Final Exam

Name: ___________________________                        Score__________/100____

Question 1 Short Takes – 1 point each unless noted otherwise.

1. An engineer measures the (step response) rise time of an amplifier as \( t_r = 0.1 \mu s \).
   Estimate the 3 dB bandwidth of the amplifier.

   Answer
   \[
   BW \cong \frac{0.35}{t_r} = \frac{0.35}{0.1 \times 10^{-6}} = 3.5 \text{ MHz}
   \]

2. Below as possible ordering for \( V_y \) for several LEDs. Circle the correct one.

   (a) \( V_y(\text{Red}) < V_y(\text{Green}) < V_y(\text{Blue}) < V_y(\text{White}) \)
   (b) \( V_y(\text{White}) < V_y(\text{Green}) < V_y(\text{Blue}) < V_y(\text{Yellow}) \)
   (c) \( V_y(\text{Blue}) < V_y(\text{Red}) < V_y(\text{Yellow}) < V_y(\text{White}) \)
   (d) \( V_y(\text{Red}) < V_y(\text{Green}) < V_y(\text{White}) < V_y(\text{Blue}) \)

   Answer: (a)

3. Which of the following depicts the correct current direction? Circle one.

   Answer: (a)

4. A forward-biased diode has a current \( I_F \) and a diffusion capacitance \( C_D \). The diode current is halved doubled. The resulting diffusion capacitance is then (circle one):

   (a) \( C_D/2 \)    (b) \( 2C_D \)    (c) \( \sqrt{2} \ C_D \)    (d) \( C_D/\sqrt{2} \)    (e) Unchanged

   Answer: (a)

5. Give one phrase/sentence that describes the primary advantage of an active load.

   Answer: Large effective resistance \( \rightarrow \) large voltage gain

6. A MOSFET in a circuit is replaced with another that has a \( W/L \) that is 50% larger. Assuming everything else stays the same, the drain current will

   (a) Decrease by 50%    (b) Increases by 50%    (c) Quadruple    (d) Stay the same

   Answer: (b)
7. Assume that your SPICE simulation software (such as Micro-Cap SPICE) do not have a photodiode “part”. Explain in 1–2 sentences how you can nevertheless simulate a photodiode.

**Answer:** One can model a photodiode with a current source.

8. Classify the filter circuit below.

(a) Low-pass filter  
(b) High-pass filter  
(c) Band-pass filter  
(d) Notch filter

**Answer:** This is a two-pole high-pass filter, so (b) is the answer.

9. Consider the following drive circuit for an IR remote control. The IR diode is replaced with another IR diode that has a turn-on voltage that is 20% lower. The new peak current through the IR diode will be

a) Unchanged  
(b) Increased by 20%  
(c) Decreased by 20%  
(d) Decreased much more than 20%, since

\[ I_D = I_S e^{V_D/V_T} \]

**Answer:** (a)

10. The output voltage of a three-terminal voltage regulator is 3.3 V @ 5 mA load, and 3.25 V @ 1.5 A load. What is the regulator’s output resistance?

(a) \( \approx 33 \text{ m}\Omega \)  
(b) \( \approx 660 \text{ \Omega} \)  
(c) \( \approx 2.2 \text{ \Omega} \)

**Answer:** \( R = \frac{\Delta V}{\Delta I} = \frac{0.05}{1.495} = 33 \text{ m}\Omega \), so (a) is the answer.

11. In the current mirrors below, neglect base currents and take \( I_{REF} = 30 \mu A \), What is \( I_{copy3} \)?

(a) 30 \( \mu A \)  
(b) \( 30 \mu A / 3 = 10 \mu A \)  
(c) \( 30 \mu A / 4 = 7.5 \mu A \)

**Answer:** (a)
12. In the circuit below, $R_1 = 10K$, $R_2 = 15K$, and $R_3$ compensates for the op-amp’s input bias current. What should it’s value be to be effective?

(a) 10K  
(b) 15K  
(c) 6K  
(d) 25K  
(e) Need additional information ($I_{OS}$)  

**Answer:** Choose $R_3 = R_1 || R_2 = 6K$, so (c) is the answer.

13. In the circuit below, what is the maximum current that can flow through $R_L$? Make reasonable assumptions. (2 points)

**Answer:** Assume that for $Q_2$, $V_{BE(ON)} = 0.7$ V. Thus, $Q_2$ will turn on and starve $Q_1$ from additional base current when the current through $R_1$ (which is also the current through $R_L$) is $I = 0.7/1.5 = 0.47$ A.

14. In the circuit below $I_C = 1$ mA and all the capacitors are large enough to be considered shorts. Estimate the midband gain $A_v = v_o/v_i$ (2 points)

(a) $\approx -6.8$  
(b) $\approx -3.4$  
(c) $\approx -g_mR_C = -0.04R_C = -272$  
(d) $\approx -g_mR_C = -0.04(R_C || R_L) = -136$

**Answer:** (d)

15. A power MOSFET has rated power of 1250 W at an ambient temperature $T_A = 25^\circ C$ and a maximum specified junction temperature of 175$^\circ C$. What is the thermal resistance between the junction and device case? (2 points)

**Answer:** $\theta_{dev\text{-}case} = (175 - 25)/1250 = 0.12 \, ^\circ C/W$
16. What is the voltage gain $A_v = v_o/v_s$ of the amplifier below if $g_m = 0.04$ S and $r_o = 100$K? \textbf{(2 points)}

(a) $-400$
(b) $400$
(c) Need additional information (i.e., $r_i$)
(d) $\approx 364$
(e) $\approx -364$

\textbf{Answer:} $A_v = -g_m(r_o||10K) = -0.04(100K||10K) = -363.6 \approx -364$, so (e).

17. An engineer designs a MOSFET-based class-AB amplifier to deliver 6.25 W (sinusoidal) signal power to a $4 \Omega$ resistive load. What is the required peak-to-peak voltage swing across the load? \textbf{(2 points)}

(a) $9.77$ V (b) $19.53$ V (c) $10$ V (d) $14.14$ V (e) $7.07$ V

\textbf{Answer:} $P = V_{rms}^2/R$, so that $V_{rms} = 5$ V, so that $V_{pp} = 14.14$ V, so (d).

18. A single-pole op-amp has an open-loop low-frequency gain of $A = 10^5$ and an open loop, 3-dB frequency of 4 Hz. If an inverting amplifier with closed-loop low-frequency gain of $|A_f| = 50$ uses this op-amp, determine the closed-loop bandwidth. \textbf{(2 points)}

\textbf{Answer:} The gain-bandwidth product is $4 \times 10^5$ Hz. The bandwidth of the closed-loop amplifier is then is $4 \times 10^5/50 = 8$ kHz.

19. A single-pole op-amp has an open-loop gain of 100 dB and a unity-gain bandwidth frequency 5 MHz. What is the open-loop bandwidth of the amplifier? The amplifier is used as a voltage follower. What is the bandwidth of the follower? \textbf{(2 points)}

\textbf{Answer:} A gain of 100 dB corresponds to $10^5$ and the gain-bandwidth product is 5 MHz. Thus, the open-loop bandwidth is $(5 \text{ MHz})/10^5 = 50$ Hz. A unity follower will have a bandwidth of 5 MHz.

20. An amplifier has gain of 800. After adding negative feedback, the gain is measured as 25. Find the loop gain. \textbf{(2 points)}

\textbf{Answer:} $A_f = A_{OL}/(1 + \beta A_{OL})$ so that $25 = 800/(1 + 800\beta)$. Solving for $T = 800\beta$ yields the loop gain $T = 31$. 


21. An amplifier with gain of 200 has a 10% variation in gain over a certain frequency range. Using negative feedback, what value of $\beta$ should one use to reduce the gain variation to 1%? (2 points)

Answer: The improvement factor we want from the negative feedback is $\Delta A_{OL}/\Delta A_f = 10%/1% = 10$. Therefore, $(1 + \beta A_{OL}) = 10 \Rightarrow (1 + 200\beta) = 10 \Rightarrow \beta = 0.045$

22. In the circuit below $I_C = 1\ mA$ and all the capacitors are large enough to be considered shorts. Estimate the midband gain $A_v = v_o/v_i$ (2 points)

(a) $\approx -12.1$
(b) $\approx -5.7$
(c) $\approx -g_m R_C = -0.04R_C = -272$
(d) $\approx -g_m R_C = -0.04(R_C||R_L) = -136$

Answer: $A_v \approx -(R_L||R_C)/560 = 3.2/0.56 = -5.7$

23. An engineer wants to reduce the output amplitude of the Wien bridge oscillator below by adjusting $R_5$. Should she increase or decrease the resistor’s value? Briefly explain you answer. (2 points)

Answer: She should decrease $R_5$’s value, as this will cause the diodes to “turn on” at a lower output voltage. With the diodes turned on, the negative feedback resistance consisting of $R_5, R_5$, and the diodes are reduced, which reduces the overall gain.

24. An amplifier has gain of 100,000, and a 20% variation in gain over a certain temperature range. Negative feedback is used to reduce the gain to 10. What is the variation in gain with temperature of the feedback amplifier? (2 points)

Answer. The gain is reduced by $1 + \beta A_{OL} = 100,000/10 = 10,000$. The temperature variations are reduced by the same factor, so the feedback amplifier’s gain varies by $20% /10^4 = 0.002%$
**Question 2** The transistor in the amplifier shown has $\beta = 350$ and $V_{BE(ON)} = 0.65$ V. Further, $C_c = 1 \mu F$.

(a) Show that $I_{CQ} \approx 1$ mA  (*2 points*)

(b) Show that $R_i \approx 13.7$ K  (*3 points*)

(c) Estimate the lower 3-dB frequency (*3 points*)

**Solution**

**Part (a)**

Since $\beta$ is large, ignore $I_{BQ}$ so that $V_B = (9)(27/(100 + 27)) = 1.9$ V.

Since $V_{BE(ON)} = 0.65$ V, then $V_{RE} = 1.9 - 0.64 = 1.25$ V. Consequently, $I_{CQ} \approx I_E = 1.25/1.3K = 0.962$ mA $\approx 1$ mA.

**Part (b)** $r_\pi = \beta/g_m = 350/(40I_{CQ}) = 8.75K$. Using BJT scaling,

$$R_i = 65K/18K(r_\pi + (1 + \beta)(1.3K)) = 13.68K$$

**Part (c)**

$$f_{3dB} = \frac{1}{2\pi R_i C_c} = \frac{1}{(2\pi)(13.68K)(1 \times 10^{-6})} = 11.64 \text{ Hz}$$

For comparison, SPICE gives $r_\pi = 8.15K$, $R_i = 13.59K$, $f_{3dB} = 11.8$ Hz
Question 3

For the non-inverting op-amp circuit, the parameters are $A_{OL} = 10^5$, $A_{vf} = 20$, $R_i = 100K$, and $R_o = 100 \, \Omega$. Determine $R_{if}$ and $R_{of}$ respectively. The op-amp has a single open-loop pole at 10 Hz. Determine the closed-loop bandwidth. (8 points)

Solution

$$A_f = \frac{A_{OL}}{1 + \beta A_{OL}} \Rightarrow 20 = \frac{10^5}{1 + \beta A_{OL}} \Rightarrow 1 + \beta A_{OL} = 5,000$$

$$R_{if} = (1 + \beta A_{OL})(100K) = 500.1M$$

$$R_{of} = \frac{100}{1 + \beta A_{OL}} = 20 \, \text{m} \Omega$$

$$BW = (1 + \beta A_{OL})(10) = 50 \, \text{kHz}$$

Question 4  A power MOSFET has thermal characteristics given below and dissipates 25 W. Design, by specifying the thermal resistance, a heat sink that will ensure the MOSFET does not overheat. The ambient temperature is 25 °C. Assume one can keep the thermal resistance between the MOSFET case and heat sink ($\theta_{case-sink}$ or $\theta_{CS}$) below 1 °C/W. (4 points)

$$\theta_{junction-case} = \theta_{JC} = 1.75 \, \text{°C}/W,$$

$$\theta_{case-ambient} = \theta_{CA} = 50 \, \text{°C}/W$$

$$T_{j,\text{max}} = 150 \, \text{°C}$$

Solution

A thermal model that captures the information is shown below:

$$T_j = T_A + P_D(\theta_{JC} + \theta_{CS} + \theta_{SA})$$

$$150 = 25 + 25(1.75 + 1 + \theta_{SA})$$

$$\theta_A = 2.25 \, \text{°C}/W$$

The heat sink’s thermal resistance must be less than this value.

Note: $\theta_{SA}$ is not part of the picture, since we will replace it with a much lower $\theta_{SA}$
**Question 5** Below is a small-signal model of a BJT amplifier. Determine the so-called Miller capacitance $C_M$, and draw an equivalent small-signal circuit that incorporates $C_M$. Next, determine the circuit time constant, 3-dB frequency, and the midband gain. Finally, does this amplifier have a high-pass or low-pass response? *(8 points)*

![Small-signal model of a BJT amplifier](image)

### Solution

The gain that “works across” $C_\mu$ is $-g_m R_L = -80$. The Miller capacitance is $C_M = (1 - A_V)C_\mu = (81)(2) = 162 \text{ pF}$. A small-signal model that incorporates $C_M$ is shown below.

![A small-signal model that incorporates $C_M$](image)

The circuit time constant is $\tau = (C_\pi || C_\mu)(r_\pi || R_s) = (162 \text{ pF} + 10 \text{ pF})(2.5\text{K}) = 430 \text{ ns}$.

The 3-dB frequency is $f_{3\text{dB}} = 1/(2\pi\tau) = 370 \text{ kHz}$.

The midband gain is

$$A_{V_{(\text{mid})}} = \frac{r_\pi}{R_s + r_\pi} (-g_m R_L) = -40$$

The amplifier has a low-pass response.
Question 6  Consider the amplifier shown. The maximum power the transistor may dissipate is $P_{Q,\text{max}} = 25 \, \text{W}$, and $C \to \infty$.

(a) Determine a load resistance $R_L$ so that the amplifier can deliver maximum power to it. \((2 \, \text{points})\)

(b) What is the maximum signal power the amplifier can deliver to $R_L$? Assume sinusoidal input signal. \((2 \, \text{points})\)

(c) For $V_p = 5 \, \text{mV}$, determine the signal power dissipated in the load. \((4 \, \text{points})\)

For the power calculations, neglect the base current

Solution

Part (a) The transistor will dissipate the maximum power (25 W) and deliver maximum power to a load when $V_C = V_{CC}/2 = 12 \, \text{V}$. One can derive this on-the-fly, but this is a result that we derived in class and used many times in this course.

From this follows that $I_{CQ} = 25/12 = 2.0843 \, \text{A}$, and $R_L = 12/2.083 = 5.76 \, \Omega$.

Part (b) The power supplied by the power supply is $P_{\text{Supply}} = V_{CC} \times I_{CQ} = 50\%$. This is a class A amplifier that a maximum efficiency of 25%, so the maximum power the amplifier can supply to $R_L = 12.5 \, \text{W}$.

Alternatively, the peak-to-peak voltage swing across the 5.67 Ω load resistor is 24 V which corresponds to an 8.485 V rms load voltage, and a power dissipation of $V_{\text{rms}}^2/R_L = 72/5.67 = 12.5 \, \text{W}$.

Part (c) The gain of the amplifier is $A_V = -g_mR_L = -40I_{CQ}R_L = -(40)(2.083)(5.76) = -480$, so that the amplitude of the signal output voltage is $0.005 \times 480 = 2.4 \, \text{V}$.

The signal power dissipated in the resistor is

$$V_{\text{rms}}^2/R_L = V_p^2/(2R_L) = 2.4^2/(2 \times 5.76) = 500 \, \text{mW} = 0.5 \, \text{W}$$
Question 7  The circuit shown is the input buffer of the IR receiver you built in the final lab, and $R_L$ is the input resistance of the next amplifier in the chain. Assume that your dc analysis show that $I_D = 0.5\, mA$, and that $K_n = 0.5\, mA/V^2$, $V_{TN} = 2\, V$, and $\lambda = 0$. Ignore the transistor’s internal capacitances and assume that $C_{c1}$ is large enough to be considered a short.

(a) Show that $R_O = (1/g_m)\| R_S \approx 1/g_m$  (6 points)
(b) Determine $C$ so that $f_{3\,dB} = 2\, kHz$.  (4 points)

Solution

Part (a) A small-signal model to determine $R_o$ is shown: the input is shorted and a test source $V_x$ drives the FET’s source, resulting in a current $I_x$, and $R_o = V_x/I_x$.

Further, $R_G = R_1\|R_2\|R_{ph}$

KCL at the source is

$$g_m v_{gs} - V_x/R_s + I_x = 0$$

However, from the circuit it follows that $v_{gs} = -V_x$, so that

$$-V_x g_m - V_x/R_s + I_x = 0$$

$$\Rightarrow R_o = \frac{V_x}{I_x} = \frac{1}{g_m} + \frac{1}{R_s} = \frac{1}{g_m} || R_s = 1K || 10K \approx 1K$$

We used the fact that $g_m = 2\sqrt{K_n I_D} = 1\, mA/V$ so that $1/g_m = 1K$.
Part (b) The circuit time constant is $\tau = C_C(R_o + R_L)$. For a 2-kHz corner frequency,

$$f_{3dB} = \frac{1}{2\pi \tau} \Rightarrow 2 \times 10^3 = \frac{1}{2\pi (1K + 8K)C_C}$$

Solving yields $C_C = 8.8$ nF. Use standard values of 8.2 nF.
Question 8 Below is a screen dump of a SPICE simulation of a Wien bridge oscillator that uses an incandescent lamp for gain control. The graph depicts the lamp resistance as a function of the voltage across the lamp.

(a) Determine the frequency of oscillation in Hz (2 points)
(b) Determine the voltage at which the output stabilizes (8 points)

Solution

Part (a) $R_1 = R_2 = R$ and $C_1 = C_2 = C$ and $f = 1/(2\pi RC) = 40.81$ Hz

Part (b) At startup $R_{lamp} \approx 9 \Omega$, and the loop gain $T = R_4/(R_{lamp} + 39) + 1 = 3.5$, enough for a Wien bridge oscillator to start oscillating.

As the output amplitude grows, $V_{lamp}$ grows, $R_{lamp}$ increases. However when $R_{lamp}$ increases, the loop gain $T = R_4/(R_{lamp} + 39) + 1$ decreases. The loop stabilizes when

$$T = R_4/(R_{lamp} + 39) + 1 = 3$$

$\Rightarrow R_{lamp} = 21 \Omega$

From the plot $R_{lamp} = 21 \Omega$ when the $V_{lamp} \approx 0.328$ V. The current flowing through the lamp is $0.38/21 = 17.86 \approx 18$ mA. The voltage at the output is $(0.018)(21 + 39 + 120) = 3.24$ V.
Question 9  The open-loop voltage amplification of an amplifier is

\[ A_v = -\frac{10^3}{\left(1 + \frac{jf}{10^5}\right)^3} \]

With \( \beta_v = 0.005 \), find the phase- and gain margins. Determine if the amplifier is stable. Give the gain margin in dB. (10 points)

Solution

For the phase margin, we check the phase of the loop gain \( T = \beta A_v \) where \( T = 1 \). The frequency where the gain equals 1, is where

\[ |T| = |\beta A_v| = \left| -\beta \frac{10^3}{\left(1 + \frac{jf}{10^5}\right)^3} \right| = 0.005 \frac{10^3}{\left(1^2 + \left(\frac{f}{10^5}\right)^2\right)^{3/2}} = 1 \]

Solving yields \( f = 138.7 \times 10^3 \) Hz. The phase at this frequency is

\[ \phi = -3 \tan^{-1}\left(\frac{f}{10^5}/1\right) = -163^\circ \]

Thus, the phase margin is \( 180^\circ - 163^\circ = 17^\circ \).

For the gain margin, we determine the magnitude of the loop gain at the frequency where the phase shift is \(-180^\circ\). The frequency where the phase shift is \(-180^\circ\), is where

\[ \phi = -3 \tan^{-1}\left(\frac{f}{10^5}/1\right) = -180^\circ \]

Solving yields \( f = 173.2 \times 10^3 \) Hz. The magnitude at this frequency is

\[ \frac{0.005 \times 10^3}{\left(1 + \left(\frac{173.2 \times 10^3}{10^5}\right)^2\right)^{3/2}} = 0.624 = -4 \text{ dB} \]

The loop gain is less that 1 (\( \equiv 0 \text{ dB} \)), so the system is stable. The gain margin is 4 dB.