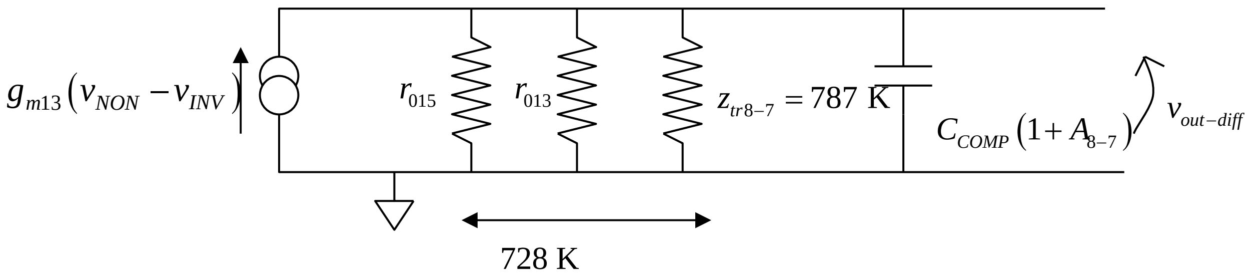
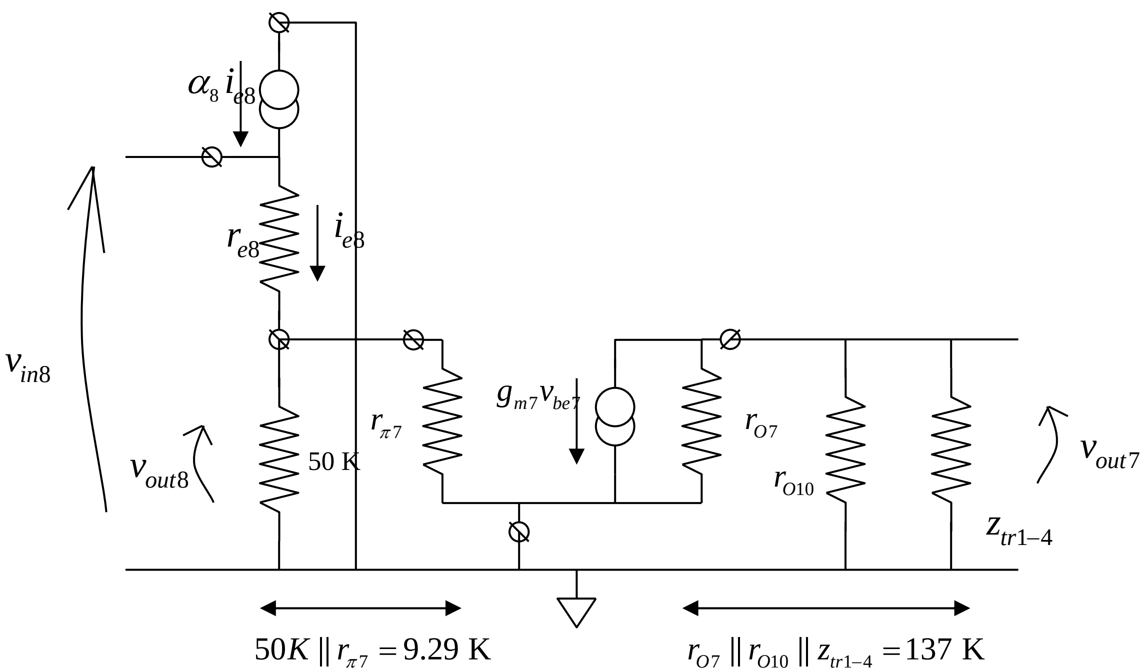
Calculation of BJT Opamp Characteristics: Small Signal Models

First stage output for differential gain:



Differential gain of first stage is $g_{m13} \cdot 7.28 \cdot 10^{+5} = 400$ (50.7 dB).
From the calculation of the gain of the second stage given below, it follows that the dominant pole frequency is $f_{DP} = \dfrac{1}{2\pi \cdot 7.28 \cdot 10^{+5} C_{COMP}(1+1000)} = 14.7$ Hz.



The input impedance of the output buffer stage (Q1-Q4) is $z_{tr1-4} \geq \beta_4 \beta_3 R_{LOAD} = 7$ Meg for a standard 1 K load.

The gain of the common collector Q8 stage is $A_8 = \dfrac{R_{E8}}{r_{e8} + R_{E8}} = \dfrac{9.29}{1.8 + 9.29} = 0.84$.

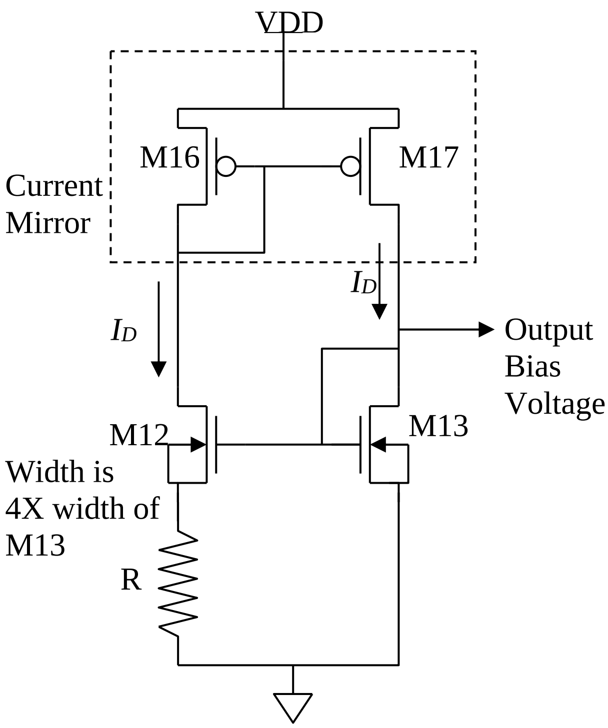
The gain of the common emitter Q7 stage is $A_7 = -g_{m7} \cdot 1.37 \cdot 10^{+5} = -1200$, making the overall second stage gain $A_{8-7} = -1010$ (60 dB).
The overall gain of the amplifier is the product of the gain of the first and second stages or $A_O = 4.0 \cdot 10^{-5}$ (112 dB) and the gain-bandwidth product is

$f_{GBW} = 15 \cdot 4.0 \cdot 10^{+5} = 6$ MHz. The dominant pole frequency is $f_{DP} = \frac{f_{GBW}}{A_0} = 15.7$ Hz.

The slew rate is $S.R. = \frac{I_{C11}}{C_{COMP}} = \frac{3 \cdot 10^{-5}}{1.5 \cdot 10^{-11}} = 2 \cdot 10^{+6}$ V/sec. The short circuit current limit is $I_{SCL} = \frac{V_{BE5}}{35} \approx \frac{0.6}{35} = 17$ mA.

MOS Opamp Calculations

Biasing: The circuit below is the heart of the one used in the class example of a simple MOSFET operational amplifier for setting the currents in the three constant current sources that bias the amplifier itself. M16 and M17 are a conventional current mirror that forces the drain currents of M12 and M13 to be equal. (In the original circuit, M12 and M13 are embedded in a Wilson current mirror but that is not critical to the central idea of the circuit.) M12 is four times the width of M13, probably achieved by wiring four copies of M13 in parallel.



The lengths of all transistors and their overvoltages are chosen so that the transistors are in "long-channel" operation and show drain currents proportional to the square of the gate-source overvoltage. That is, the drain current of M13 is $I_{D13} = KV_{OV13}^2$ where K is the proportionality constant dependent on geometry, oxide capacitance and electron mobility and the overvoltage is $V_{OV} \equiv (V_{GS} - V_{TH})$. Notice from the wiring that $V_{OV13} = V_{OV12} + I_D R$. Then

$$4K(V_{OV13} - I_D R)^2 = KV_{OV13}^2 .$$

This equation has two solutions. Either $V_{OV12} = V_{OV13} = 0$ and $I_D = 0$ or $V_{OV13} = 2I_D R$. We avoid the first condition by using a startup circuit shown on the left side of the opamp schematic. The second condition is easily manipulated to get two results. First, the transconductance of M13 and by extension the transconductances of other transistors locked to M13 by replicated current sources, is $g_{m13} = \frac{2I_D}{V_{OV13}} = \frac{1}{R}$. Thus multiple transistor transconductances can be locked to a single fixed resistor. Second, the overall current is set as: $I_{D13} = \frac{1}{4KR^2}$. This is less attractive since it means the tolerance of R becomes very important in setting a target operating current because the current depends on the square of R.

I "designed" my circuit by using SPICE and adjusted RGM to get nearly 40 microamperes for the current sources across the amplifier.

Gains: I want to calculate the gains of the two stages and the overall gain. As with the BJT amplifier, my programme will include finding the low-frequency output resistance, the dominant pole frequency and the gain-bandwidth product. The results of the calculation are given in the table in the earlier part of this handout. The critical step is finding the differential first stage gain. (The common source second stage is trivial to calculate. Its gain is $G_{out} = -g_{m8}\left(r_{O8} \| r_{O9}\right) = -65$ (36.2 dB) .)

The input stage is a differential pair connected to a cascoded current mirror. The current into the output node by the usual argument for a differential pair is $i_{out} = g_{M1}\left(v_{inv} - v_{non}\right)$. The gain depends then on the output node resistance of the stage. That is the parallel combination of the output impedance of the differential pair with the same impedance for the current mirror. Without proving it here, we can write that the mirror output resistance is $r_{MIRROR} = r_{O5}\left(1 + g_{m5}r_{O7}\right) + r_{O7} \approx r_{O5}g_{m5}r_{O7} = 1.4 \cdot 10^{+8}$. Similarly the output resistance of the differential pair is simply $r_{O3} = 1.36 \cdot 10^{+6}$. Because the latter is so much smaller, the gain is $G_{DIFF} = g_{m3}r_{O3} = 300$ (49.6 dB). The overall gain is the product of the two gains or about 20,000 (86 dB).

The common mode gain is difficult to calculate. The drain currents in the differential pair under common mode excitation divided by the voltage, the common mode transconductance of the pair, is simply $g_{CM} = \frac{g_{m2}}{1 + 2g_{m2}r_{o1}}$. However the current mirror subtracts the two nominally equal drain currents and the error in that difference is largely from the finite output resistance of the mirror transistors. I leave it to you to find the expression for the fractional difference error as part of your last assignment.

Other Properties: The output resistance of the second stage at low frequency is $z_{out} = r_{o8} \| r_{o9} = 2.77 \cdot 10^{+5}$ ohms. There is no short-circuit protection for this opamp as the currents are too low and the output terminal too inaccessible to require such protection.

The dominant pole frequency is $f_D \approx \frac{1}{2\pi C_{COMP}\left(1+A_{2nd}\right)\left(r_{O3} \parallel r_{Omirror\_M5}\right)} = 400$ Hz because the Miller capacitance forms a single pole with the output resistance of the first stage.

The gain-bandwidth product is $f_{GBW} = A_0 f_D = 8 \cdot 10^{+6}$ Hz. From the graph of the SPICE simulation, the actual unity gain frequency, the point at which the Bode plot crosses the 0 dB axis, is 5.6 MHz. This is the result of an additional pole near or above the gain-bandwidth product frequency. The frequency of the zero in the transfer function is in the left half plane at a value given by $f_{zero} = \frac{1}{2\pi C_{COMP}\left(RM1 - 1/g_{m8}\right)} = 16$ MHz.

The slew rate is given by $S.R. = \frac{I_{D1}}{C_{COMP}} = \frac{3.8 \cdot 10^{-5}}{5.5 \cdot 10^{-12}} = 7 \cdot 10^{+6}$ V/sec.

As shown on the Bode plot, the phase margin, that is, the difference between the phase at the unity gain frequency and 180 degrees, is 60 degrees.