EE 538 Spring 2020
Analog Circuits for Sensor Systems
University of Washington Electrical & Computer Engineering

Instructor: Jason Silver
Homework #3 (40 points)
Due Saturday, April 25, Submit on Canvas

Please show your work.

Problem 1: Common-emitter versus common-source amplifier

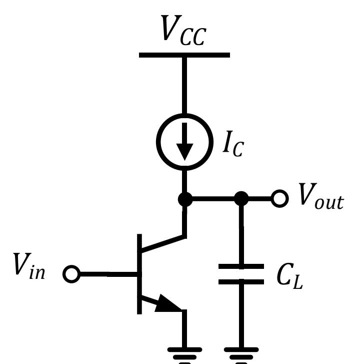

Figure 1a. Common-emitter (CE) amplifier

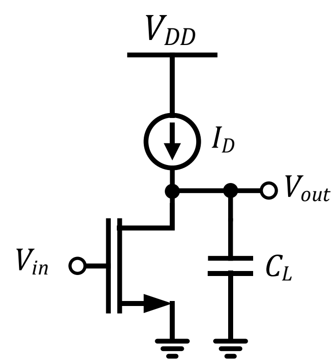

Figure 1b. Common-source (CS) amplifier

For the following, T = 300K, V_A = 100V, $V_{GS} - V_{th}$ = 500mV, λ = 0.1V^{-1}, C_L = 10pF and $I_C = I_D$ = 1mA.

a) (5 points) Calculate the DC voltage gain v_{out}/v_{in} for each structure. Determine the ratios g_m/I_C and g_m/I_D (transconductance efficiency).

b) (5 points) For each structure, determine the small-signal transfer function v_{out}/v_{in} as a function of frequency. Plot the Bode magnitude and phase (by hand or using MATLAB/Python). For each, calculate the transit frequency f_T, the frequency at which the magnitude of the transfer function is equal to 1V/V.

c) (5 points) The so-called "square-law" model of the FET incorrectly predicts that current becomes arbitrarily small (and g_m arbitrarily large) as $V_{GS} - V_{th}$ approaches zero. For values of V_{GS} smaller than V_{th} (subthreshold operation), the drain current is better described as

$$I_D = I_S e^{V_{GS}/nV_T},$$

where I_S and n are technology parameters related to the device structure. For n = 1.5, calculate the transconductance efficiency (g_m/I_D) of the FET assuming subthreshold operation. How does it compare to your answers in Part a)?

Problem 2: Temperature-independent voltage reference (BJT DC analysis)

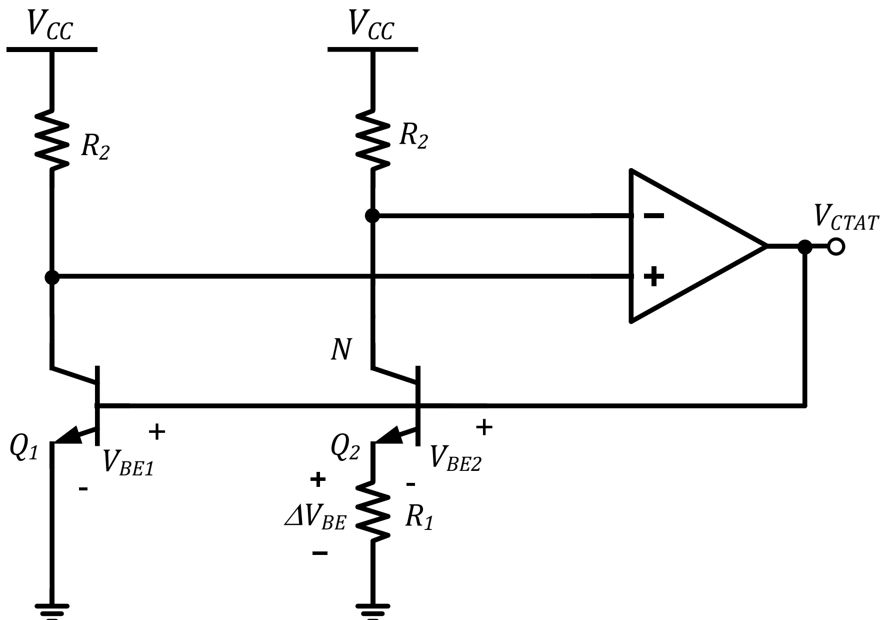

Figure 2. PTAT Voltage Generator

Temperature-insensitive voltage and current references are critical components of precision sensor systems. A temperature-independent reference is created by combining something (e.g. a voltage) that has a positive temperature coefficient (proportional-to-absolute-temperature, PTAT) with something that has a negative temperature coefficient (complementary-to-absolute-temperature, CTAT). When biased with a constant current, the V_{BE} of a BJT exhibits a slope of *approximately* –2mV/°C (CTAT). Combining this with the *difference* of the V_{BE}'s of two BJT's biased with different current densities (which is PTAT), properly scaled, will yield a voltage that is (approximately) independent of temperature:

$$V_{BG} = V_{CTAT} + V_{PTAT} = V_{BE}(T) + M \times \Delta V_{BE}(T)$$

Note that different current densities for Q_1 and Q_2 are achieved by connecting N transistors in parallel for Q_2.

For the following, use the 2N3904 npn transistor ($I_S = 10^{-14}$A, $\beta = 300$, $V_A = 100$) and the UniversalOpamp2 models in Ltspice. Use $V_{CC} = 5$V for the supply voltage.

a) (5 points) Determine values for N and R_1 such that $I_{C1} = I_{C2} = 50\mu$A at room temperature (27C).
b) (5 points) Determine the temperature slope of V_{BE1} via simulation and calculate the value of M that would satisfy the above equation.
c) (5 points) Verify the design of the PTAT generator in Ltspice, plotting the expression $V_{BE}(T) + M \times \Delta V_{BE}(T)$ as a function of temperature. Include your schematic in your submission, showing all relevant voltages and currents at room temperature. Evaluate
   1. the value of V_{BG} at room temperature, and
   2. the maximum deviation from this value over the temperature range –40C to 125C.

Bonus (2 points): Complete the design of the Brokaw bandgap circuit.

Problem 3: Nonlinear distortion in a common-source amplifier

The output voltage of a resistor-loaded common-source amplifier is expressed (neglecting λ) as

$$V_{out} = V_{DD} - \kappa(V_{in} - V_{th})^2 R_D$$

a) (5 points) Assuming the amplifier is driven with a sinusoidal voltage $V_{in} = a_{in} \times \sin(2\pi \cdot f_0 \cdot t) + V_{DC}$, where $V_{DC} = V_{th} + 500\text{mV}$, determine expressions for the *amplitudes* of the fundamental (sinusoid at f_0 with amplitude a_1) and second harmonic (sinusoid at $2f_0$ with amplitude a_2) using the trigonometric relationship

$$\sin^2(x) = \frac{1}{2}[1 - \cos(2x)]$$

b) (5 points) Calculate the ratio of a_2/a_1 for a_{in} = 1mV and a_{in} = 10mV.