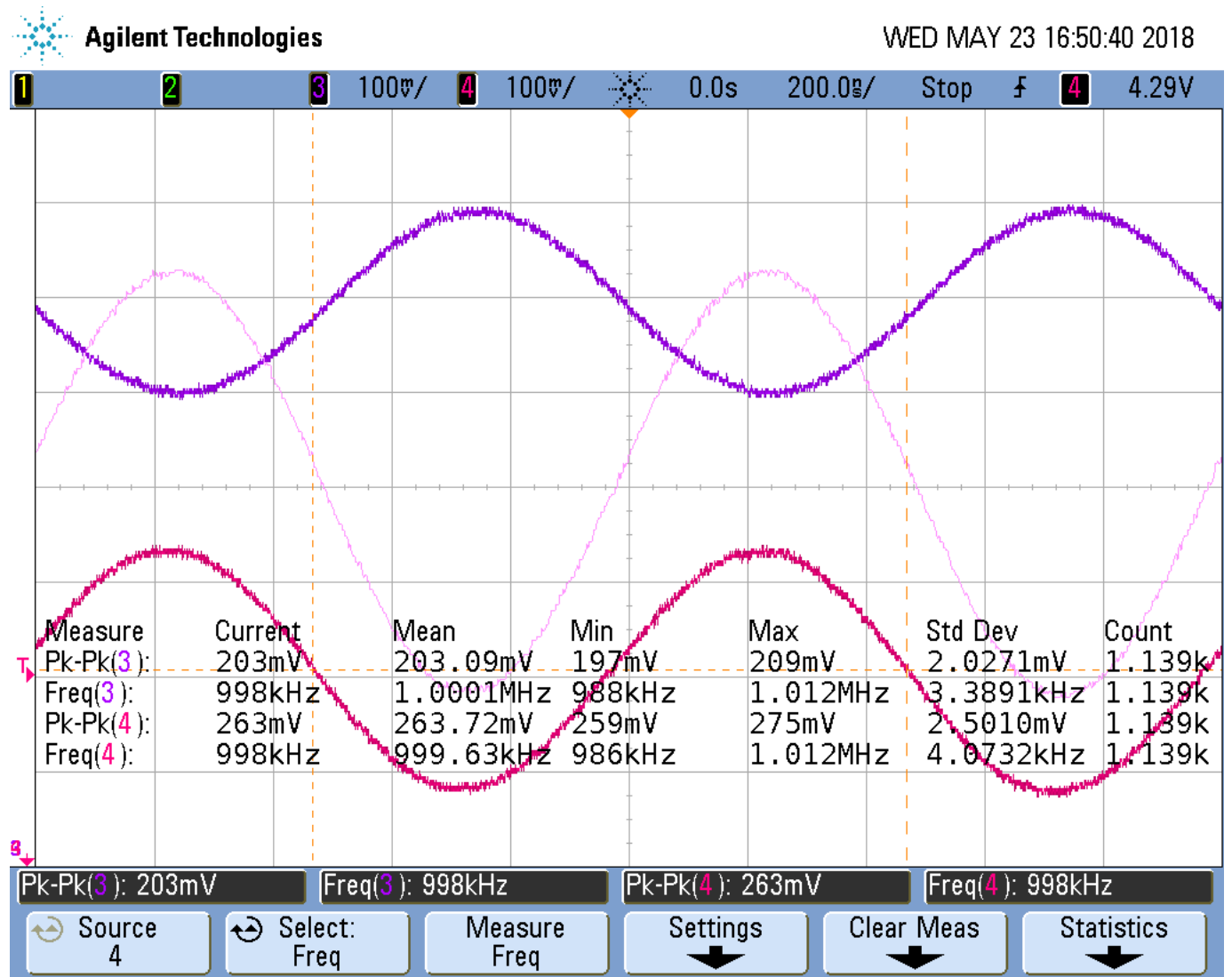


Figure 2:  $V_{out+}$  (4),  $V_{out-}$  (3), and  $V_{out+} - V_{out-}$  for  $100\text{mV}$  input at  $1\text{MHz}$

As expected,  $V_{out+}$  and  $V_{out-}$  are  $180$  degrees out of phase. The peak-to-peak amplitudes of  $V_{out+}$  and  $V_{out-}$  are  $263$  and  $203\text{mV}$ , respectively. By taking the difference of the amplitudes,  $V_{out+} - V_{out-} = 466\text{mV}$

peak-to-peak.

The voltage applied to  $V_{in-}$  has an ac amplitude of 100mV. The voltage applied to  $V_{in+}$  has no ac component. From these input signals, the differential-mode component of the input  $v_{in(dm)} = v_{in+} - v_{in-} = -100\text{mV}$  amplitude or 200mV peak-to-peak. The common-mode component of the input  $v_{in(cm)} = \frac{1}{2}(v_{in+} + v_{in-}) = 50\text{mV}$  amplitude or 100mV peak-to-peak.

### 3.2 Clamping & Distortion

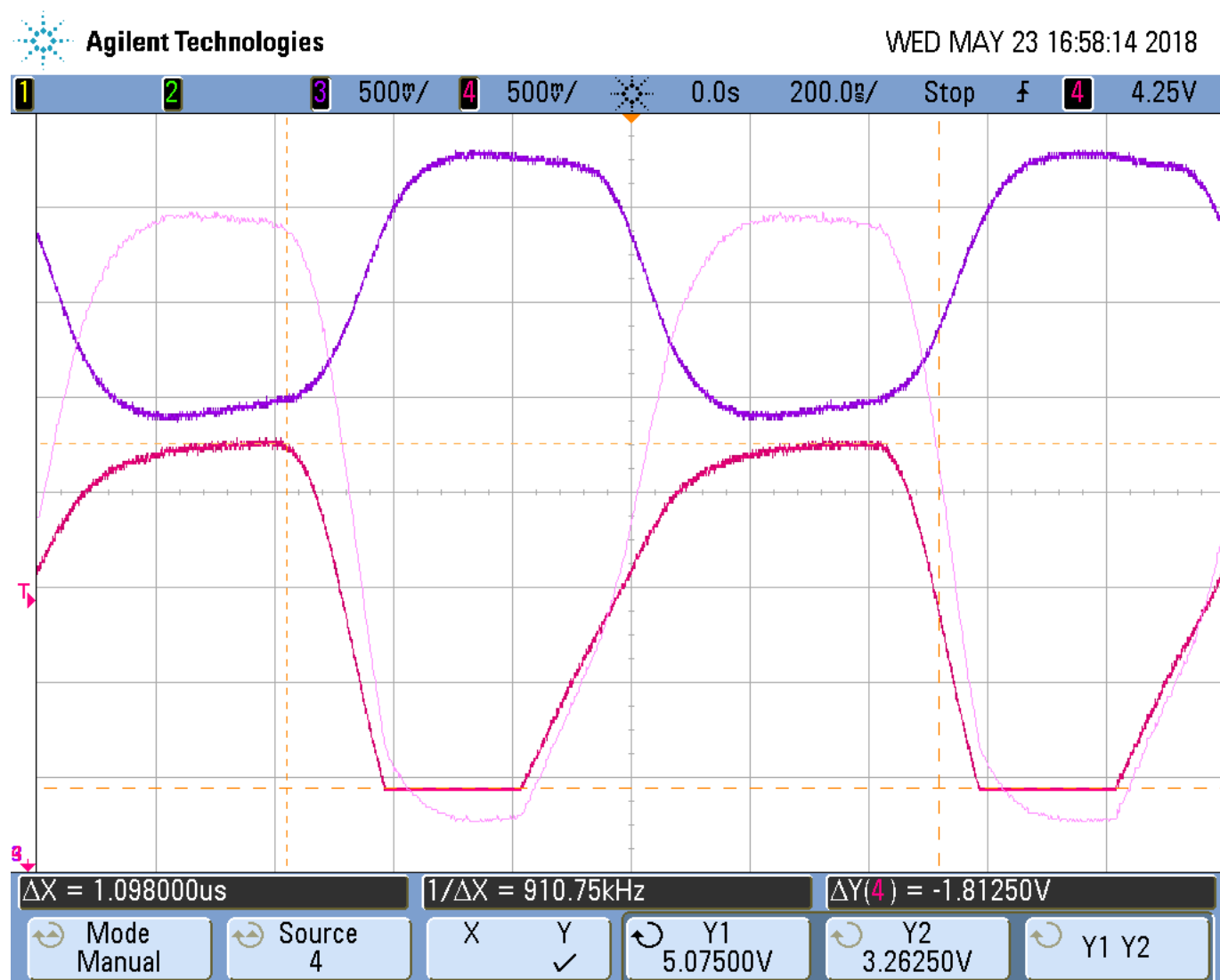


Figure 3: Measured maximum signal swing of  $V_{out+}$  from a 2V p/p input at 1MHz

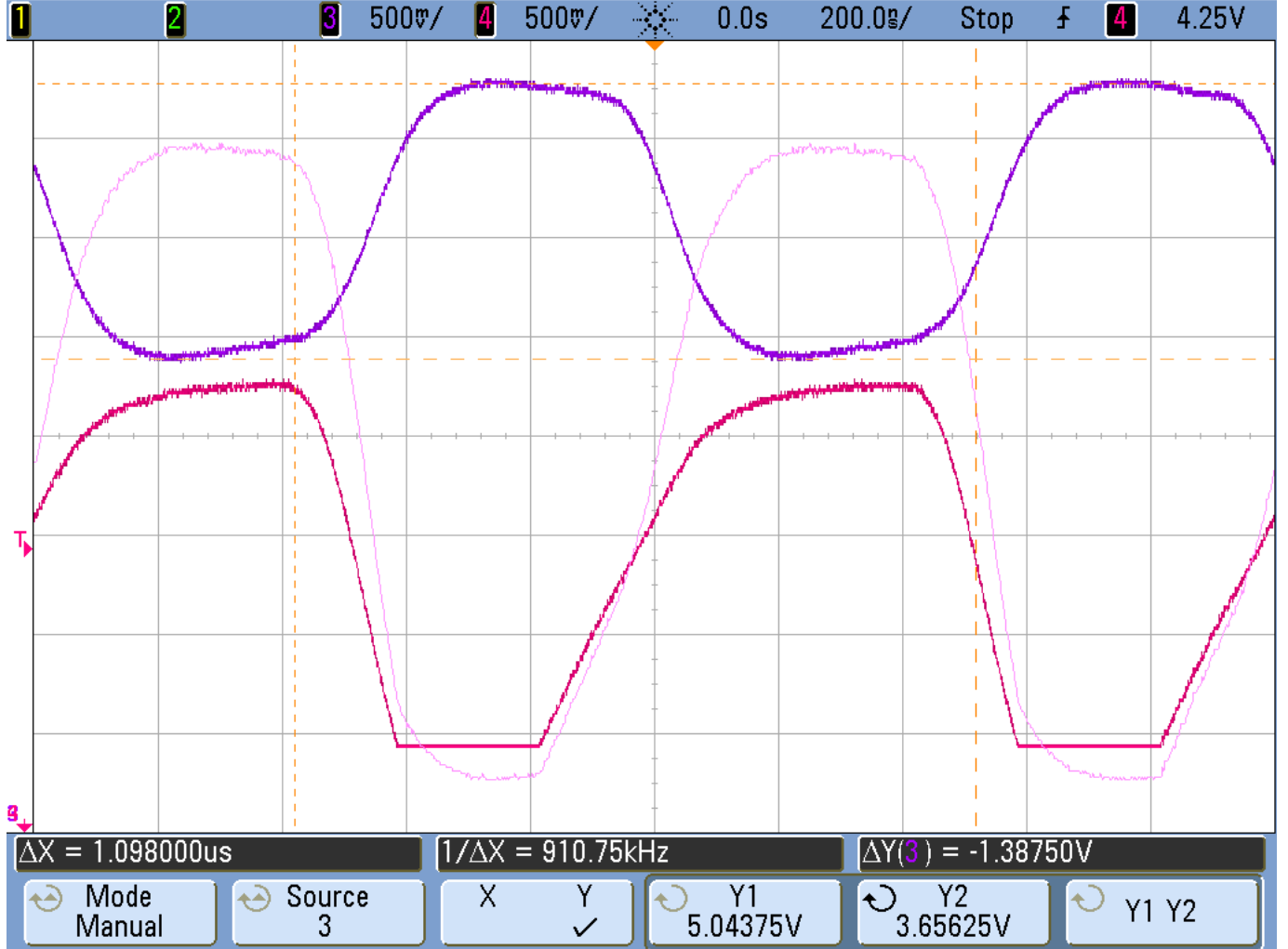


Figure 4: Measured maximum signal swing of  $V_{out-}$  from a 2V p/p input at 1MHz

From the cursors in (3),  $V_{out+}$  ranges from 5.075 to 3.262 V, resulting in a swing of 1.81V. Similarly, the cursors in (4) reveal a range of 1.38V for  $V_{out-}$ . Thus, the voltage range for the signal  $V_{out+} - V_{out-}$  is the sum of these two ranges, or 3.19V. From these parameters, an input signal that will avoid clipping should have an amplitude lower than  $3.19V / A_{dm} \approx 1.37V$ .

## 4 Analysis

### 4.1 Differential-Mode & Common-mode Gain

The differential-mode gain and common-mode gain from simulations performed prior to this lab are approximately 20 and 0.01 V/V.  $v_{out(dm)}$  and  $v_{out(cm)}$  can be found by evaluating the product of the corresponding gain values and input components. Thus,  $v_{out(dm)} = A_{dm}v_{in(dm)} = 4V$  peak-to-peak and  $v_{out(cm)} = A_{cm}v_{in(cm)} = 1mV$  peak-to-peak. However, the result for  $v_{out(dm)}$  is much too large when compared to the amplitudes seen on the oscilloscope. Also, because amplitude of  $V_{out+}$  and  $V_{out-}$  differ significantly more than 1mV, the common-mode gain from the simulation is much too small.

Using the results from the oscilloscope,  $v_{out(dm)}$  is given by  $V_{out+} - V_{out-} = 466\text{mV}$  peak-to-peak. The differential-mode gain can then be found:  $A_{dm} = \frac{v_{out(dm)}}{v_{in(dm)}} = 2.33 \text{ V/V}$ . This is significantly lower than the value from the simulation. The common-mode gain  $v_{out(cm)}$  is given by  $\frac{1}{2}(V_{out+} + V_{out-}) = 30\text{mV}$  peak-to-peak. The common-mode gain can then be found:  $A_{cm} = \frac{v_{out(cm)}}{v_{in(cm)}} = 0.3 \text{ V/V}$ . This is significantly higher than the value from the simulation. With both gain values, the common-mode rejection ratio is given by  $CMRR = |\frac{A_{dm}}{A_{cm}}| = 7.77$ . This indicates that the performance of the differential amplifier is worse than the simulated results by a significant margin.

## 4.2 Clamping & Distortion

Given the voltage ranges in which the amplifying transistors operate from figures (3) and (4),  $V_{out+}$  seems to exhibit a larger swing. Although we biased these transistors as identically as we could with the current mirrors and DC voltage dividers, they still exhibit some differences. Notably, the transistor for  $V_{out+}$  clearly hits cutoff where the one for  $V_{out-}$  does not. The voltage variation in  $V_{out+} - V_{out-}$  was earlier found to be  $3.19\text{V}$ . This indicates that although our input magnitude was quite large, it was not large enough to drive the transistors far enough into triode region to exhibit the maximum possible output swing of  $V_{DD}$ . Since the gain in the triode region is so low, demonstrating that  $V_{out+} - V_{out-}$  is at maximum  $5\text{V}$  would require a very large input magnitude.

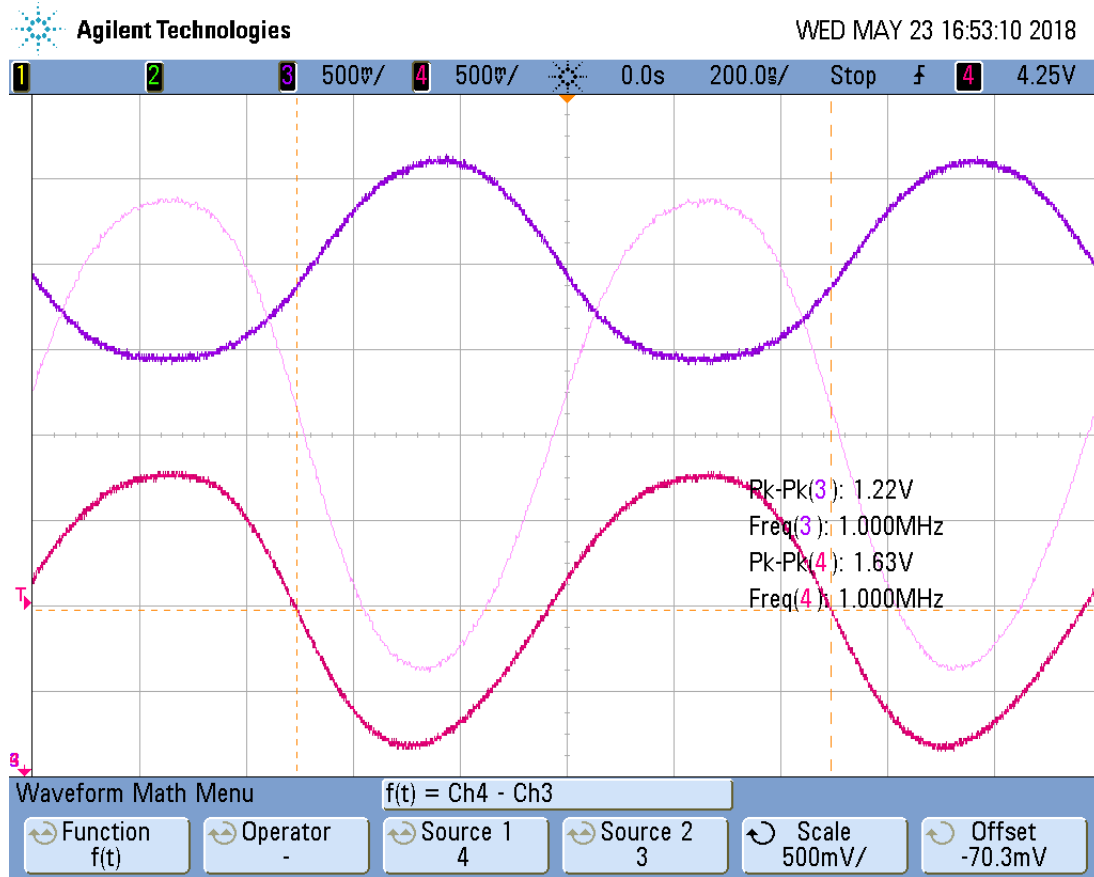


Figure 5: Measured maximum signal swing of  $V_{out+}$  and  $V_{out-}$  from a  $1.5\text{V}$  p/p input at  $1\text{MHz}$

Therefore, for this differential amplifier, the input signal magnitude should be no greater than  $1.5\text{V}$  p/p to avoid significant distortion in signal. This quantity is similar to the output voltage swing divided by  $A_{dm}$ .

## 5 Conclusion

### 5.1 Differential-Mode & Common-mode Gain

The differential amplifier produced results that are clear and easily measurable when a small signal input is applied. However, the differential-mode gain of the amplifier is observed to be a whole order of magnitude lower than the result from simulation. Also, the common-mode gain of the amplifier is observed to be a whole order of magnitude higher than the result from simulation. This may be partly due to high frequency attenuation since the circuit is operating at a relatively fast 1MHz frequency. When the frequency of  $v_{in}$  is changed to 1kHz, the output amplitudes increase.

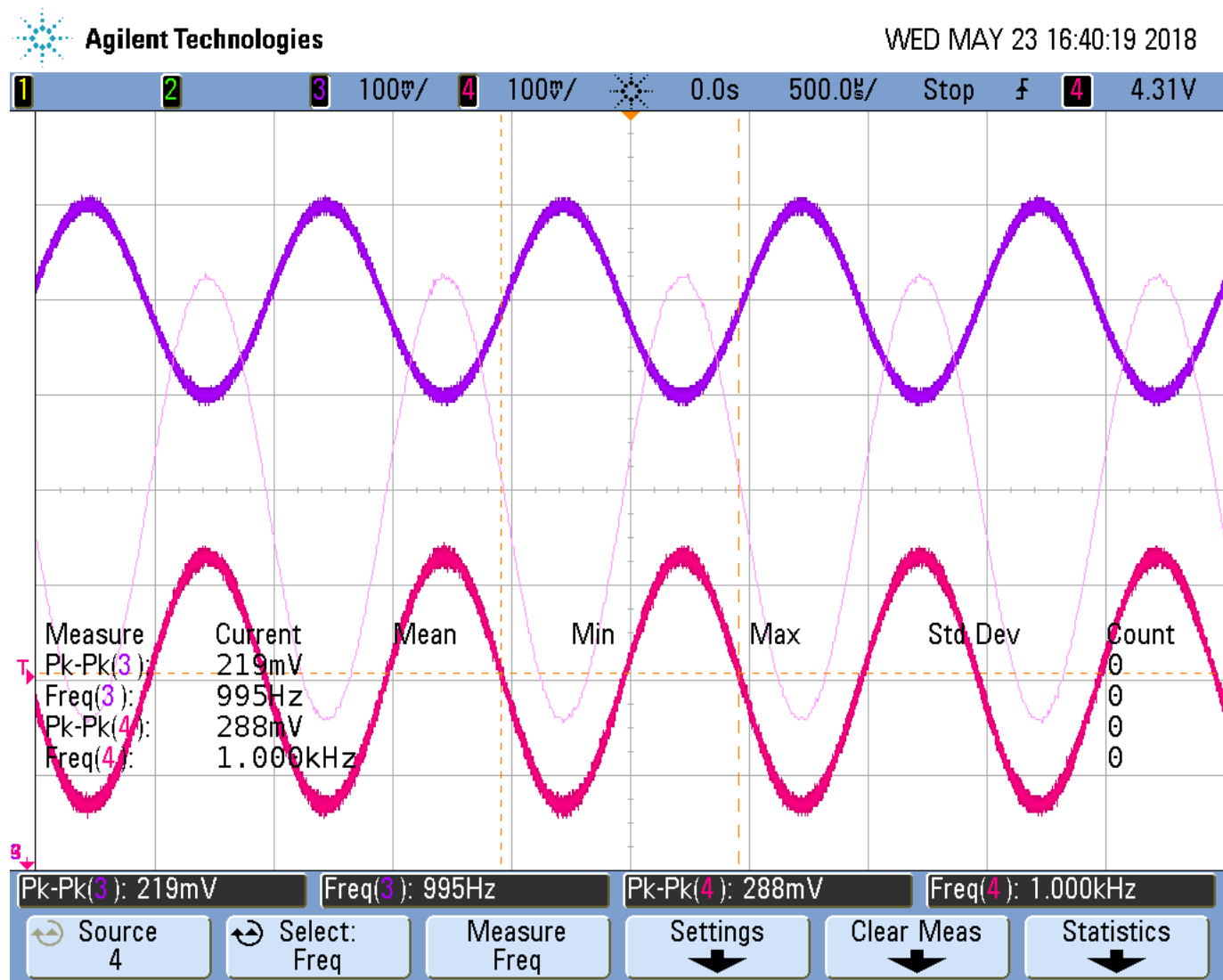


Figure 6:  $V_{out+}$  (4),  $V_{out-}$  (3), and  $V_{out+} - V_{out-}$  for 100mV input at 1kHz

Also, it is observed that transistors M1A and M1B are mismatched as  $V_{out+}$  and  $V_{out-}$  vary by 60mV and the drain currents on each side of the differential amplifier vary by 6 $\mu$ A. Other inconsistencies may be due to slight variations in resistor values as well. Overall, the differential amplifier exhibited behavior within the realm of expectation. However, the performance of the amplifier is significantly worse than what simulation results would seem to indicate.

## 5.2 Clamping & Distortion

The output voltage swing of  $V_{in+}$ ,  $V_{in-}$ , and of  $V_{in+} - V_{in-}$  is overall consistent with the simulated differential amplifier. When one transistor is near cutoff, the other is near triode, and vice-versa so that the differential mode output is large. The value of the differential mode output swing is near the expected value of  $V_{DD} - V_t$ , which when divided by  $A_{dm}$  is consistent with the maximum input amplitude that we found to incur only slight distortion.