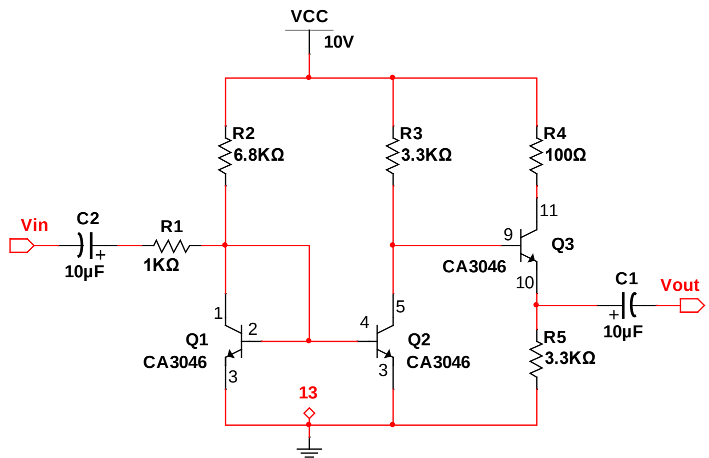
# BEE 332 Devices and Circuits II
# Spring 2017
# Lab 4: Multi-stage amplifiers instructor's notes*

## 3 Wideband CE-EF amplifier

### 3.1 Circuit

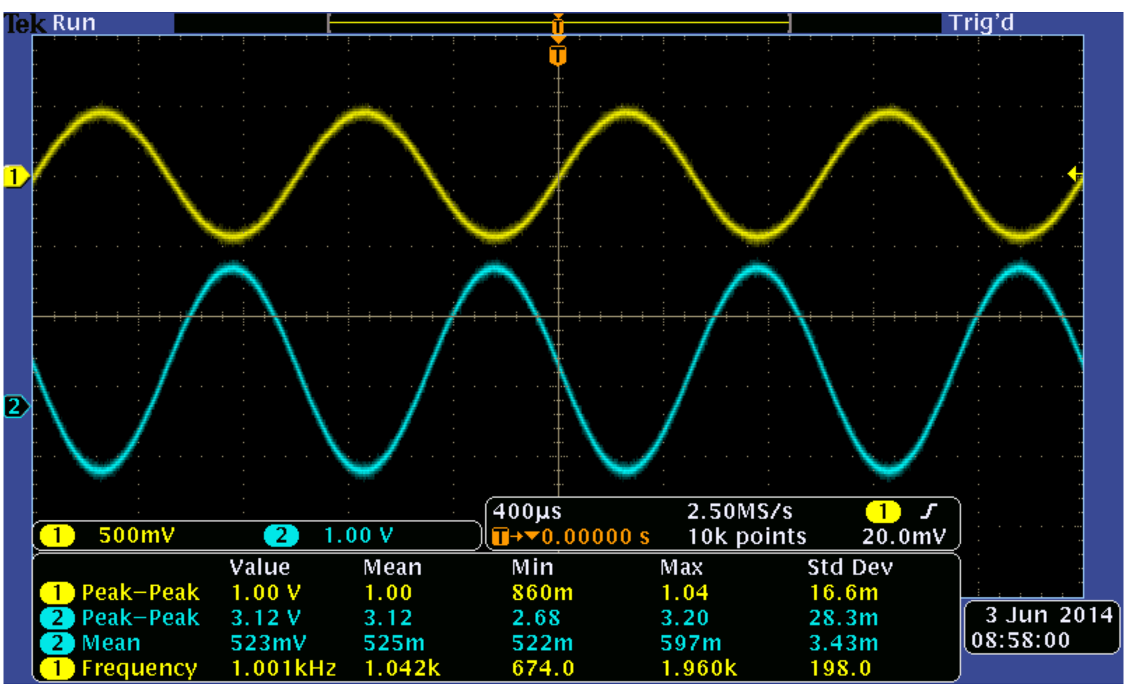
My measured values. I now also ask for quiescent Q1, Q2, Q3 terminal voltages.

VCC = 10.0685 V
R1 = 981 Ω
R2 = 6.80 KΩ
R3 = 3.29 KΩ
R4 = 99.8 Ω
R5 = 3.28 KΩ




### 3.2 Measurements

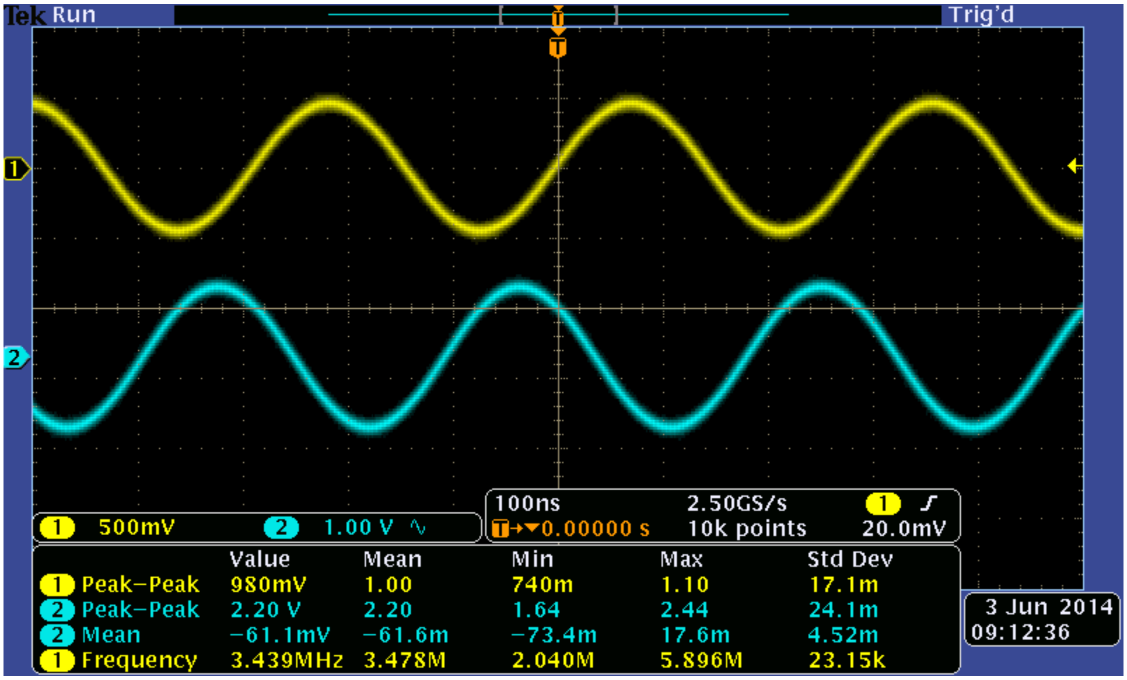
1. Set Vin = 1 Vpp, 1.0 KHz sine wave, 0 V DC offset.
2. Capture an oscilloscope screenshot. (You were asked to position cursors, not shown here. I've changed the instructions, so some of my measurements are a little different than I asked you to make.)



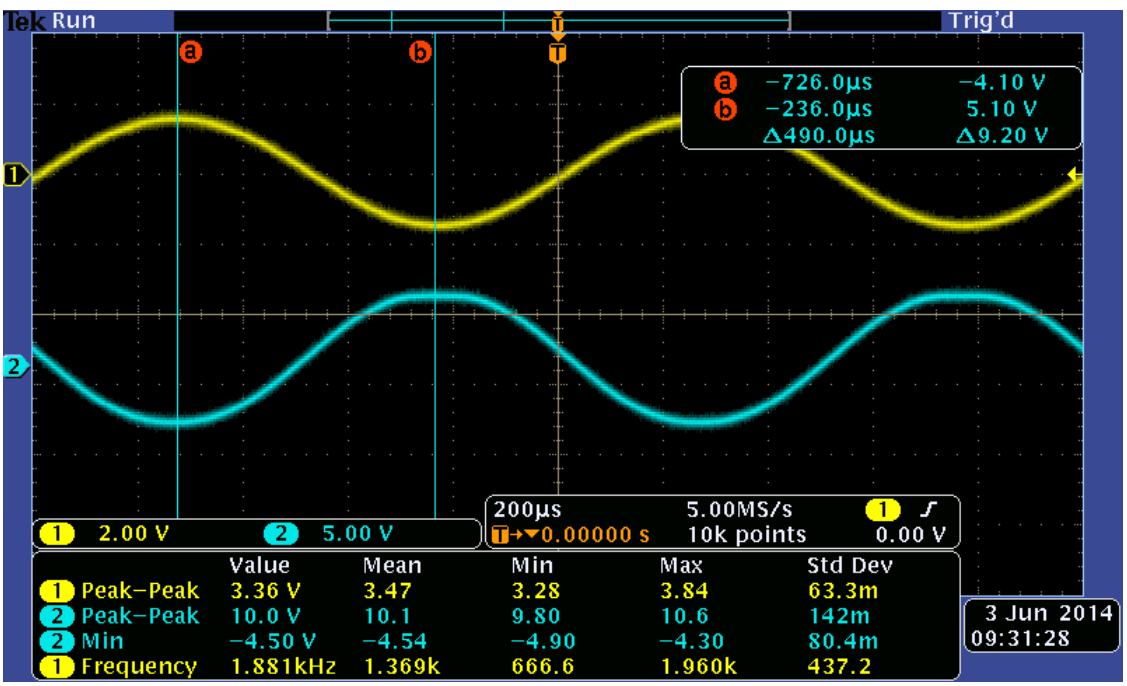

* These notes were written by Nicole Hamilton.

3. Av = 3.12.

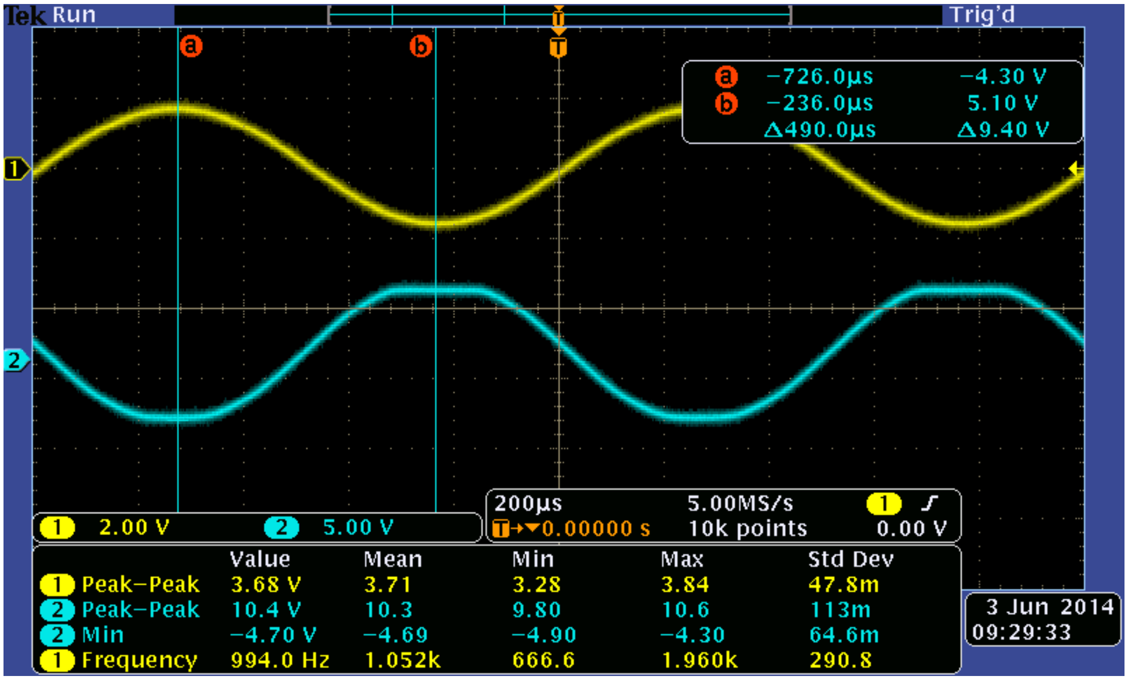
4. Increase the frequency of Vin until Av has fallen by 3 dB. At 3 dB point, Av = .7071 * 3.12 = 2.206. Shown here, Av = 2.20 at 3.5 MHz.



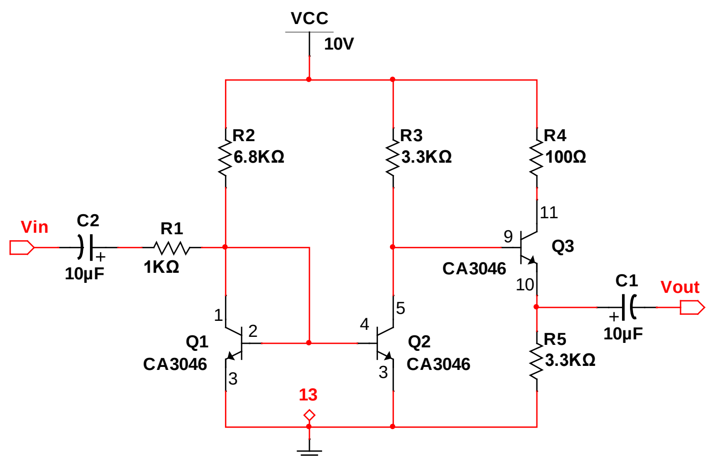

5. Onset of clipping on positive peaks happens at Vin = 3.47 Vpp and Vout = 10.1 Vpp. Clipping is at Vout between 5.10 V (cursors) and 10.1 – 4.54 = 5.56 V (P-P + Min).



6. Clipping on negative peaks happens at Vin = 3.71 Vpp and Vout = 10.3 Vpp. Positive peaks are clipped between 5.10 V (cursors) and 10.3 – 4.69 = 5.61 V (P-P + Min). Negative peaks are clipped at between -4.30 V (cursors) and -4.69 V (Min).




## 3.3 Analysis




1. Explain how the Q1-Q2 pair sets the bias level for Q3.

   Q1 and Q2 form a current mirror. With expected Q1 VCE = 0.7 V, Iref = IR2 = (10 – 0.7) / 6.8 K = 1.4 mA. Assuming Iref ≅ IC1, IR3 will be about the same, meaning VB3 = 10 – 3.3K * 1.4 mA = 5.38 V. Quiescent VE3 should be about 5.4 – 0.7 = 4.7 V.

2. Explain why Av is approximately given by R3/R1.

   The EF follower stage has roughly unity gain, so all the gain is at VC2.

   The first stage is a current mirror. Both Q1 and Q2 are in forward active and matched with VBE1 = VBE2, causing IC1 = IC2. That also means that if we inject a small additional current into IC1, it will be matched in IC2. *Since VBE can be assumed constant at 0.7 V, we can ignore R2.*

$$\Delta Iref = \frac{\Delta Vin}{R1} \cong \Delta \text{IC1} = \Delta \text{IC2} \cong \Delta \text{IR3}$$

$$\Delta VC2 = -R3 * \Delta IR3 = -R3\left(\frac{\Delta Vin}{R1}\right) = -\left(\frac{R3}{R1}\right)\Delta Vin$$

$$Av = \frac{\Delta VC2}{\Delta Vin} = -\frac{R3}{R1}$$

3. Explain what sets the clipping levels for this amplifier.

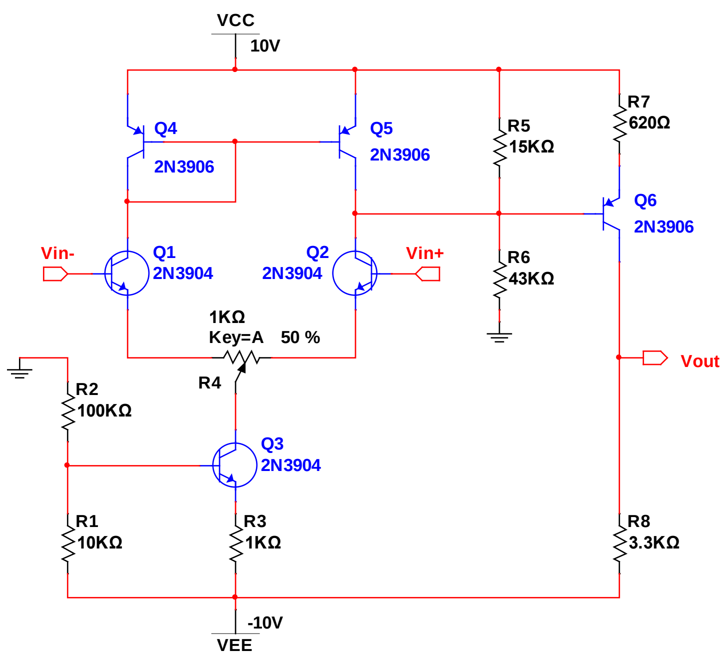
   Clipping is set by the power supply limits and by the biasing of the transistors. We know that EF amplifiers clip on the bottom, not on the top, so the clipping at positive peaks has to be happening in the first stage when Q1 and Q2 turn off as VB1 and VB2 drop below 0.7 V.

   Clipping on negative peaks could occur when Q3 goes into cutoff or when Q2 goes into saturation. But because VCEsat is about 0.2 V versus VBE = 0.7 V in forward active and because there is an IR drop in R5, we can eliminate Q2. Clipping on negative peaks must be happening when Q3 goes into cutoff.

   We could reduce the clipping by increasing the power supply voltages or (if clipping happens on one peak before the other) by adjusting R4 and R5.

## 4 An active load: A simple opamp

### 4.1 Circuit




My measured values. You also need quiescent voltages.

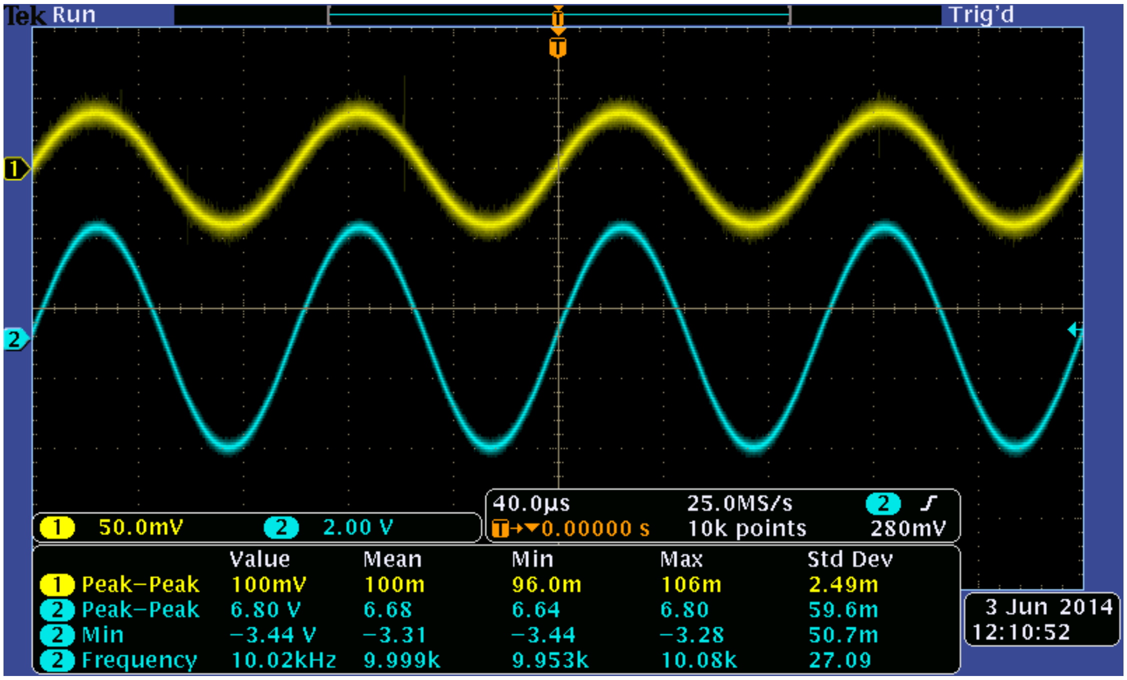
VCC = 10.0166 V
VEE = -9.9993 V
R1 = 9.82 KΩ
R2 = 99.3 KΩ
R3 = 983 Ω
R4 = 976 Ω
R5 = 14.7 KΩ
R6 = 42.5 KΩ
R7 = 609 Ω
R8 = 3.29 KΩ

### 4.2 Measurements

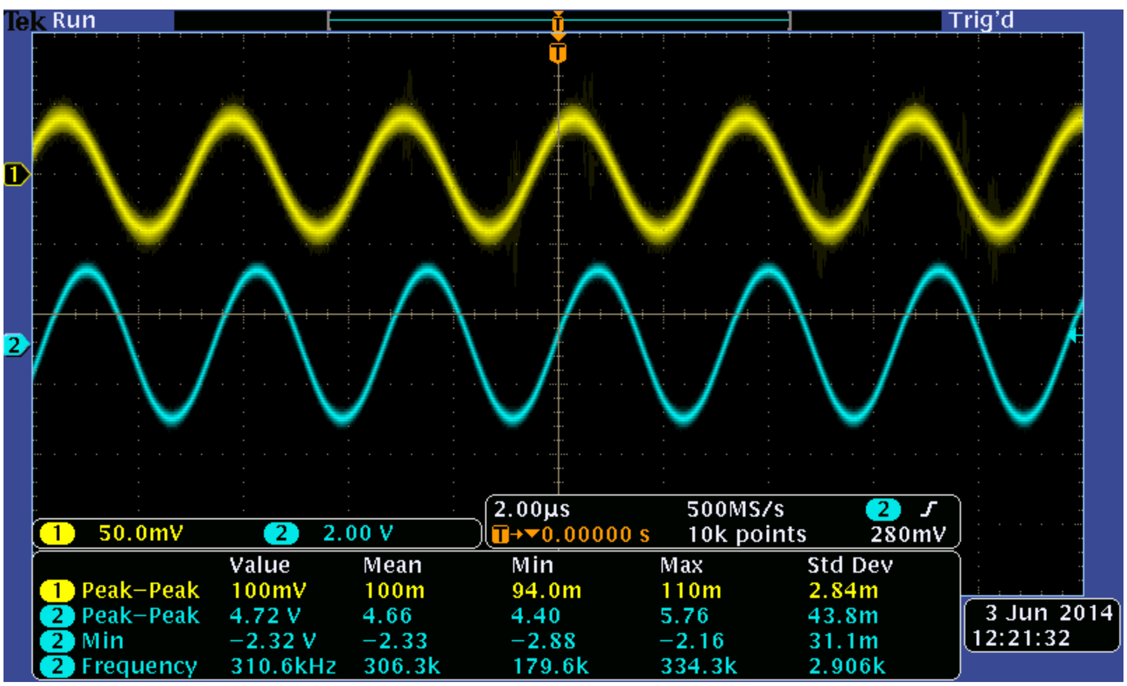
1. Trim the circuit by grounding both Vin+ and Vin–, then adjusting the trimpot to set Vout = 0 V.

   With R4, and set to 428 Ω Q1-to-Q3 and 559 Ω Q3-to-Q2, quiescent Vout ≅ 6 mV.

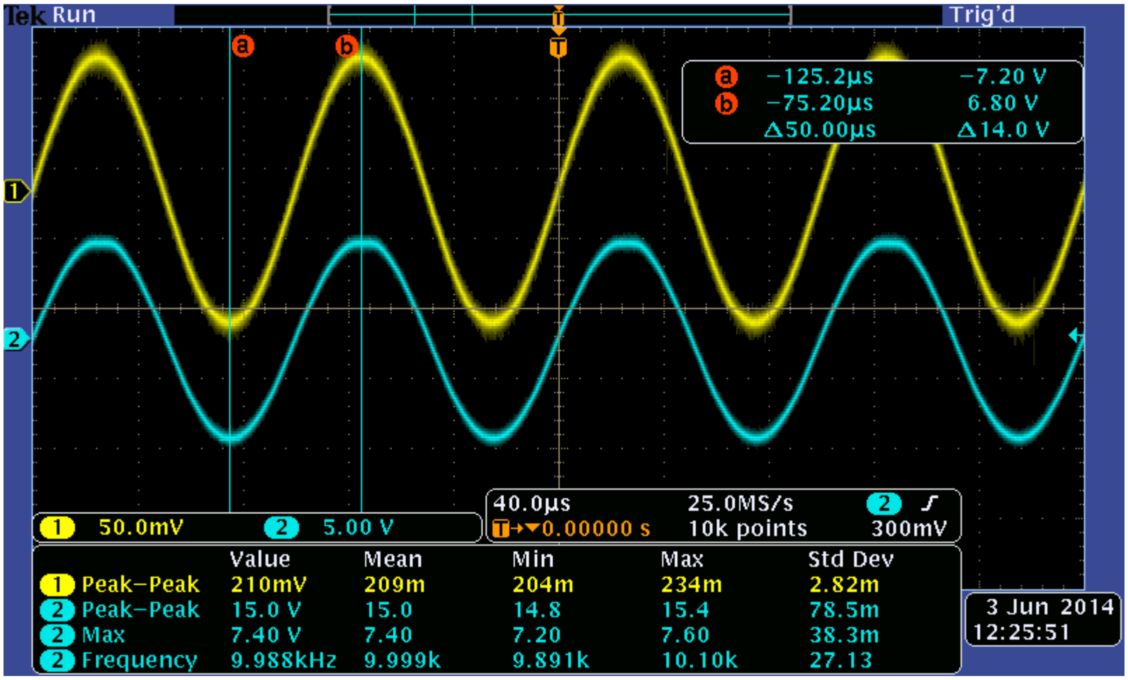
2. Ground Vin– and set Vin+ = 100 mVpp, 1 KHz sine wave, 0 V DC offset. (This shows Vin = 100 mVpp *at 10 KHz;* I've changed the instructions.) Av = 66.8 = 36.5 dB.



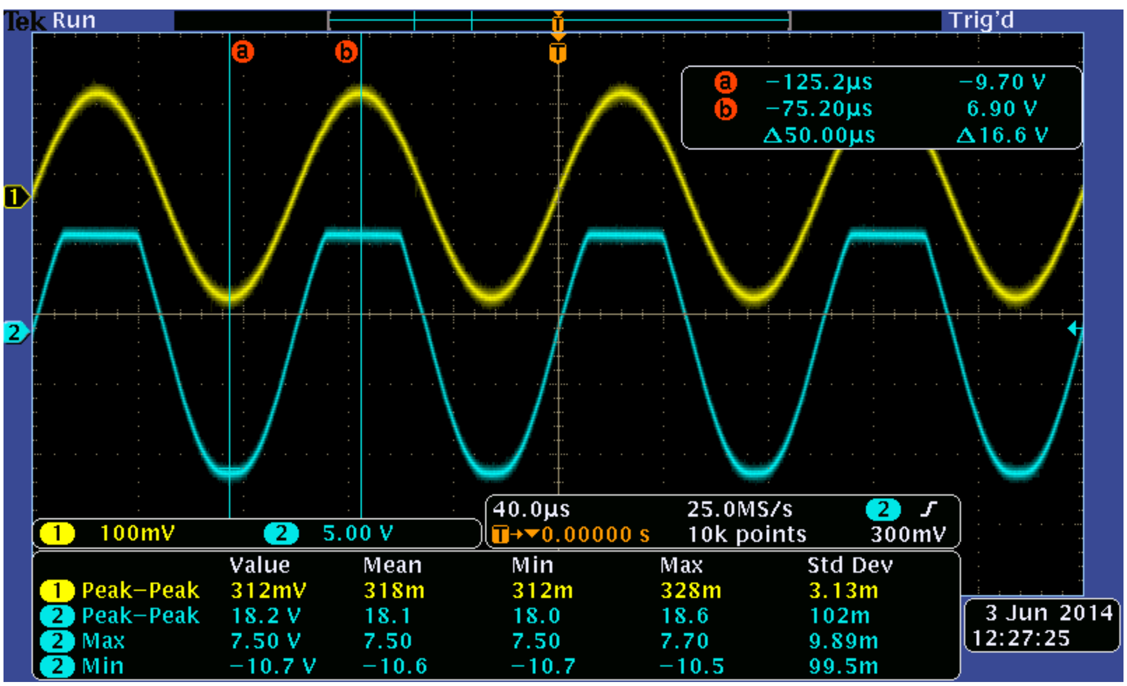

3. Increase the frequency of Vin+ until Av has fallen by 3 dB. At the 3 dB point, Av = .7071 * 66.8 = 47.2. Shown here, Av = 47.2 at 310.6 KHz.



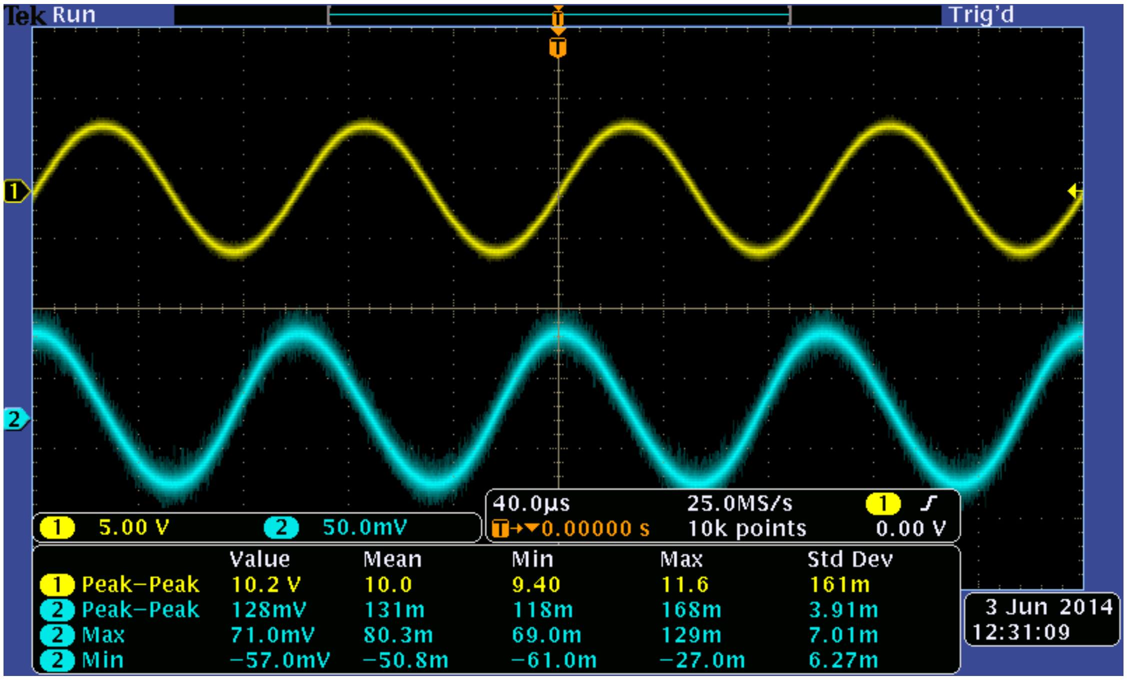
4. Clipping on one peak at Vin = 209 mVpp, Vout = 15.0 Vpp. Vout is clipping between 6.80 V (cursor) and 7.40 V (Max).




5. Clipping on both peaks occurs at Vin = 318 mVpp, Vout = 18.1 Vpp. Vout tops are clipping between 6.90 V (cursors) and 7.50 V (Max). Bottoms are clipping between -9.70 (cursors) and -10.6 V (Min).



6. Set Vin– = Vin+ = 10 Vpp, 1.0 KHz sine wave, 0 V DC offset. Shown here, Av(common mode) = 131 mVpp / 10.0 Vpp = .013.




## 4.3 Analysis

1. Calculate the differential-mode voltage gain of the amplifier in dB.

   $Differential\ mode\ gain\ (dB) = 20\ log10(Av) = 20\ log10(66.8) = 36.5\ dB$

2. Calculate the common-mode voltage gain of the amplifier in dB.

   $Common\ mode\ gain\ (dB) = 20\ log10(Av) = 20\ log10(.013) = -37.7\ dB$

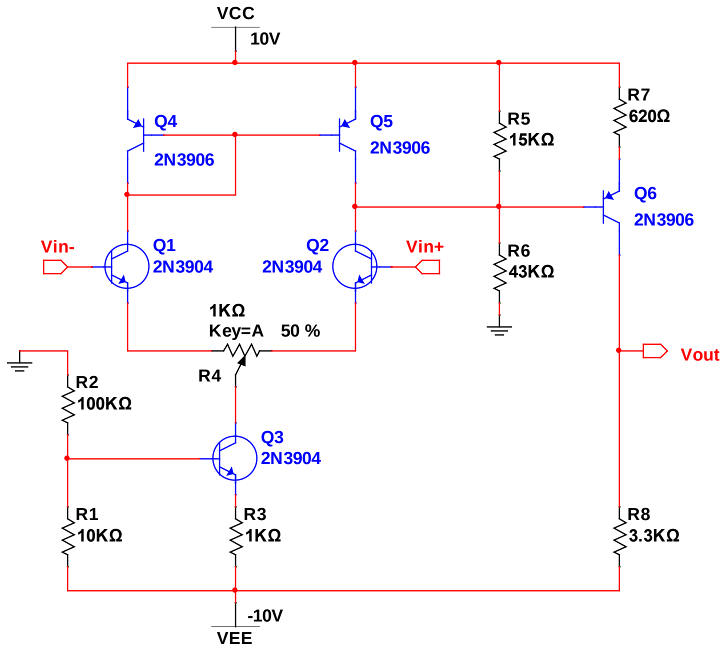
3. Calculate the common-mode rejection ratio (CMRR) for this amplifier in dB.

   $CMRR\ (dB) = Differential\ mode\ gain\ (dB) - Common\ mode\ gain\ (db)$

   $CMRR(dB) = 36.3 + 37.7 = 74\ dB$

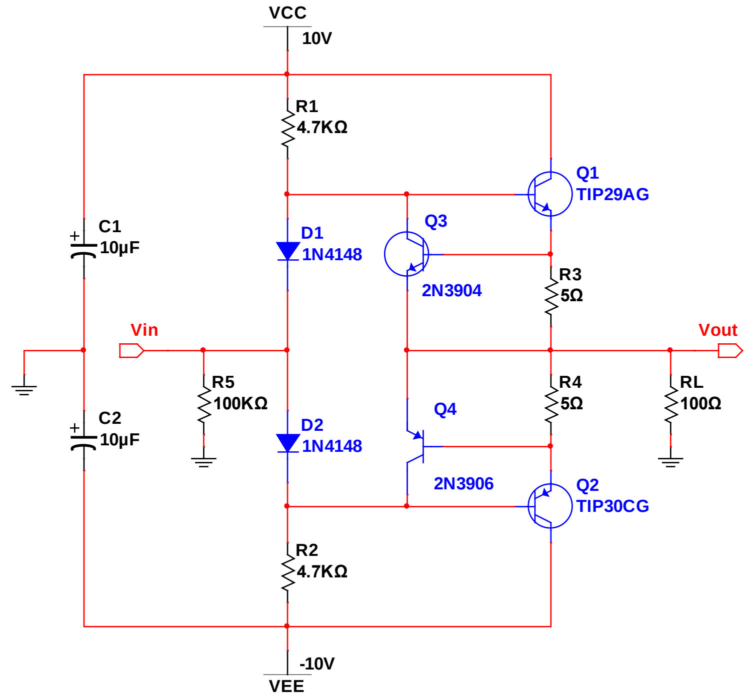
4. Explain what determines the clipping voltage levels.

   Clipping on the bottom happens when Q6 enters cutoff. Clipping on the top happens when Q6 saturates. Clipping could be reduced by increasing the supply voltages or, if it's happening on one peak before the other, by trimming R5 and R6.



# 5 Complementary class-AB output stage

## 5.1 Circuit




My measured values. You also need quiescent voltages.

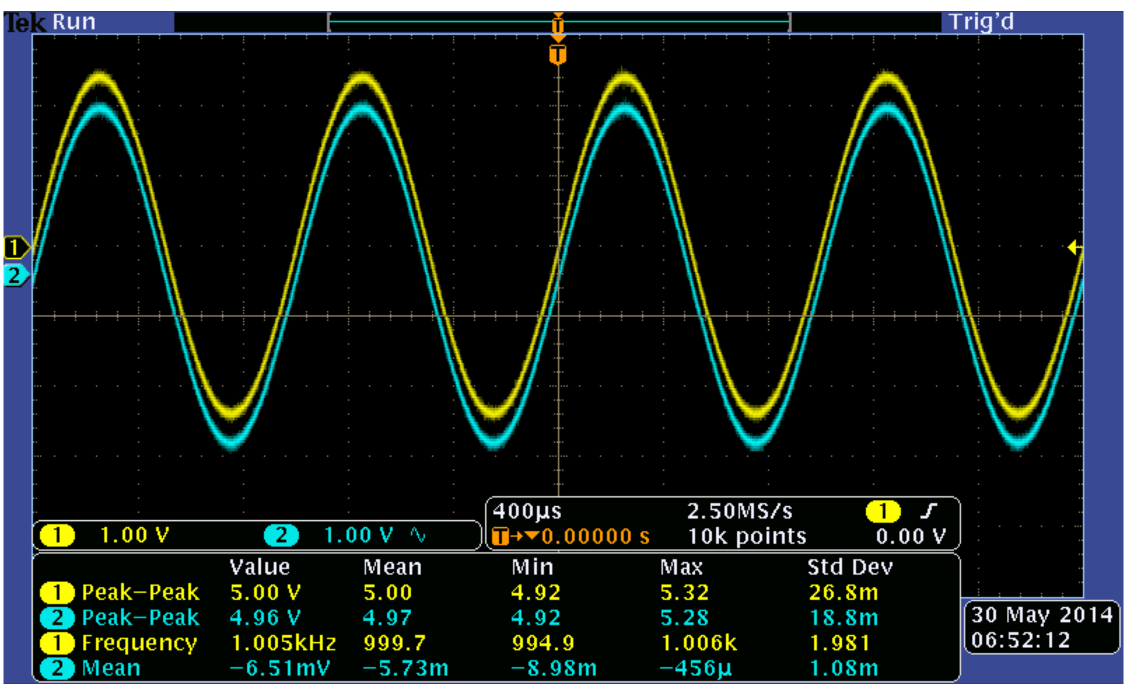
VCC = 10.0703 V
VEE = -10.0955 V

R1 = 4.60 KΩ
R2 = 4.63 KΩ
R3 = 5.25 Ω
R4 = 5.33 Ω
R5 = 99.3 KΩ

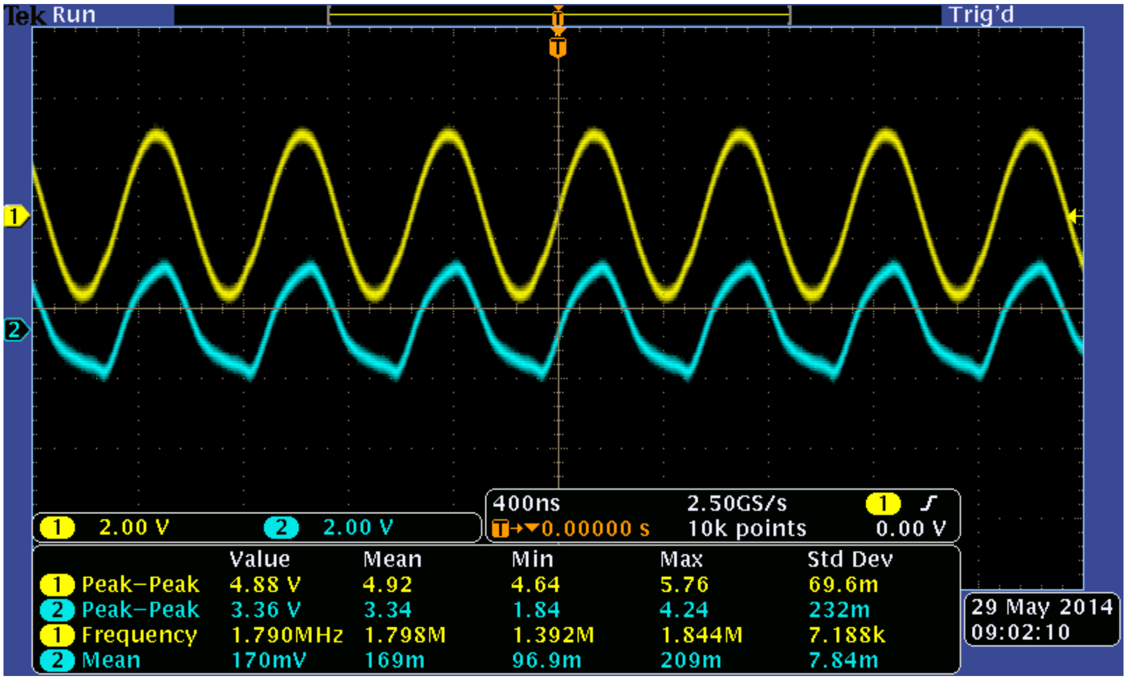
## 5.2 Measurements

1. Set Vin = 5.0 Vpp, 1.0 kHz. Capture a screenshot and calculate Av.

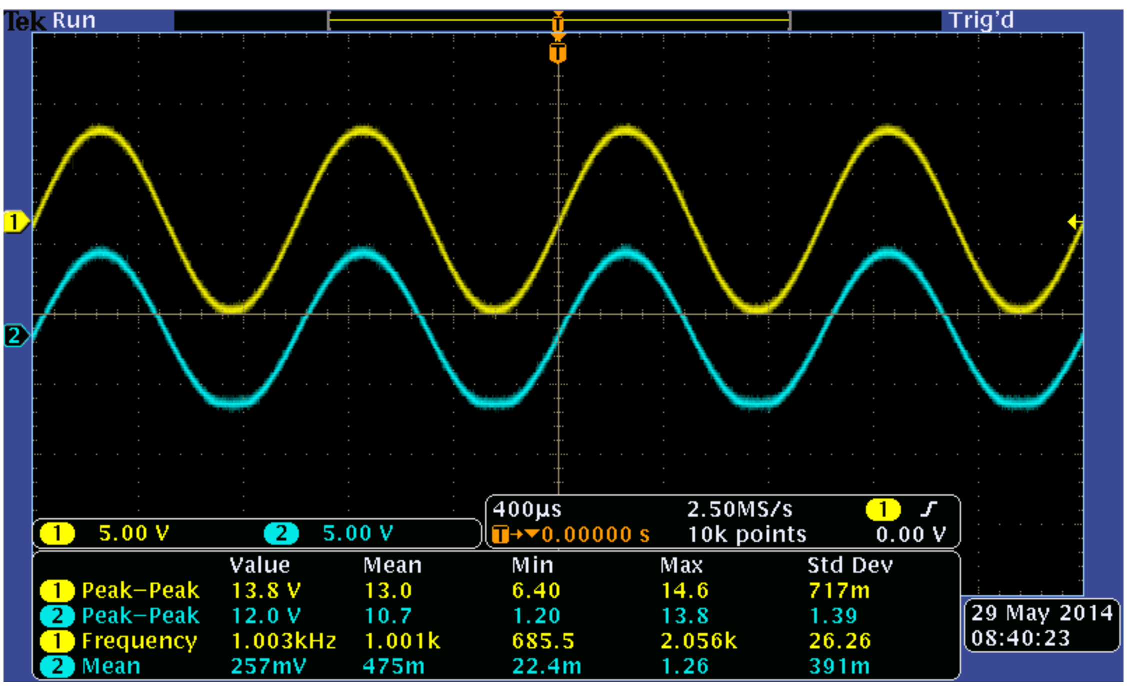
   Av = 4.97 / 5.00 = .99, just under unity, and non-inverting. Vout has only a -5.7 mV DC offset. Not seen here but possible is some “crossover distortion”, a dead zone as Vout crosses 0 V and Q1 and Q2 are both off. That would happen if the diode drops across D1 and D2 are less than min VBE for Q1 an Q2 to enter active mode.



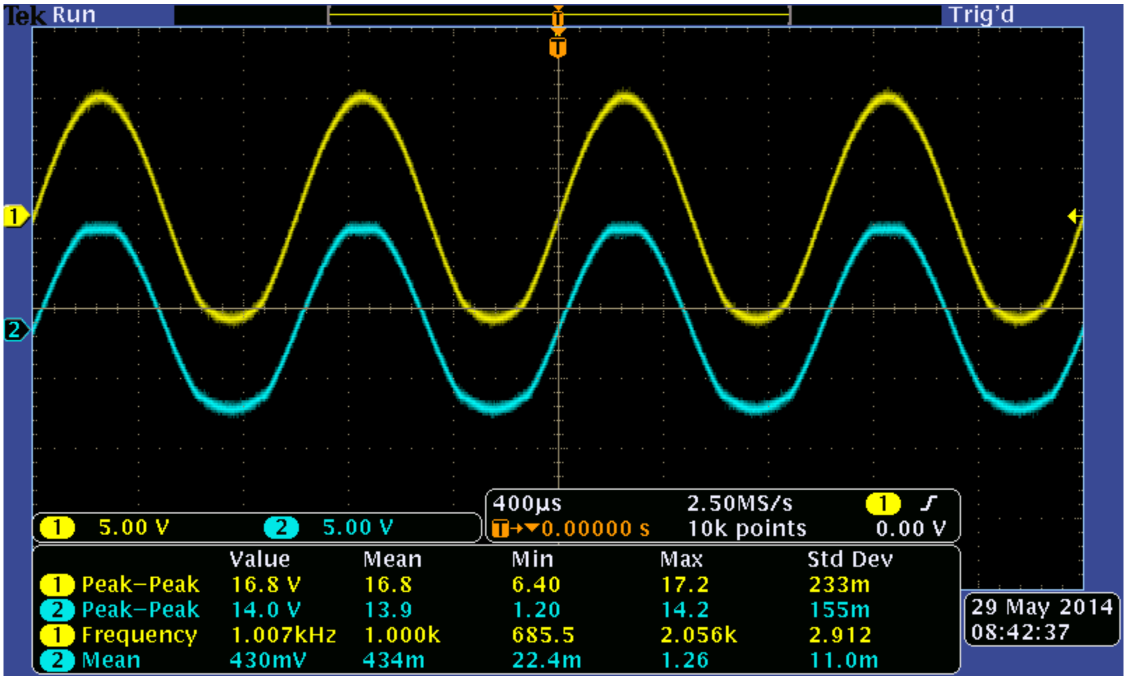
2. Find the 3 dB point. For my circuit, this would be where Av = .7071 * .99 = .70. Shown here, Av = 3.34 / 4.92 = .68 at 1.8 MHz. But note the distortion.




3. Reset Vin to 1.0 KHz and increase the amplitude until Vout begins clipping on either peak. Clipping on negative peaks is at Vin = 13.0 Vpp, Vout = 10.7 Vpp.



4. Continue increasing the amplitude of Vin until Vout begins clipping on the other peak. Clipping on both peaks occurs at Vin = 16.8 Vpp, Vout = 13.9 Vpp.




## 5.3 Analysis

1. Calculate the voltage gain for this output stage.

   Av = 4.97 / 5.00 = .99

2. Comment on any distortion that is seen in the output voltage waveform.

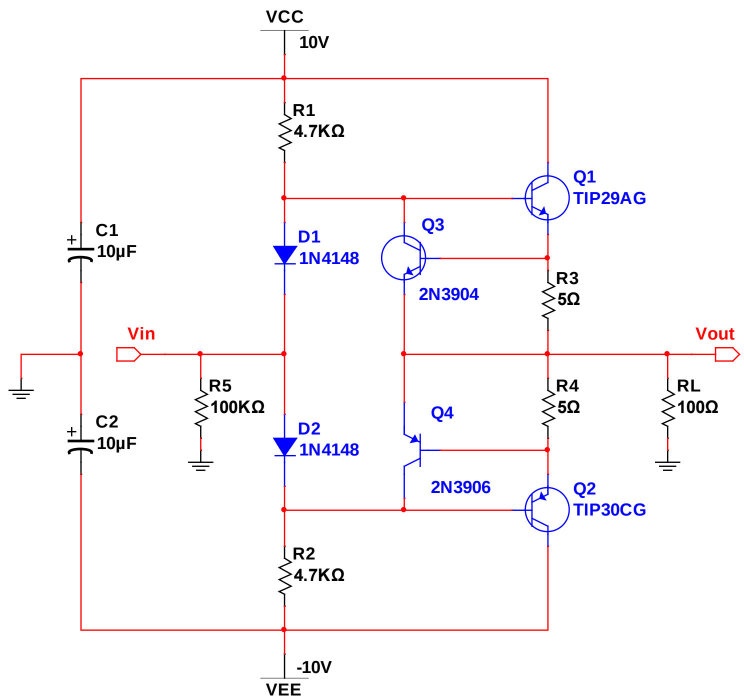
   It's not symmetric and it's not a sharp clipping. The way my (untrimmed) circuit happened to be biased, it began clipping first on the bottom and displayed a lot of distortion at high frequencies, likely due to crossover distortion and mismatch between the output transistors.

3. Calculate the output current that will cause the short-circuit protection to become active.

   R3 and R4 are sense resistors. When VR3 or VR4 > 0.7 V, transistor Q3 or Q4 will turn on, turning off Q1 or Q2. That happens when IR3 or IR4 = 0.7 / 5 = 140 mA.

4. If clipping happens on one peak before the other, explain how the circuit might be trimmed with a potentiometer instead of one of the resistors.

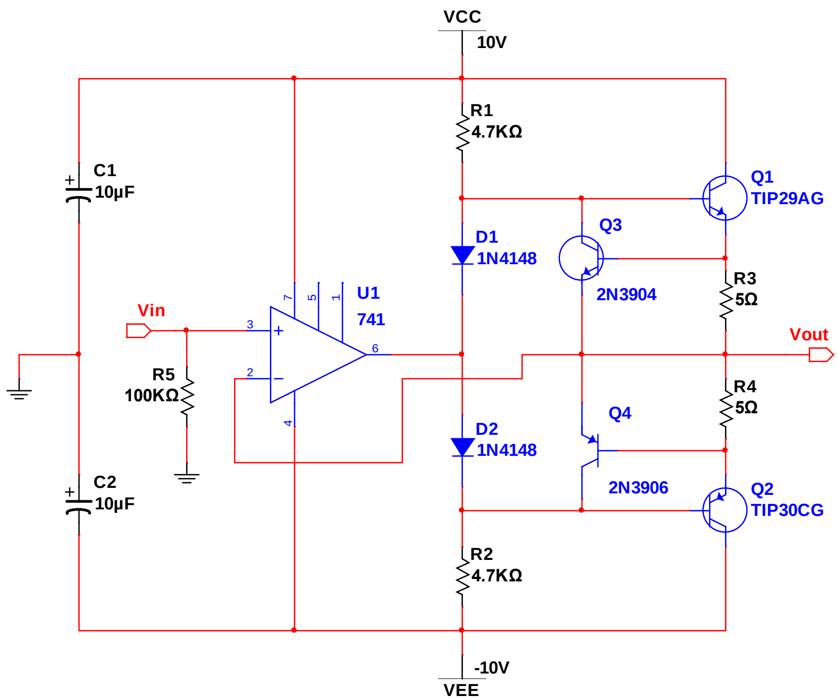
   One of the bias resistors, R1 or R2, can be replaced with a 5K potentiometer to adjust the bias point up or down slightly.



# 6 Multi-stage amplifier with feedback

## 6.1 Circuit

My measured values. You also need quiescent terminal voltages.



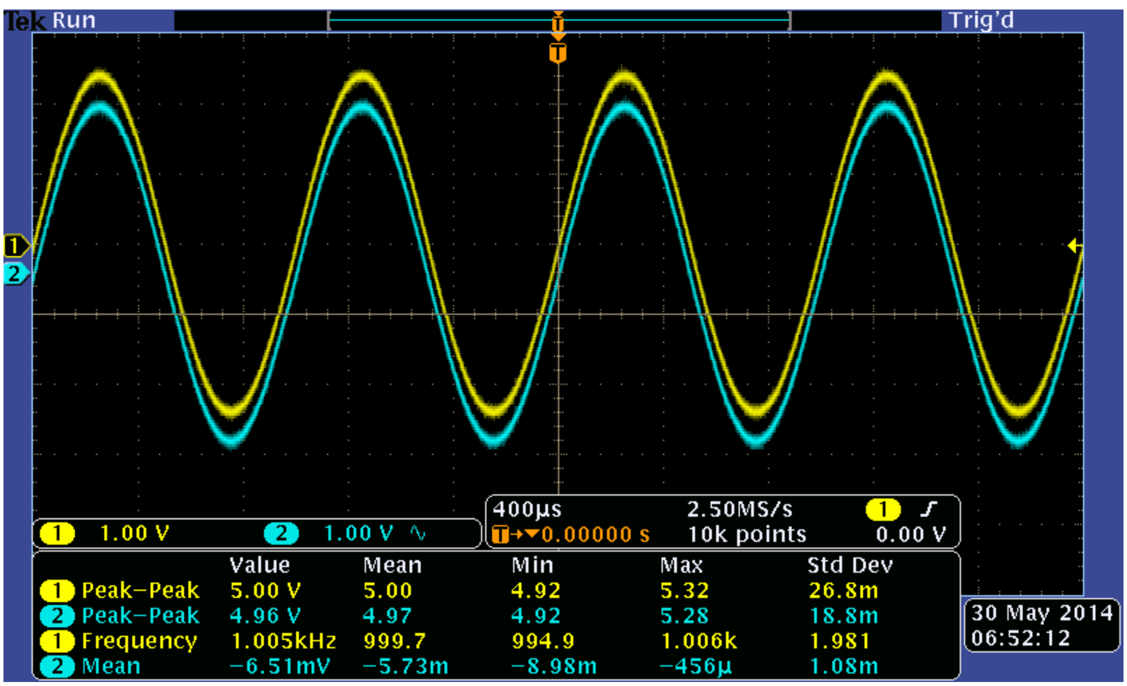

VCC = 10.0703 V
VEE = -10.0955 V

Q1 = TIP31 (PNP)
Q2 = TIP32 (NPN)

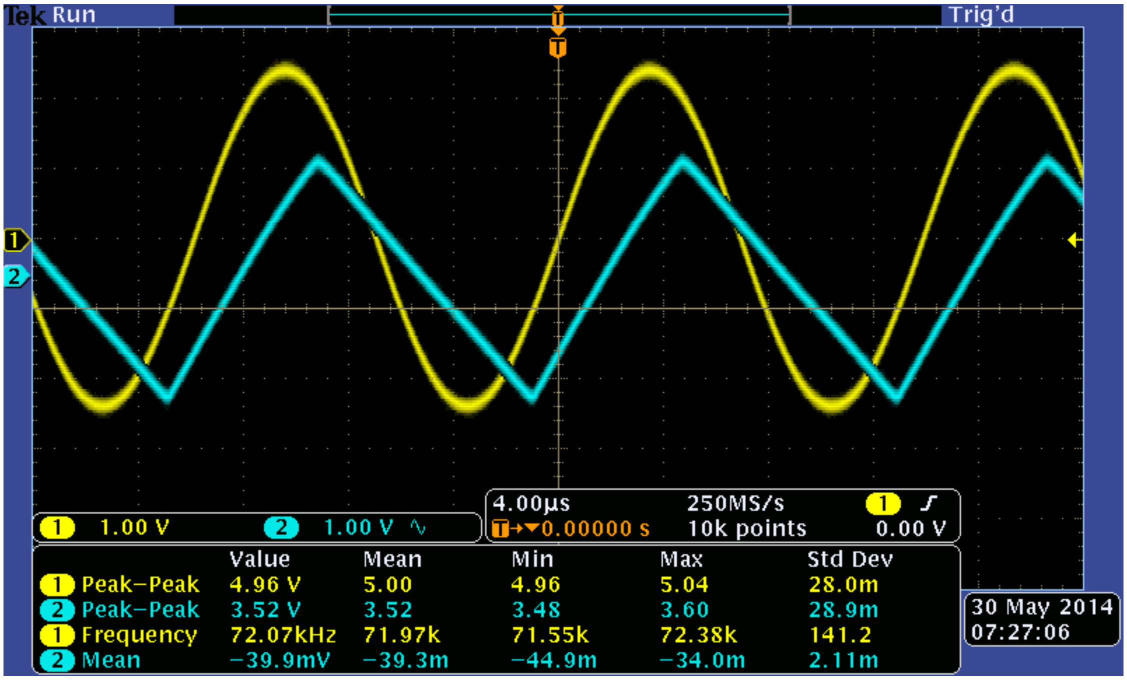
R1 = 4.60 KΩ
R2 = 4.63 KΩ
R3 = 5.25 Ω
R4 = 5.33 Ω
R5 = 99.3 KΩ

## 6.2 Measurements

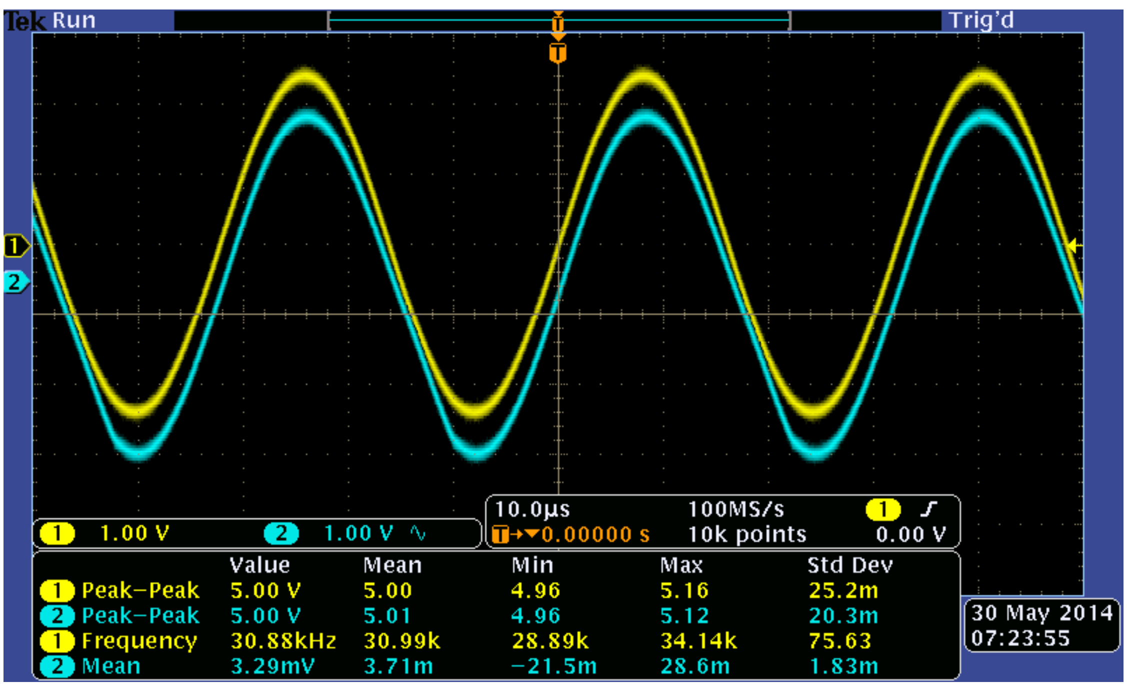
1. Set Vin = 5.0 Vpp, 1.0 kHz. Av is near unity.



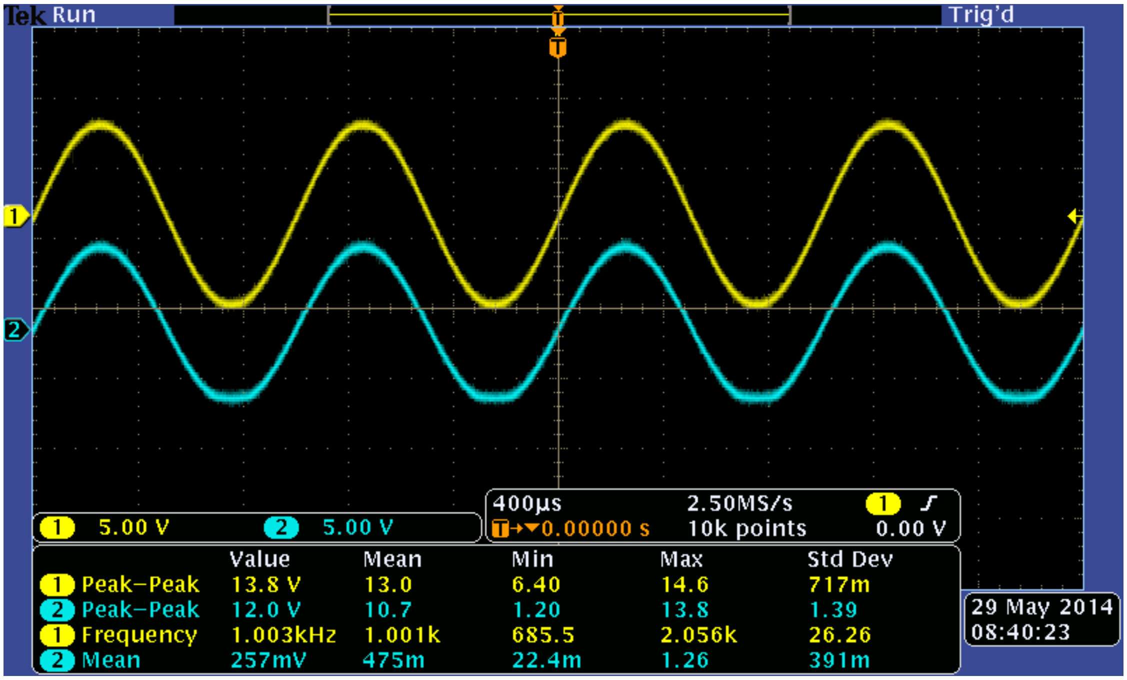
2. Find 3 dB point. Shown here, Av = 3.52 / 5.00 = .704 at 72 KHz. But note the distortion. The output is almost a triangle because we've hit the opamp's slew rate.



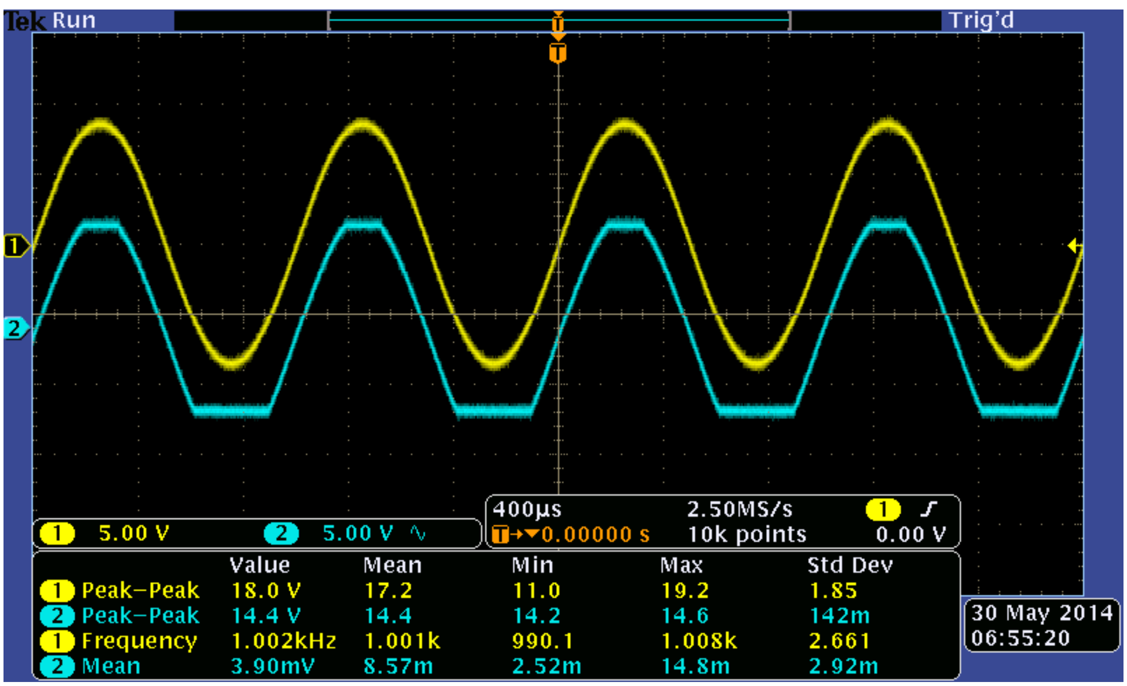

Shown here (not required), we begin to hit the slew rate at about 31 KHz for Vin = 5.0 Vpp.



3. Increase Vin until clipping begins. Shown here, it's clipping negative at Vin = 13.0 Vpp, Vout = 12.0 Vpp. (I should have let the mean settle, so I'm using the current value, which better matches the trace.) You may not be able to get your circuit to clip if your function generator doesn't go high enough.




4. Clipping both peaks happens at Vin 17.2 Vpp, Vout = 14.4 Vpp.



## 6.3 Analysis

1. Compare the clipping levels and bandwidth of the circuit to that of the output stage without the opamp.

   The clipping levels are improved with the opamp front end and we get a cleaner output but a much lower 3 dB point.

| | Without opamp | With opamp |
|---|---|---|
| Vout Initial clipping | 10.7 Vpp | 12.0 Vpp |
| Vout Clipping both peaks | 13.9 Vpp | 14.4 Vpp |
| Bandwidth | 1.8 MHz | 72 KHz |

2. Compare the distortion of the opamp circuit to that of the output stage without the opamp. What are the tradeoffs?

   My own measurements didn't display a lot of difference at low frequencies. The increased clipping levels with the opamp mean it can deliver a slightly higher maximum undistorted power output. If I had encountered any significant crossover or other distortion, the feedback loop would have helped by causing the opamp's output to slew in the right direction until Q1 or Q2 turned on and the output was corrected. But notice the far lower bandwidth caused by hitting the opamp's slew rate. One way to improve the bandwidth for this amp, since the problem appears to be the opamp's slew rate, might be to add a voltage gain stage between the opamp and the AB output stage.