EEE 51 Assignment 8 Solution

2nd Semester SY 2017-2018

1. **CS amplifier with source degeneration frequency response.** For the given circuit below, assume that there is no body effect and channel length modulation is ignored.

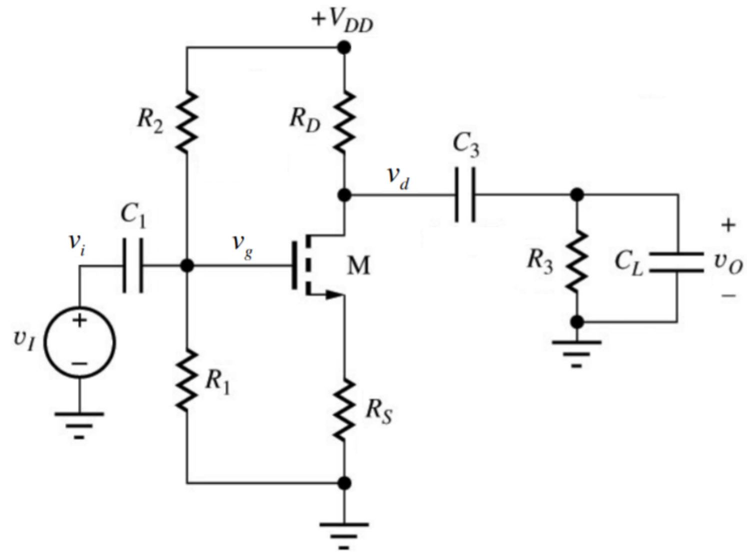

Figure 1: CS Amplifier with Source Degeneration

   (a) Draw the small-signal equivalent circuit including C_{GD} and C_{GS}. [2 pts]

   Capacitors C_1 and C_3 are coupling capacitors and are shorted when the small-signal model is drawn. Given that the channel length modulation is ignored, $r_o \to \infty$. To further simplify the small-signal analysis for the problem, we can express $R_L = R_D \parallel R_3$ and $R_G = R_1 \parallel R_2$.

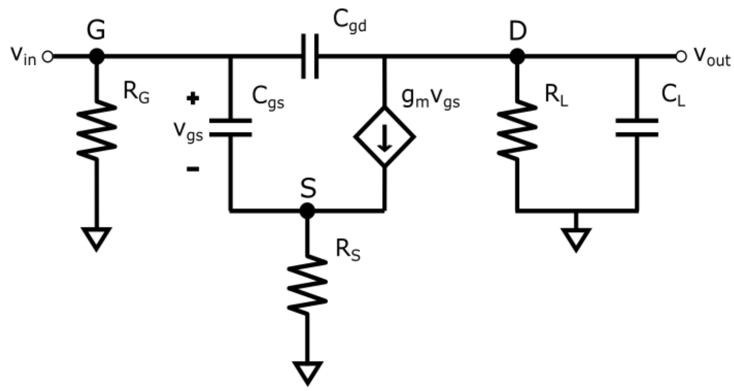

Figure 2: Small-signal Equivalent Circuit

   (b) Find the expression for the small-signal transfer function of the circuit. State *all* assumptions and show your *complete* solution. [5 pts]

   Starting by obtaining the expression for v_{gs} in terms of v_i, apply KCL at node v_s. This yields,

$$\frac{v_s}{R_S} + \frac{v_s - v_i}{\frac{1}{sC_{gs}}} = g_m v_{gs} \tag{1}$$

Since $v_{gs} = v_i - v_s$, values of v_{gs} and v_i can be substituted yielding,

$$\frac{v_i - v_{gs}}{R_S} + (-v_{gs})(sC_{gs}) = g_m v_{gs} \tag{2}$$

Simplifying and solving for v_{gs},

$$v_{gs} = v_i \frac{1}{1 + g_m R_S + sR_S C_{gs}} \tag{3}$$

Next, the expression for v_o in terms of v_i and v_{gs} is obtained. Applying KCL at node v_o,

$$\frac{v_o}{R_L \parallel 1/sC_L} + \frac{v_o - v_i}{\frac{1}{sC_{gd}}} + g_m v_{gs} = 0 \tag{4}$$

Isolating v_o to the left and both v_i and v_{gs} to the right,

$$v_o\left(\frac{1}{R_L \parallel 1/sC_L} + sC_{gd}\right) = v_i(sC_{gd}) - g_m v_{gs} \tag{5}$$

Temporarily expressing (3) into $v_{gs} = v_i(1/k)$ where $k = 1 + g_m R_S + sR_S C_{gs}$ and substituting this yields,

$$v_o\left(\frac{1}{R_L \parallel 1/sC_L} + sC_{gd}\right) = v_i\left(sC_{gd} - \frac{g_m}{k}\right) \tag{6}$$

$$\frac{v_o}{v_i} = \frac{sC_{gd} - g_m/k}{\frac{1}{R_L \parallel 1/sC_L} + sC_{gd}} = \frac{skC_{gd} - g_m}{k\left(\frac{1}{R_L \parallel 1/sC_L} + sC_{gd}\right)} \tag{7}$$

$$\frac{v_o}{v_i} = \frac{skC_{gd} - g_m}{k\left(\frac{1+sR_L C_L}{R_L} + sC_{gd}\right)} = \frac{skC_{gd} - g_m}{\left(\frac{1}{R_L}\right)(k)(1 + sR_L(C_L + C_{gd}))} \tag{8}$$

Substituting the expression for k,

$$\frac{v_o}{v_i} = (R_L)\frac{sC_{gd}(1 + g_m R_S + sR_S C_{gs}) - g_m}{(1 + g_m R_S + sR_S C_{gs})(1 + sR_L(C_L + C_{gd}))} \tag{9}$$

Simplifying, we get the expression for $\frac{v_o}{v_i}$,

$$\frac{v_o}{v_i} = (R_L)\frac{s^2[R_S C_{gd} C_{gs}] + s[C_{gd}(1 + g_m R_S)] - g_m}{[1 + g_m R_S + sR_S C_{gs}][1 + sR_L(C_L + C_{gd})]} \tag{10}$$

Substituting $R_L = R_D \parallel R_3$, we get,

$$\frac{v_o}{v_i} = \left(\frac{R_D R_3}{R_D + R_3}\right)\frac{s^2[R_S C_{gd} C_{gs}] + s[C_{gd}(1 + g_m R_S)] - g_m}{[1 + g_m R_S + sR_S C_{gs}][1 + s\left(\frac{R_D R_3}{R_D + R_3}\right)(C_L + C_{gd})]} \tag{11}$$

Simplifying,

$$\frac{v_o}{v_i} = (R_D R_3)\frac{s^2[R_S C_{gd} C_{gs}] + s[C_{gd}(1 + g_m R_S)] - g_m}{[1 + g_m R_S + sR_S C_{gs}][R_D + R_3 + s(R_D R_3)(C_L + C_{gd})]} \tag{12}$$

$\boxed{\frac{v_o}{v_i} = (R_D R_3)\frac{s^2[R_S C_{gd} C_{gs}] + s[C_{gd}(1+g_m R_S)] - g_m}{[1+g_m R_S+sR_S C_{gs}][R_D+R_3+s(R_D R_3)(C_L+C_{gd})]} \text{ [5 pts]}}$

(c) Determine the expression(s) for the pole(s) and/or zero(s) of the circuit. [3 pts]

Using the equation for $\frac{v_o}{v_i}$ from (1b), we get the expressions for the poles and zeros of the circuit. For the zeros, we apply the quadratic formula to obtain the corresponding expressions.

$$\boxed{\begin{aligned} p_1 &= -\tfrac{1+g_m R_S}{R_S C_{gs}}, \\ p_2 &= -\tfrac{R_D+R_3}{(R_D R_3)(C_L+C_{gd})}, \\ z_{1/2} &= \tfrac{-C_{gd}(1+g_m R_S)\pm\sqrt{(C_{gd}(1+g_m R_S))^2+4g_m R_S C_{gd} C_{gs}}}{2R_S C_{gd} C_{gs}} \end{aligned}}$$

2. **Emitter-degenerated BJT Amplifier**. A BJT Q_1 with $\beta = 100$, $I_S = 10\,\text{fA}$, $V_{CE,sat} = 0.2\,\text{V}$ and $V_A = 200\,\text{V}$ is biased with resistors. Assume that the BJT has no parasitic capacitances. The resistors used are $R_C = 500\,\Omega$, $R_B = 50\,\text{k}\Omega$, $R_E = 300\,\Omega$. The supply voltage V_{CC} is 5 V. A DC-blocked input is connected to the base, as shown in Figure 3. The DC block is not ideal, with a finite capacitance $C_{in} = 1\,\mu\text{F}$. A capacitor is placed in parallel to the emitter resistor, with $C_E = 1\,\text{fF}$. The amplifier drives a load capacitor, $C_L = 1\,\text{nF}$.

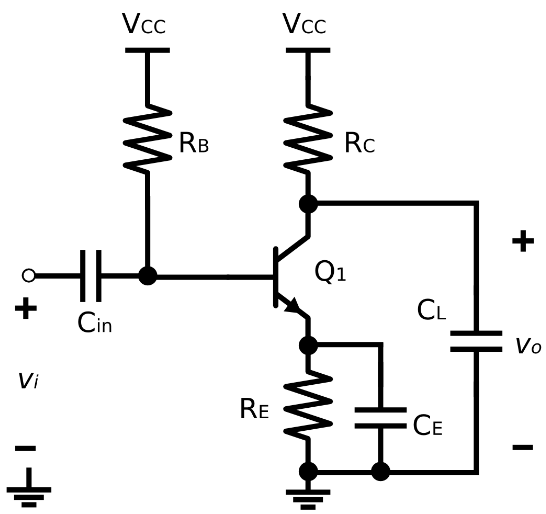

Figure 3: Emitter-degenerated amplifier with load capacitance

(a) Solve for the overall transfer function $H(s) = \frac{v_o(s)}{v_i(s)}$. Write this in terms of the small-signal parameters and component values. [7 pts]

In order to begin solving for H(s), the small-signal parameters must first be obtained. However, since this amplifier setup should be familiar, as it is nearly identical to a previous setup (HW #2 Problem 2), it can be shown that the small-signal parameters are identical, as in large-signal DC analysis for the biasing the capacitors only act as open.

Therefore, the values $r_\pi = 485.8\,\Omega$, $g_m = 205.85\,\text{mA}\,\text{V}^{-1}$, and $r_o = 37.369\,\text{k}\Omega$ can be used.

Also using the information that this setup is similar, all that is needed is to add the effects of the capacitors to the old derived solutions. It would be useful to know the two-port characteristics in order to solve for H(s), after all.

Firstly, C_L is in parallel with R_C, and C_E is in parallel with R_E. Therefore we can determine the equivalent impedances

$$Z_C = R_C || \frac{1}{sC_L} \tag{13}$$

$$Z_E = R_E || \frac{1}{sC_E} \tag{14}$$

With these we can start solving for G_m, Z_o, and Z_i. Had the DC block been ideal, the transfer function H(s) would only need to be $-G_m Z_o$, but since it is not then a loading effect occurs at the input. This creates a voltage division such that

$$H\left(s\right) = -\frac{Z_i}{Z_i + \frac{1}{sC_{in}}} G_m Z_o \tag{15}$$

G_m can be determined using what was previously derived for it, with some modification.

$$G_m = g_m \left(\frac{1 - \frac{Z_E}{r_o r_\pi g_m}}{g_m Z_E + \frac{Z_E}{r_\pi} + 1 + \frac{Z_E}{r_o}} \right) \tag{16}$$

Note that previous assumptions that certain terms dominate over others no longer apply unless it can now be shown to be applicable independent of frequency.
Doing the same with Z_i and Z_o,

$$Z_i = r_\pi \left(1 + g_m \left(r_o || Z_E \right) + \frac{\left(r_o || Z_E \right)}{r_\pi} \right) || R_B \tag{17}$$

$$Z_o = r_o \left(1 + g_m \left(Z_E || r_\pi \right) + \frac{Z_E || r_\pi}{r_o} \right) || Z_C \tag{18}$$

First begin with calculating the loading effect, which is dependent on the input impedance,

$$A_{LE} = \frac{Z_i}{Z_i + \frac{1}{sC_{in}}} \tag{19}$$

or, in order to simplify its use later,

$$A_{LE} = \frac{sZ_i C_{in}}{1 + sZ_i C_{in}} \tag{20}$$

The input impedance must then be simplified into a fraction between polynomials of s, so first simplify the parallel operations.

$$Z_i = \left(r_\pi + \frac{g_m r_\pi + 1}{\frac{1}{r_o} + \frac{1}{R_E} + sC_E} \right) || R_B \tag{21}$$

$$Z_i = \left(\frac{\frac{r_\pi}{r_o} + \frac{r_\pi}{R_E} + sC_E r_\pi + g_m r_\pi + 1}{\frac{1}{r_o} + \frac{1}{R_E} + sC_E} \right) || R_B \tag{22}$$

$$Z_i = \frac{1}{\frac{1}{R_B} + \frac{\frac{1}{r_o} + \frac{1}{R_E} + sC_E}{\frac{r_\pi}{r_o} + \frac{r_\pi}{R_E} + g_m r_\pi + 1 + sC_E r_\pi}} \tag{23}$$

$$Z_i = \frac{1}{\frac{\frac{r_\pi}{r_o} + \frac{r_\pi}{R_E} + g_m r_\pi + 1 + sC_E r_\pi + \frac{R_B}{r_o} + \frac{R_B}{R_E} + sC_E R_B}{\frac{r_\pi R_B}{r_o} + \frac{r_\pi R_B}{R_E} + g_m r_\pi R_B + R_B + sC_E r_\pi R_B}} \tag{24}$$

$$Z_i = \frac{\frac{r_\pi R_B}{r_o} + \frac{r_\pi R_B}{R_E} + g_m r_\pi R_B + R_B + sC_E r_\pi R_B}{\frac{r_\pi}{r_o} + \frac{r_\pi}{R_E} + g_m r_\pi + 1 + \frac{R_B}{r_o} + \frac{R_B}{R_E} + sC_E\left(R_B + r_\pi\right)} \tag{25}$$

So to start calculating for the loading effect,

$$sZ_iC_{in} = \frac{s^2 C_{in} C_E r_\pi R_B + sC_{in}\left(\frac{r_\pi R_B}{r_o} + \frac{r_\pi R_B}{R_E} + g_m r_\pi R_B + R_B\right)}{sC_E\left(R_B + r_\pi\right) + \frac{r_\pi}{r_o} + \frac{r_\pi}{R_E} + g_m r_\pi + 1 + \frac{R_B}{r_o} + \frac{R_B}{R_E}} \tag{26}$$

$$1 + sZ_iC_{in} = \frac{s^2 C_{in} C_E r_\pi R_B + s\mathbf{B_i} + \frac{r_\pi}{r_o} + \frac{r_\pi}{R_E} + g_m r_\pi + 1 + \frac{R_B}{r_o} + \frac{R_B}{R_E}}{sC_E\left(R_B + r_\pi\right) + \frac{r_\pi}{r_o} + \frac{r_\pi}{R_E} + g_m r_\pi + 1 + \frac{R_B}{r_o} + \frac{R_B}{R_E}} \tag{27}$$

where

$$\mathbf{B_i} = C_{in}\left(\frac{r_\pi R_B}{r_o} + \frac{r_\pi R_B}{R_E} + g_m r_\pi R_B + R_B\right) + C_E\left(R_B + r_\pi\right) \tag{28}$$

just so the equation will fit on this sheet.
The loading effect is then

$$A_{LE} = \frac{s^2 C_{in} C_E r_\pi R_B + sC_{in}\left(\frac{r_\pi R_B}{r_o} + \frac{r_\pi R_B}{R_E} + g_m r_\pi R_B + R_B\right)}{s^2 C_{in} C_E r_\pi R_B + s\mathbf{B_i} + \frac{r_\pi}{r_o} + \frac{r_\pi}{R_E} + g_m r_\pi + 1 + \frac{R_B}{r_o} + \frac{R_B}{R_E}} \tag{29}$$

This produces 2 poles and 2 zeroes.

$$A_{LE} = \frac{s\left(s + \frac{C_{in}\left(\frac{r_\pi R_B}{r_o} + \frac{r_\pi R_B}{R_E} + g_m r_\pi R_B + R_B\right)}{C_{in} C_E r_\pi R_B}\right)}{s^2 + s\frac{C_{in}\left(\frac{r_\pi R_B}{r_o} + \frac{r_\pi R_B}{R_E} + g_m r_\pi R_B + R_B\right) + C_E\left(R_B + r_\pi\right)}{C_{in} C_E r_\pi R_B} + \frac{\frac{r_\pi}{r_o} + \frac{r_\pi}{R_E} + g_m r_\pi + 1 + \frac{R_B}{r_o} + \frac{R_B}{R_E}}{C_{in} C_E r_\pi R_B}} \tag{30}$$

The output impedance is similar in form to the input impedance.

$$Z_o = \left(r_o + g_m r_o\left(Z_E || r_\pi\right) + Z_E || r_\pi\right) || Z_C \tag{31}$$

$$Z_o = \left(r_o + \frac{g_m r_o + 1}{\frac{1}{r_\pi} + \frac{1}{R_E} + sC_E}\right) || \frac{1}{\frac{1}{R_C} + sC_L} \tag{32}$$

$$Z_o = \frac{\frac{r_o}{r_\pi} + \frac{r_o}{R_E} + sC_E r_o + g_m r_o + 1}{\frac{1}{r_\pi} + \frac{1}{R_E} + sC_E} || \frac{1}{\frac{1}{R_C} + sC_L} \tag{33}$$

$$Z_o = \frac{1}{\frac{sC_E + \frac{1}{r_\pi} + \frac{1}{R_E}}{sC_E r_o + \frac{r_o}{r_\pi} + \frac{r_o}{R_E} + g_m r_o + 1} + \frac{1}{R_C} + sC_L} \tag{34}$$

$$Z_o = \frac{1}{\frac{sC_E R_C + \frac{R_C}{r_\pi} + \frac{R_C}{R_E} + sC_E r_o + \frac{r_o}{r_\pi} + \frac{r_o}{R_E} + g_m r_o + 1 + sC_L\left(sC_E r_o R_C + \frac{r_o R_C}{r_\pi} + \frac{r_o R_C}{R_E} + g_m r_o R_C + R_C\right)}{sC_E r_o R_C + \frac{r_o R_C}{r_\pi} + \frac{r_o R_C}{R_E} + g_m r_o R_C + R_C}} \tag{35}$$

$$Z_o = \frac{1}{\frac{s^2 C_L C_E r_o R_C + s\left(C_E\left(R_C + r_o\right) + C_L\left(\frac{r_o R_C}{r_\pi} + \frac{r_o R_C}{R_E} + g_m r_o R_C + R_C\right)\right) + \frac{R_C}{r_\pi} + \frac{R_C}{R_E} + \frac{r_o}{r_\pi} + \frac{r_o}{R_E} + g_m r_o + 1}{sC_E r_o R_C + \frac{r_o R_C}{r_\pi} + \frac{r_o R_C}{R_E} + g_m r_o R_C + R_C}} \tag{36}$$

$$Z_o = \frac{sC_E r_o R_C + \frac{r_o R_C}{r_\pi} + \frac{r_o R_C}{R_E} + g_m r_o R_C + R_C}{s^2 C_L C_E r_o R_C + s\mathbf{B_o} + \frac{R_C}{r_\pi} + \frac{R_C}{R_E} + \frac{r_o}{r_\pi} + \frac{r_o}{R_E} + g_m r_o + 1} \tag{37}$$

where

$$\mathbf{B_o} = C_E\left(R_C + r_o\right) + C_L\left(\frac{r_o R_C}{r_\pi} + \frac{r_o R_C}{R_E} + g_m r_o R_C + R_C\right) \tag{38}$$

again, just so it would fit.
The output impedance then has two poles and one zero.

$$Z_o = \frac{1}{C_L}\frac{s + \frac{1}{C_E r_\pi} + \frac{1}{C_E R_E} + \frac{g_m}{C_E} + \frac{1}{C_E r_o}}{s^2 + s\frac{C_E(R_C+r_o)+C_L\left(\frac{r_o R_C}{r_\pi}+\frac{r_o R_C}{R_E}+g_m r_o R_C+R_C\right)}{C_L C_E r_o R_C} + \frac{\frac{R_C}{r_\pi}+\frac{R_C}{R_E}+\frac{r_o}{r_\pi}+\frac{r_o}{R_E}+g_m r_o+1}{C_L C_E r_o R_C}} \tag{39}$$

The transconductance is

$$G_m = \frac{g_m - \frac{Z_E}{r_o r_\pi}}{g_m Z_E + \frac{Z_E}{r_\pi} + 1 + \frac{Z_E}{r_o}} \tag{40}$$

$$G_m = \frac{g_m - \frac{1}{\frac{r_o r_\pi}{R_E} + sC_E r_o r_\pi}}{\frac{g_m + \frac{1}{r_\pi} + \frac{1}{r_o}}{\frac{1}{R_E} + sC_E} + 1} \tag{41}$$

$$G_m = \frac{\frac{\frac{g_m r_o r_\pi}{R_E} + sC_E r_o r_\pi g_m - 1}{\frac{r_o r_\pi}{R_E} + sC_E r_o r_\pi}}{\frac{g_m + \frac{1}{r_\pi} + \frac{1}{r_o} + \frac{1}{R_E} + sC_E}{\frac{1}{R_E} + sC_E}} \tag{42}$$

$$G_m = \frac{\frac{g_m r_o r_\pi}{R_E} + sC_E r_o r_\pi g_m - 1}{(r_o r_\pi)\left(g_m + \frac{1}{r_\pi} + \frac{1}{r_o} + \frac{1}{R_E} + sC_E\right)} \tag{43}$$

$$G_m = \frac{sC_E r_o r_\pi g_m + \frac{g_m r_o r_\pi}{R_E} - 1}{sC_E r_o r_\pi + g_m r_o r_\pi + r_o + r_\pi + \frac{r_o r_\pi}{R_E}} \tag{44}$$

$$G_m = g_m\frac{s + \frac{1}{C_E R_E} - \frac{1}{C_E g_m r_o r_\pi}}{s + \frac{g_m}{C_E} + \frac{1}{C_E r_\pi} + \frac{1}{C_E r_o} + \frac{1}{C_E R_E}} \tag{45}$$

The transconductance then has one pole and one zero.

$$\boxed{H(s) = -A_{LE} G_m Z_o \text{ [1 pt]}}$$

$$\boxed{A_{LE} = \frac{s\left(s + \frac{C_{in}\left(\frac{r_\pi R_B}{r_o} + \frac{r_\pi R_B}{R_E} + g_m r_\pi R_B + R_B\right)}{C_{in} C_E r_\pi R_B}\right)}{s^2 + s\frac{C_{in}\left(\frac{r_\pi R_B}{r_o} + \frac{r_\pi R_B}{R_E} + g_m r_\pi R_B + R_B\right) + C_E(R_B + r_\pi)}{C_{in} C_E r_\pi R_B} + \frac{\frac{r_\pi}{r_o} + \frac{r_\pi}{R_E} + g_m r_\pi + 1 + \frac{R_B}{r_o} + \frac{R_B}{R_E}}{C_{in} C_E r_\pi R_B}} \text{ [2 pts]}}$$

$$\boxed{Z_o = \frac{1}{C_L}\frac{s + \frac{1}{C_E r_\pi} + \frac{1}{C_E R_E} + \frac{g_m}{C_E} + \frac{1}{C_E r_o}}{s^2 + s\frac{C_E(R_C+r_o)+C_L\left(\frac{r_o R_C}{r_\pi}+\frac{r_o R_C}{R_E}+g_m r_o R_C+R_C\right)}{C_L C_E r_o R_C} + \frac{\frac{R_C}{r_\pi}+\frac{R_C}{R_E}+\frac{r_o}{r_\pi}+\frac{r_o}{R_E}+g_m r_o+1}{C_L C_E r_o R_C}} \text{ [2 pts]}}$$

$$\boxed{G_m = g_m\frac{s + \frac{1}{C_E R_E} - \frac{1}{C_E g_m r_o r_\pi}}{s + \frac{g_m}{C_E} + \frac{1}{C_E r_\pi} + \frac{1}{C_E r_o} + \frac{1}{C_E R_E}} \text{ [2 pts]}}$$

(b) Compute for and list all the pole and zero frequencies in H(s). If multiple poles or zeroes are on the same frequency, list them separately. [3 pts]

All that is needed now is to evaluate all of these pole and zero frequencies. For the loading effect the first zero is at zero, and the second zero is simple as s has been isolated in (30).

$$z_{LE_1} = 0 \tag{46}$$

$$z_{LE_2} = 211 \times 10^{12} \frac{rad}{s} \tag{47}$$

The poles can be solved for using quadratic formula.

$$p_{LE_1} = 52.7 \frac{rad}{s} \tag{48}$$

$$p_{LE_2} = 211 \times 10^{12} \frac{rad}{s} \tag{49}$$

It seems that a pole and zero cancel out at the same frequency. Therefore the loading effect could have been thought to have one pole and one zero.

$$\boxed{p_1 = 52.7 \frac{rad}{s},\ z_1 = 0 \text{ [1 pt]}}$$

By repeating this process with the equations for transconductance and output impedance, the remaining poles and zeroes can be obtained.

$$z_{Z_o} = 211 \times 10^{12} \frac{rad}{s} \tag{50}$$

$$p_{Z_{o1}} = 2.00 \times 10^{6} \frac{rad}{s} \tag{51}$$

$$p_{Z_{o2}} = 211 \times 10^{12} \frac{rad}{s} \tag{52}$$

Again, another pole-zero cancellation.

$$\boxed{p_2 = 2.00 \times 10^{6} \frac{rad}{s} \text{ [1 pt]}}$$

$$z_{g_m} = 3.33 \times 10^{12} \frac{rad}{s} \tag{53}$$

$$p_{g_m} = 211 \times 10^{12} \frac{rad}{s} \tag{54}$$

$$\boxed{p_3 = 211 \times 10^{12} \frac{rad}{s},\ z_2 = 3.33 \times 10^{12} \frac{rad}{s} \text{ [1 pt]}}$$

3. **Two-stage differential amplifier frequency response.** Given the circuit with the parameters below, solve for the following:

$V_{DD} = 5V$, I_{M8}=$50uA$, $k_{1,2,8} = 100\frac{uA}{V^2}$, $k_{3,4} = 75\frac{uA}{V^2}$, $k_{5,6,7,9} = 50\frac{uA}{V^2}$, $\lambda = 0.02V^{-1}$, and $|V_{TH_{n|p}}| = 1V$

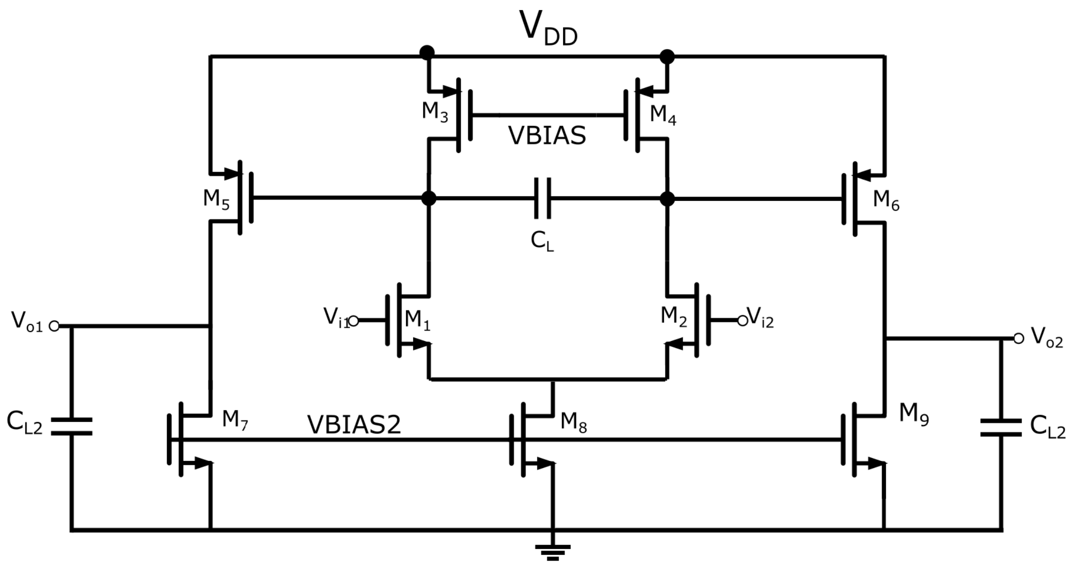

Figure 4: Two-stage differential amplifier.

(a) Plot the magnitude and phase response of the amplifier. [2 pts=overall graph]

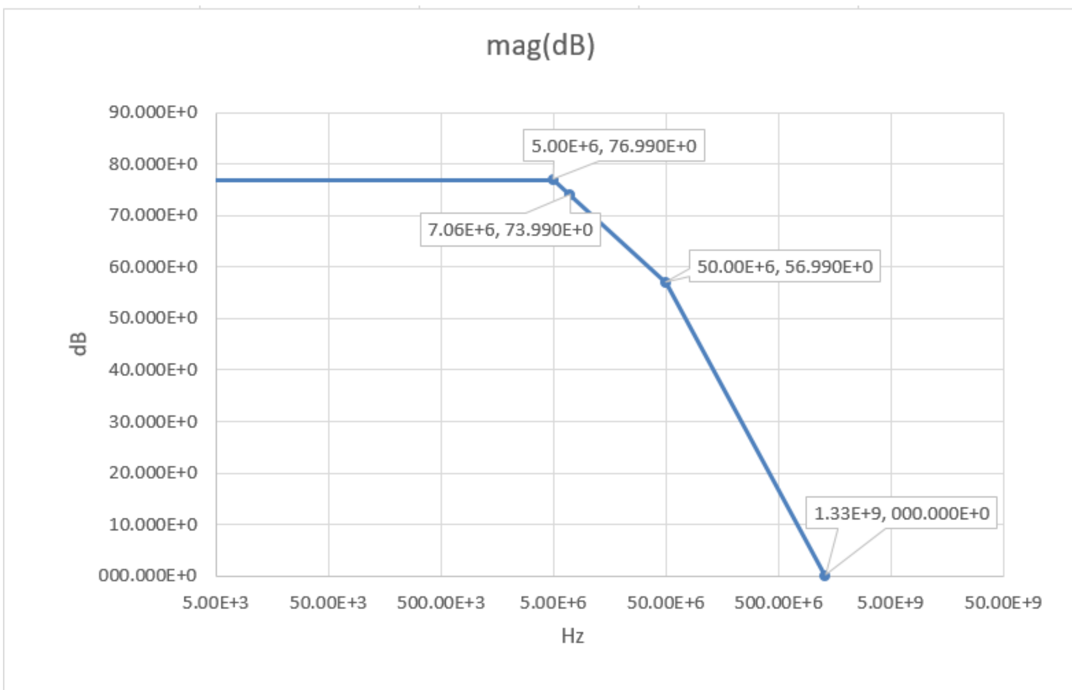

Figure 5: Magnitude Response

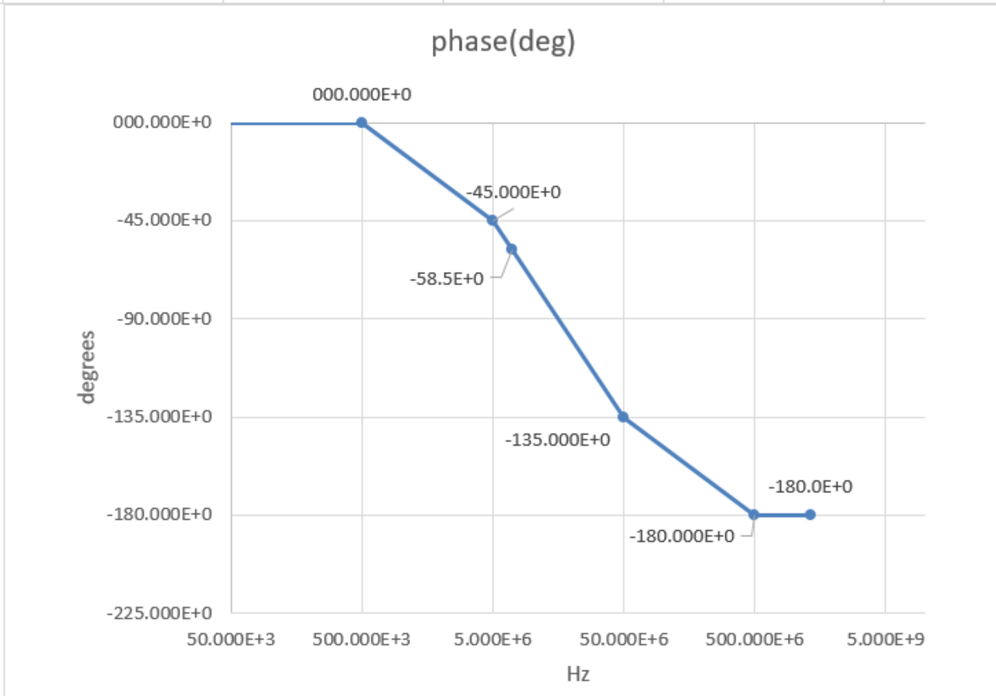

Figure 6: Phase response.

(b) Determine ω_{p1} [2 pts], ω_{p2} [2 pts], $-3dB$ point [2 pts], and unity gain bandwidth [2 pts].

$$Av_{stage1} = \frac{-g_{m2} * r_{o2} * r_{o4}}{(r_{o2} + r_{o4})(1 + \frac{s2C_L r_{o2} r_{o4}}{r_{o2}+r_{o4}})} \tag{55}$$

$$Av_{stage2} = \frac{-g_{m6} * r_{o6} * r_{o9}}{(r_{o6} + r_{o9})(1 + \frac{sC_{L2} r_{o6} r_{o9}}{r_{o6}+r_{o9}})} \tag{56}$$

$$Av_1 = \frac{-g_{m2} * r_{o2} * r_{o4}}{(r_{o2} + r_{o4})} = 100 \tag{57}$$

$$Av_2 = \frac{-g_{m6} * r_{o6} * r_{o9}}{(r_{o6} + r_{o9})} = 70.71 \tag{58}$$

$$Av = \frac{Av_1}{1 + \frac{s}{\omega_{p1}}} * \frac{Av_2}{1 + \frac{s}{\omega_{p2}}} \tag{59}$$

$$\omega_{p1} = \frac{r_{o2} + r_{o4}}{2C_L r_{o2} r_{o4}} = 5MHz \tag{60}$$

$$\omega_{p2} = \frac{r_{o6} + r_{o9}}{C_{L2} r_{o6} r_{o9}} = 50MHz \tag{61}$$

$$\omega_{3dBpoint=73.99dB} = \omega_{p1} * 10^{\frac{(73.99dB-76.99dB)}{-20}} = 7.06MHz \tag{62}$$

$$\omega_{0dB|UGB} = \omega_{p2} * 10^{\frac{(0dB-56.99dB)}{-40}} = 1.3296GHz \tag{63}$$

$\omega_{p1} = 5MHz$ [2 pts], $\omega_{p2} = 50MHz$ [2 pts], $\omega_{3dBpoint=73.99dB} = 7.06MHz$ [2 pts], $\omega_{0dB|UGB} = 1.3296GHz$ [2 pts] (Note: All placed in graphs.)