Second Edition

Analog circuit Drill

Solutions
Test Drill I
Test Drill II

A K Tripathi
MD, Mechasoft Publishers and Educators
and
Asstt. Prof. Electronics Engineering Department
IERT, Degree Division, Allahabad (INDIA)

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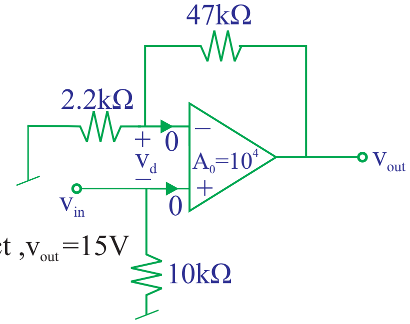
Solutions

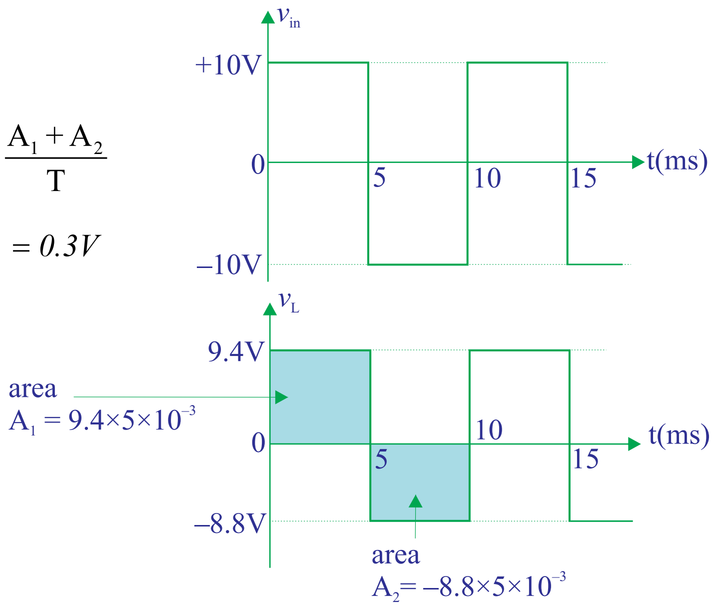
Q1. Assume linear operation to get



$$v_{out} = v_{in} \times \frac{1+\frac{47}{2.2}}{1+\frac{1+\frac{47}{2.2}}{10^4}} = 1\times\frac{22.36}{1+22.36\times10^{-4}} = 22.31V$$

Since, calculation gives $v_{out} > 15V$,op-amp is in saturation . In fact ,v_{out}=15V and $v_d = 15\times10^{-4}$ V= *1.5mV*

Q2. $f = 100Hz$



$$T = \frac{1}{100} = 0.01 = 10\,msec$$

$$\text{dc component} = \frac{\text{area over one time period}}{T} = \frac{A_1 + A_2}{T}$$

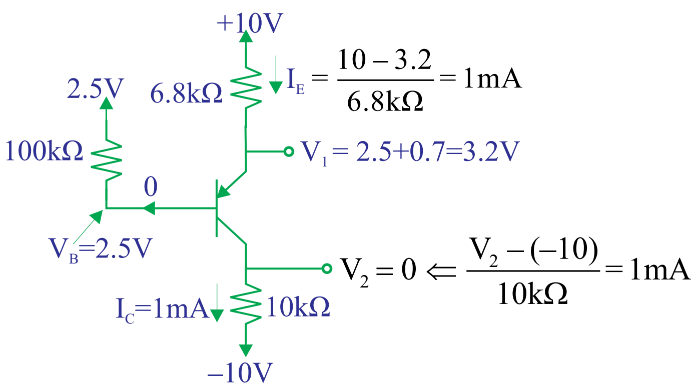
$$= \frac{9.4\times5\times10^{-3} - 8.8\times5\times10^{-3}}{10\times10^{-3}} = 0.3V$$

Q3. Let v_{in} = A sin ω_0t . Then , $v_{out} = -\left(10\times10^3\times0.01\times10^{-6}\right)\frac{d}{dt}(A\sin\omega_0 t)$

$$= -10^{-4}A\omega_0\cos\omega_0 t$$

$$|v_{in}| = |v_{out}| \Rightarrow A = 10^{-4}A\omega_0 \Rightarrow \omega_0 = 10\,krad/sec \text{ and } f_0 = \frac{10}{2\pi} = 1.59\,kHz$$

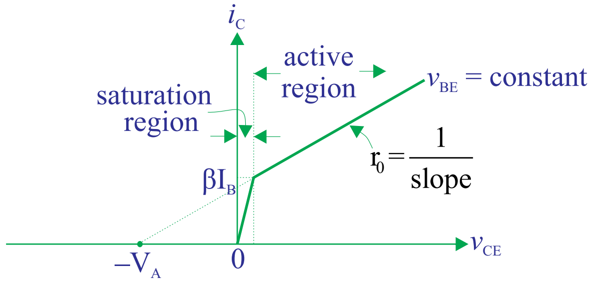
Q4. (c) $V_1 - V_2 = 3.2V$ as demonstrated below.



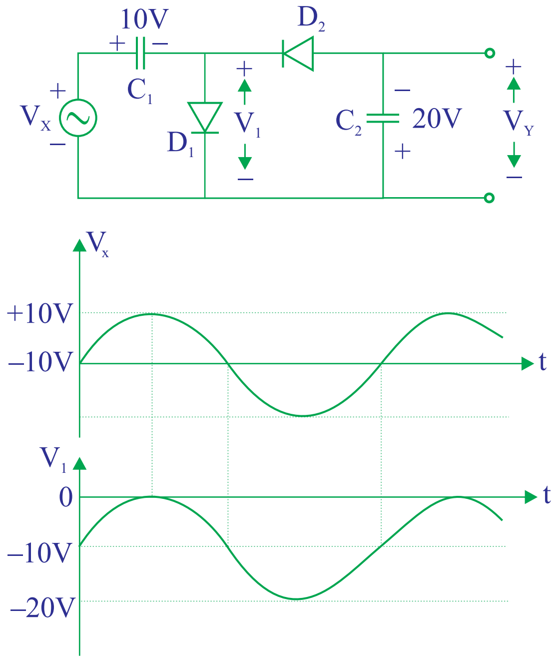
Q5. The output resistance

$$r_0 = \frac{V_A}{\beta I_B} = \frac{200}{100 \times 50 \times 10^{-6}} = 4 \times 10^4 \Omega$$

$$= 40k\Omega$$



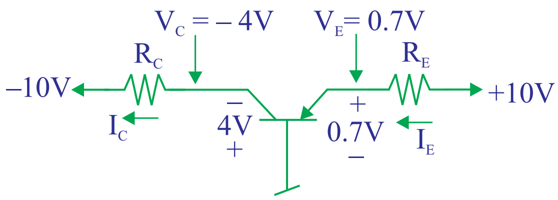
Q6. (c) When V_X varies sinusoidally from zero to peak value 10V , the capacitor C_1 charges instantaneously to 10V with polarity as shown , while D_1 remains on. After C_1 has charged to 10V, D_1 turns off and in steady state, $V_1 = V_X - 10 = 10\cos\omega t - 10$ has extremities at 0 and –20V as depicted below. While V_1 varies from 0 to –20V , D_2 turns on to allow the capacitor C_2 to charge instantaneously to 20V with polarity as shown .Thereafter, D_2 turns off and C_2 does not find any path to discharge .Thus, $V_Y = -20V$.



Q7.(d) $\alpha = 1 \Rightarrow I_B = 0$ and $I_C = I_E = 1mA$

$$\frac{-4-(-10)}{R_C} = \frac{10-0.7}{R_E} = 1mA$$

$$R_E = 9.3k\Omega \text{ and } R_C = 6k\Omega$$



Q8(b). Q_1 and Q_2 both are in saturation.

$K(V_{GS1} - V_t)^2 = K(V_{GS2} - V_t)^2$; $V_{GS1} = V_{DD} - V_B$ and $V_{GS2} = V_A$

$(V_{DD} - V_B - V_t)^2 = (V_A - V_t)^2$

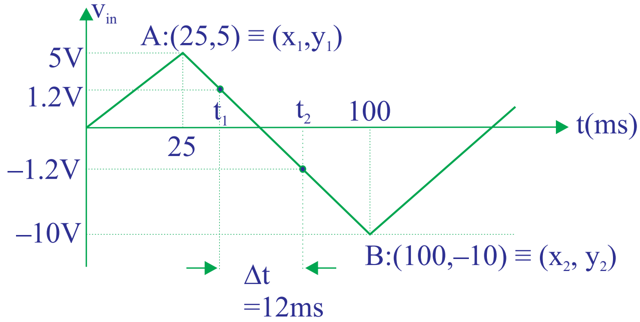
$V_{DD} - V_B - V_t = \pm (V_A - V_t)$

either $V_{DD} - V_B - V_t = V_A - V_t \Rightarrow V_{DD} = V_A + V_B$

or $V_{DD} - V_B - V_t = V_t - V_A$

but $V_{GS1} = V_{DD} - V_B$ must be greater than V_t ,that is, $V_{DD} - V_B - V_t$ must be positive and this demands $V_t > V_A$ which is not possible. In fact ,$V_{GS2} = V_A$ must be greater than V_t.
Thus , $V_{DD} = V_A + V_B$

Q9. The diodes D_1 and D_3 turn on when $v_{in} > 1.2V$ while the diodes D_2 and D_4 turn on when $v_{in} < -1.2V$.
During time $t \in [25ms, 100ms]$, when V_{in} decreases from $+1.2V$ to $-1.2V$, all diodes D_1, D_2, D_3 and D_4 remain off and $i_L = 0$.
The equation of line segment AB is



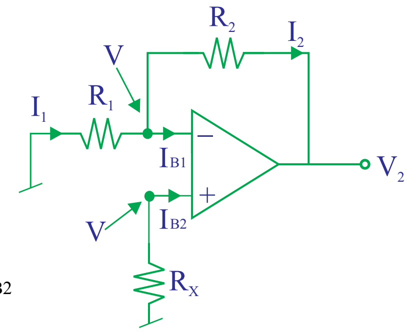
$$y - 5 = \frac{-10-5}{100-25}(x - 25) \quad ; \; y \text{ represents } v_{in} \text{ and } x \text{ represents time } t, \text{in ms}$$

$$v_{in} = -0.2t + 10$$

$$1.2 = -0.2t_1 + 10 \text{ gives } t_1 = 44ms \text{ and } -1.2 = -0.2\,t_2 + 10 \text{ gives } t_2 = 56ms$$

$$\Delta t = t_2 - t_1 = 56 - 44 = 12ms$$

Q10. $I_{ios} = 0 \Rightarrow I_{B1} - I_{B2} = 0 \Rightarrow I_{B1} = I_{B2}$



$$V = -I_{B2}\,R_X \quad and \quad I_1 = \frac{0-V}{R_1} = \frac{I_{B2}\,R_X}{R_1}$$

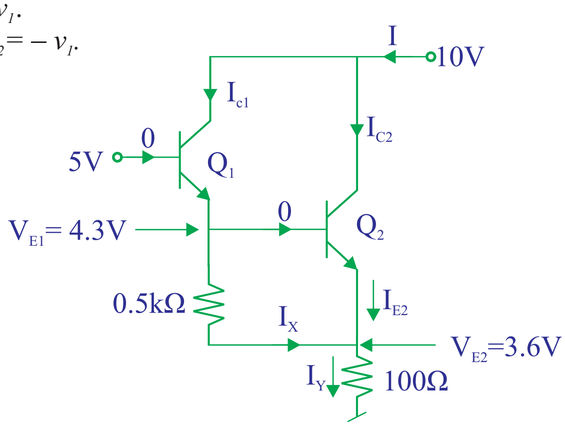
$$I_2 = I_1 - I_{B1} = \frac{I_{B2}\,R_X}{R_1} - I_{B1}$$

$$V - I_2R_2 = V_2 = 0 \Rightarrow -I_{B2}\,R_X - \left[\frac{I_{B2}\,R_X}{R_1} - I_{B1}\right]R_2 = 0 \quad ; \; I_{B1} = I_{B2}$$

$$R_X + \frac{R_X\,R_2}{R_1} = R_2 \Rightarrow R_X = \frac{R_1\,R_2}{R_1 + R_2} = \frac{5 \times 7.5}{5 + 7.5} = 3k\Omega$$

Q11(a). For $v_1 > 0$, diode D is reverse biased and $v_2 = v_1$.
For $v_1 < 0$, diode D is forward biased and $v_2 = -v_1$.

Q12(b). $V_{E2} = 5 - 0.7 - 0.7 = 3.6V$



$$I_Y = \frac{3.6}{100}A = 36mA$$

$$I = I_{C1} + I_{C2} = I_X + I_{E2} = I_Y = 36mA$$

Q13(c). For PLL in lock mode

$$\omega_i = \omega_0 + k_v \times V_C$$

$$\text{and } V_C = \frac{\omega_i - \omega_0}{k_v} = \frac{2\pi(f_i - f_0)}{2\pi \times 10^3} = \frac{250-500}{10^3} = -0.25V$$

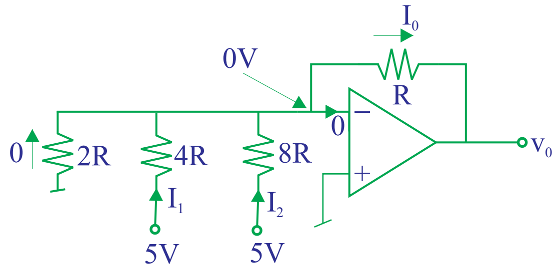
Q14. The circuit for $b_1b_2b_3 = 011$, is sketched below.

$$I_0 = I_1 + I_2$$

$$\frac{0 - v_0}{R} = \frac{5-0}{4R} + \frac{5-0}{8R}$$

$$v_0 = -(1.25 + 0.625)$$

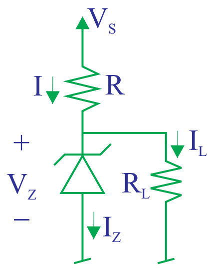
$$= -1.875V$$



Q15(b). $I_Z = I - I_L > 0$ or $I > I_L$ ensures consistent regulation.

$$\frac{V_S - V_Z}{R} > \frac{V_Z}{R_L}$$

$$R_L > R\left[\frac{V_Z}{V_S - V_Z}\right] \text{ or } R_L > R\left[\frac{V_S}{V_Z} - 1\right]^{-1}$$



Q16. The diode ac resistance , $r_f = \frac{V_T}{I} = \frac{25mV}{0.1mA} = 250\Omega$

$$v_y = \frac{v_x r_f}{r_f + r_x} = \frac{250 v_x}{250 + 250} = \frac{v_x}{2}$$

$$v_y = 0.5 v_x \Rightarrow \lambda = 0.5$$

Q17(b). $v_0(t) = \left[\lambda \cos(10^4 t)\right]\left(1 + \frac{90}{10}\right) = 10\lambda \cos 10^4 t \text{ V}$

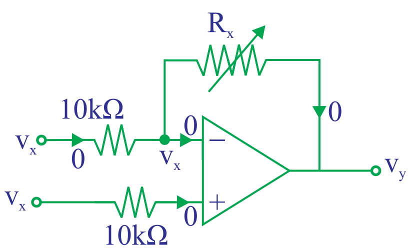
$$\dot{v}_0(t) = 10^5 \lambda \cos 10^4 t \text{ and } \dot{v}_0(t)\big|_{max} = 10^5 \lambda \text{ V/sec}$$

For no distortion, $\dot{v}_0(t)\big|_{max} \le 0.4 \times 10^6 \Rightarrow 10^5 \lambda \le 0.4 \times 10^6$

$\lambda \le 4V$

Q18(b). $v_y = v_x$

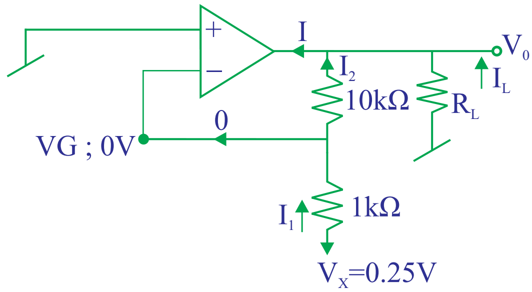
The current through R_x is zero.



Q19(b). $I_1 = I_2 = \frac{0.25 - 0}{1k\Omega} = 0.25mA$ and $\frac{0 - V_0}{10k\Omega} = 0.25mA \Rightarrow V_0 = -2.5V$

$$I_2 + I_L = I \le 25mA \quad \Rightarrow \left[0.25mA + \frac{2.5}{R_L}\right] \le 25mA$$

$$R_L \ge 100\Omega$$

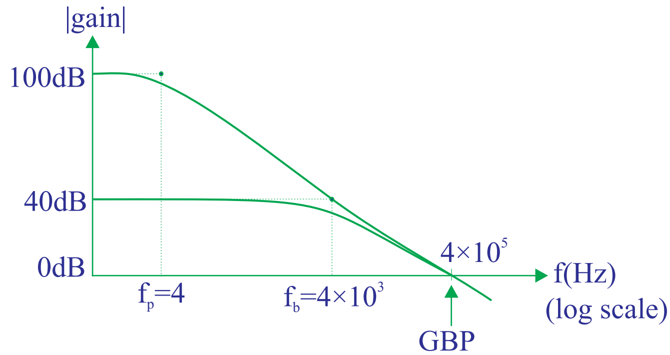


Q20. The gain-band width product,
$GBP = A_0 f_p = (100dB) \times 4Hz = (10^5 V/V) \times 4Hz = 400kHz$

$|A_{fb}| = 100$ and band width $f_b = \dfrac{A_0 f_p}{|A_{fb}|} = \dfrac{400kHz}{100}$

$= 4kHz$

It is important to note that GBP remains constant.



Q21(a) The dc equivalent circuit is sketched below with ac source v_s shorted. Transistors Q_a, Q_b and Q_c are in saturation, have equal drain currents and equal $V_{GS} = 5V$.
Assume Q_3 in saturation.
$I_{D3} = K_3(V_{GS3} - V_t)^2 = [8mA/V^2](5-3-1)^2 = 8mA$
Q_1 and Q_2 are identical and allow equal drain currents.
Let $V_{GS1} = V_{GS2} = V_1$

$I_{D1} = I_{D3} \Rightarrow K_1(V_{GS1} - V_t)^2 = 8mA \Rightarrow (V_1 - 1)^2 = 8$

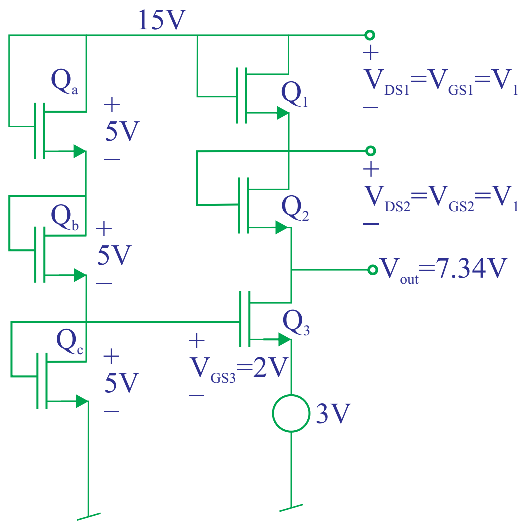
$V_1 = 1 \pm 2\sqrt{2}$ V

Since, V_1 can not be negative, $V_1 = 1 + 2\sqrt{2} = 3.83V$

$V_{OUT} = 15 - 2 \times 3.83 = 7.34V$

Note that $V_{GD3} = 5 - 7.34 = -2.34 < V_t$; $V_t = 1V$,

Q_3 is, indeed, in saturation.



Q22(a). $I_{D_1} = I_{ref} = \dfrac{1}{2} K'_n (V_{GS1} - V_t)^2$

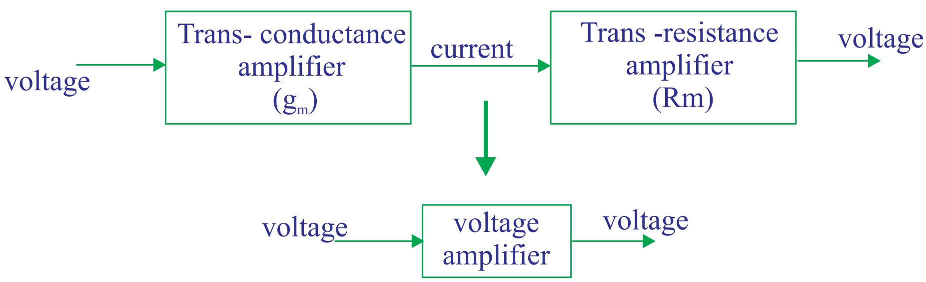
$100 \times 10^{-6} = \dfrac{1}{2} \times 200 \times 10^{-6} (V_{GS1} - 1)^2 \Rightarrow V_{GS1} = 1 \pm 1 = 0$ or $2V$

Note that V_{GS} can not be 0. So, $V_{GS1} = 2V$ and $R_x = \dfrac{5-2}{100\mu A} = 30k\Omega$

The transistor Q_2 will remain in saturation if $V_{DS} \geq V_{GS} - V_t$ or $V_0 \geq 2 - 1$ or $V_0 \geq 1V$.

$V_{0,min} = 1V$

Q23(b).



Q24(d). Corrigendum ; please note that Fig.(b) shows relation between v_x and v_y, and not between v_x and v_z. The error in Q24 is regretted.

$$v_y = -v_x \text{ for } v_x > 0$$
$$= 0 \text{ for } v_x < 0$$
$$v_z = -v_x - 2v_y = -v_x - 2(-v_x) = v_x \quad \text{for } v_x > 0$$
$$= -(-v_x) - 2\times 0 = v_x \text{ for } v_x < 0$$

The block diagram realizes absolute value operation .

Q25(b). $g_m = \dfrac{I_{CQ}}{V_T} \Rightarrow \dfrac{0.8\,mA}{26mV} \le g_m \le \dfrac{1.2mA}{26mV}$ or $30.77 \le g_m \le 46.15\,mA/V$

$$r_{\pi,max} = \frac{\beta_{max}}{g_{m,min}} = \frac{180}{30.77\times 10^{-3}} = 5.85\,k\Omega$$

Q1(c). Corrigendum : the value of $v\_$ at $t = 100ms$ is to be evaluated.

At $t = 0$, $v_{out} = 0$ and $v_C = 0$.
In linear region for $t > 0$

$$v_{out} = -\frac{1}{20\times10^3\times1\times10^{-6}}\int_0^t v_{in}(t)dt = -50\int_0^t 2.dt = -100t \text{ while } v_C(t) = 0 - v_{out} = 100t.$$

The output voltage v_{out} will linearly fall and reach saturation limit of –8V at time

$$t_1 = \frac{-8}{-100} = 0.08\text{sec} = 80\,\text{ms while } v_C\big|_{t=80ms} = 8V$$

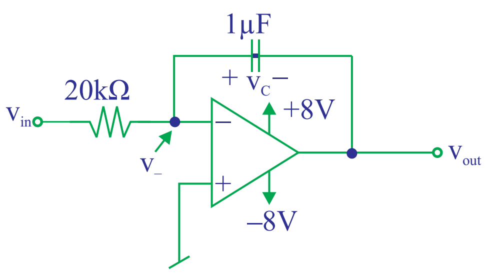
For $t > t_1$ or $t > 80ms$, the op amp is no more in linear region and inverting terminal of op amp is no more at virtual ground. The capacitor charges exponentially with time constant $\tau = 20\times10^3\times10^{-6} = 20\times10^{-3} = 20ms$ till the voltage at inverting terminal $v\_ = 2V$ and $v_C = v\_ - v_{out} = 2-(-8) = 10V$.

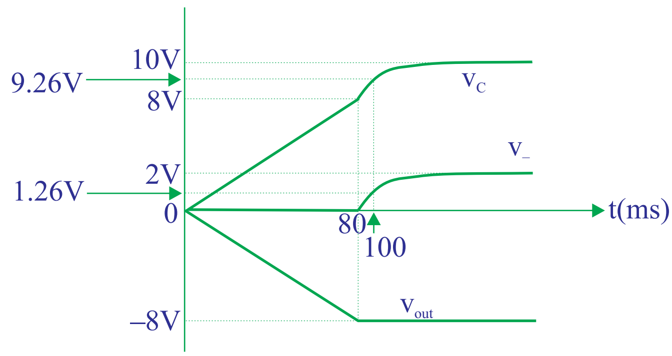
$$\text{For } t > t_1,\ v_C(t) = v_C(t_1) + [v_C(\infty) - v_C(t_1)]\left(1-e^{-(t-t_1)/\tau}\right) = 8 + (10-8)\left(1-e^{-(t-t_1)/\tau}\right) = 8+2\left(1-e^{-(t-t_1)/\tau}\right)$$

$$\text{and } v\_ = v_{out} + v_C = -8+8+2\left(1-e^{-(t-t_1)/\tau}\right) = 2\left(1-e^{-(t-t_1)/\tau}\right)$$

$$v_C(t)\big|_{t=100ms} = 8+2\left[1-e^{-(100-80)/20}\right] = 9.26V$$

At $t = 100ms$, $v_C = 9.26V$, $v_{out} = -8V$ and $v\_ = v_{out} + v_C = -8 + 9.26 = 1.26V$

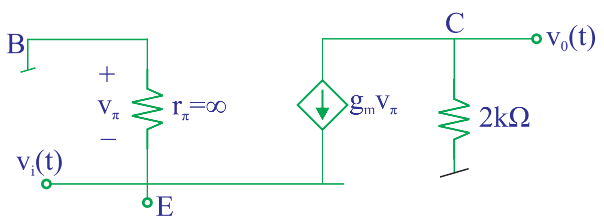


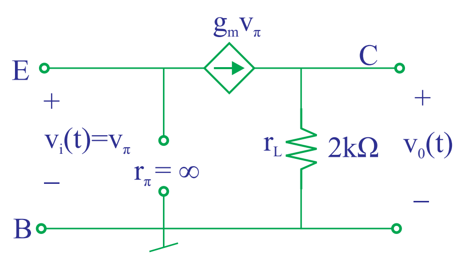


$$I_{B_1} = I_{B_2} = 0 \text{ and } I_{C1} = \frac{5.4-0.7}{4.7k\Omega} = 1mA$$

Q2. $$I_{C2} = 2\,I_{C1} = 2mA = I_{C3} \text{ and } g_{m3} = \frac{I_{C3}}{V_T} = \frac{2mA}{25mA} = 0.08\ A/V$$

$$Q_3 \text{ has } g_m = 0.08\ A/V \text{ and } r_\pi = \frac{\beta}{g_m} = \infty$$





$$v_0(t) = g_m v_\pi r_L = g_m v_i(t) r_L = 0.08\times10^{-2}\cos(1000\pi t)\times2\times10^3 \Rightarrow V_0 = 1.6V$$

Q3. Both transistors M_1 and M_2 have $V_{GD} = 0$ and therefore, both M_1 and M_2 are obviously in saturation .

$$I = 0.5I_1 \Rightarrow I_1 = I_2$$

$$K_1(V_{GS1} - V_{t1})^2 = K_2(V_{GS2} - V_{t2})^2 \; ; \; V_{GS1} = V_{GS2} = V_x$$

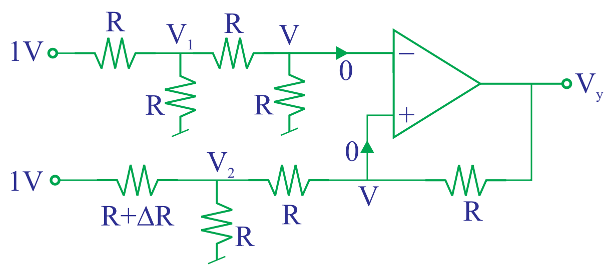
$$K_1(V_x - V_{t1})^2 = K_2(V_x - V_{t2})^2$$

$$0.5\times10^{-3}(V_x - 1)^2 = 2\times10^{-3}(V_x - 2)^2 \quad \text{or} \quad V_x - 1 = \pm\, 2(V_x - 2)$$

$$V_x - 1 = 2(V_x - 2) \quad \text{gives} \quad V_x = 3V \text{ and } V_x - 1 = -2(V_x - 2) \quad \text{gives } V_x = \frac{5}{3}\text{ V}$$

Note that $V_{GS1}=V_{GS2}=V_x$ must be larger than V_{t1} and V_{t2} both . Thus, $V_x = 3V$

Q4. The circuit is re-sketched below in more convenient form .



$$\frac{1 - V_1}{R} = \frac{V_1}{R} + \frac{V_1 - V}{R} \quad \text{gives} \quad V_1 = \frac{1 + V}{3}$$

$$\frac{V_1 - V}{R} = \frac{V}{R} \quad \text{gives} \quad V = \frac{V_1}{2} = \frac{1}{2}\left[\frac{1+V}{3}\right] \Rightarrow V = 0.2$$

$$\frac{1 - V_2}{R + \Delta R} = \frac{V_2}{R} + \frac{V_2 - V}{R} \quad \text{and} \quad \frac{V_2 - V}{R} = \frac{V - V_y}{R}$$

$$\frac{1 - V_2}{R + \Delta R} = \frac{V_2}{R} + \frac{V_2 - 0.2}{R} \quad \text{and} \quad V_2 - 0.2 = 0.2 - V_y \Rightarrow V_2 = 0.4 - V_y$$

$$\frac{1 - (0.4 - V_y)}{R + \Delta R} = \frac{0.4 - V_y}{R} + \frac{0.4 - V_y - 0.2}{R}$$

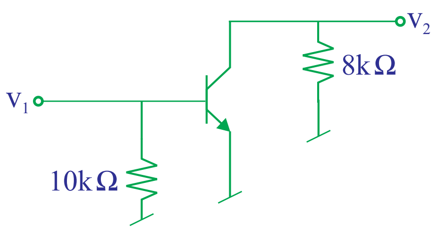
$$\frac{0.6 + V_y}{1 + \dfrac{\Delta R}{R}} = 0.4 + 0.4 - 0.2 - 2V_y \quad ; \quad \frac{\Delta R}{R} = 0.06$$

$$\frac{0.6 + V_y}{1 + 0.06} = 0.6 - 2V_y \Rightarrow V_y = 0.011538V = \mathit{11.54mV}$$

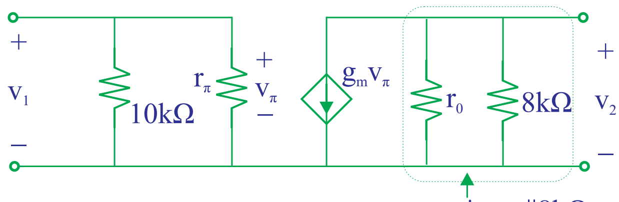
Q5(c). $g_m = \dfrac{I_C}{V_T} = \dfrac{1mA}{25mV} = 0.04 \text{ A/V}, r_\pi = \dfrac{\beta}{g_m} = \dfrac{100}{0.04} = 2500\Omega = 2.5k\Omega$

$$r_0 = \frac{V_A}{I_C} = \frac{100V}{1mA} = 100k\Omega$$

ac model



ac equivalent circuit

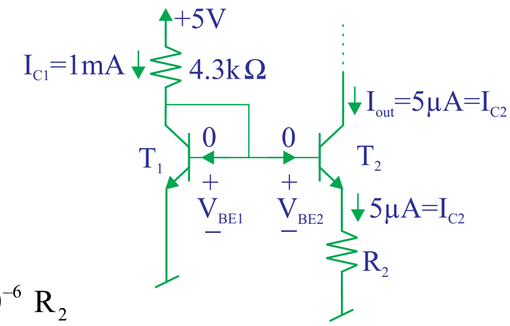


$r_L^* = r_0 \| 8k\Omega$
$= 100k\Omega \| 8k\Omega$
$= 7.4k\Omega$

$$v_2 = -g_m v_\pi r_L^* \; ; \; v_\pi = v_1$$

$$\frac{v_2}{v_1} = -0.04 \times 7.4 \times 10^3 = -296 \quad \text{and} \quad \left|\frac{v_2}{v_1}\right| = \mathit{296}$$

Q6. $I_C = I_S e^{V_{BE}/V_T}$ and $V_{BE} = V_T \ln(I_C/I_S)$



$$V_{BE1} = V_{BE2} + I_{C2} R_2$$

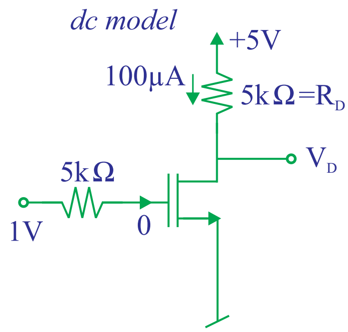
$$V_T \ln\left(\frac{I_{C1}}{I_S}\right) = V_T \ln\left(\frac{I_{C2}}{I_S}\right) + 5\times10^{-6} R_2$$

$$I_{C1} = \frac{5-0.7}{4.3k\Omega} = 1mA$$

$$V_T \ln\left(\frac{I_{C1}}{I_{C2}}\right) = 5\times10^{-6} R_2 \Rightarrow 25\times10^{-3} \ln\left(\frac{10^{-3}}{5\times10^{-6}}\right) = 5\times10^{-6} R_2$$

$$R_2 = 0.02649\times10^6\Omega = \mathit{26.5k\Omega}$$

Q7. Assuming saturation



$$I_D = \frac{1}{2}\mu_n C_{ox} \frac{W}{L}(V_{GS}-V_t)^2$$

$$= \frac{1}{2}\times100\times10^{-6}\times50(1-0.8)^2$$

$$= 100\times10^{-6}\,A = 100\mu A$$

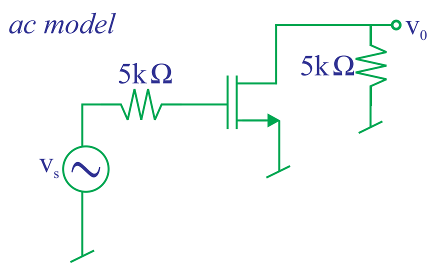
$$V_D = 5 - 100\times10^{-6}\times5\times10^3 = 4.5\,V$$

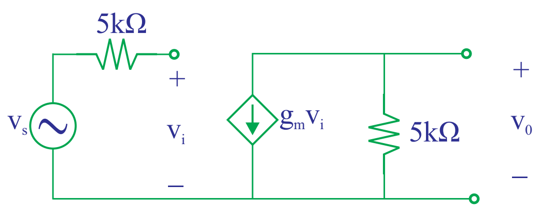
$$V_{GD} = 1 - 4.5 = -3.5\,V$$

Since , $V_{GD} < V_t$, the saturation mode of opration is justified .

$$g_m = \frac{\partial I_D}{\partial V_{GS}} = \mu_n C_{ox}\frac{W}{L}(V_{GS}-V_t) = 100\times10^{-6}\times50(1-0.8) = 10^{-3}\,A/V$$

For $\lambda = 0$, $V_A = \infty$ and $r_0 = \infty$





$$v_0 = -g_m v_i \times 5\times10^3 \;;\; v_i = v_s$$

$$\left|\frac{v_0}{v_s}\right| = 10^{-3}\times5\times10^3 = \mathit{5}$$

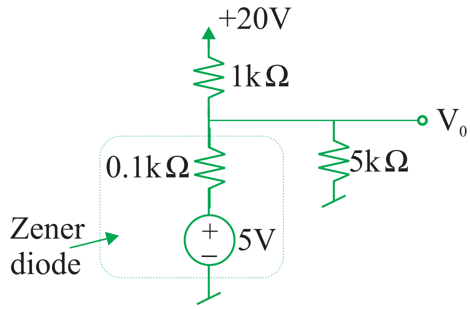
Q8(c). $\dfrac{V_0-20}{1k\Omega}+\dfrac{V_0-0}{5k\Omega}+\dfrac{V_0-5}{0.1k\Omega}=0$

$5V_0-100+V_0+50V_0-250=0$

$V_D=6.25V$

$P_Z=I_Z^{\,2}R_Z+V_ZI_Z\quad ;\ I_Z=\dfrac{6.25-5}{0.1k\Omega}=12.5mA$

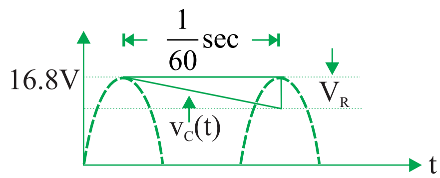
$=I_Z[I_ZR_Z+V_Z]=12.5\ [12.5\times0.1+5]=\mathit{78.125mW}$



Q9. $v_C(t)=(17.8-1)e^{-t/RC}$

$\dot{v}_C(t)=\dfrac{-16.8}{RC}e^{-t/RC}$

$\dot{v}_C(0)=\dfrac{-16.8}{RC}=\dfrac{-V_R}{1/60}$



Peak to peak ripple volttage , $V_R=\dfrac{16.8}{60RC}=\dfrac{16.8}{60\times15\times25000\times10^{-6}}=0.75V$

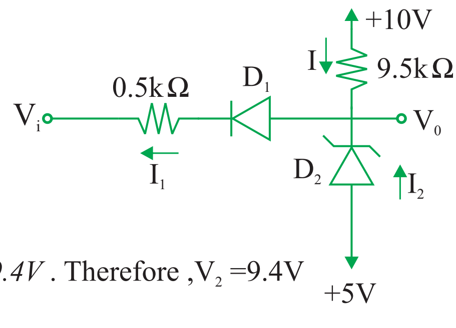
dc output voltage , $V_0=16.8-\dfrac{1}{2}\times0.75=\mathit{16.4V}$

Q10. Until some value of V_i, both diodes D_1 and D_2 are on . Obviously $I_2=(I_1-I)>0$ and $V_0=4.4V$

$I<I_1\Rightarrow\dfrac{10-4.4}{9.5k\Omega}<\dfrac{4.4-0.6-V_i}{0.5k\Omega}\Rightarrow V_i<3.5V$

Thus, $V_1=3.5V$
For $V_i>3.5V$, D_2 turns off

and $\dfrac{V_0-10}{9.5k\Omega}+\dfrac{V_0-0.6-V_i}{0.5k\Omega}=0\Rightarrow V_0=0.95V_i+1.07$



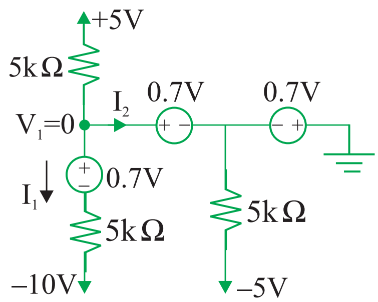
Thus, for $V_i>3.5V$,V_0 linearly increases as V_i increases until V_i equals *9.4V* . Therefore ,V_2 =9.4V
For $V_i>9.4V$, D_1 also turns off and V_0=10V
$|V_1-V_2|=|3.5-9.4|=\mathit{5.9V}$

Q11(d). Assume that all three diodes D_1 ,D_2 and D_3 are on as it appears so .
Thus , the equivalent circuit gives

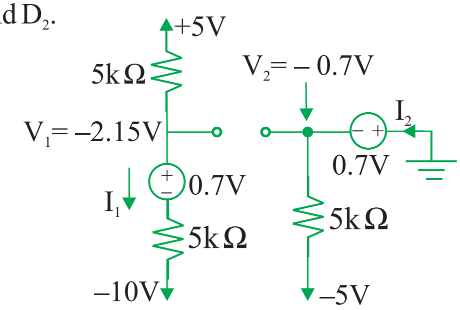
$\dfrac{5-0}{5k\Omega}=\dfrac{0-0.7-(-10)}{5k\Omega}+I_2$

or $I_2=-0.86mA$ which is not possible.

Thus , D_2 is off while D_1 and D_3 are on.



The circuit is redrawn below with D_2 off, to examine the state of diodes D_1 and D_2.

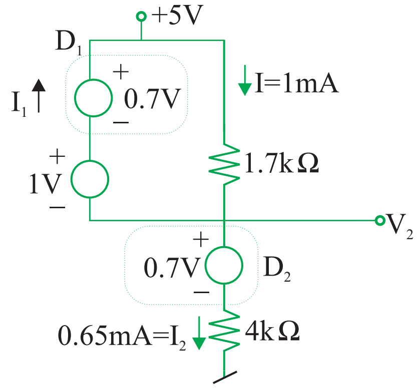


$$I_1 = \frac{5-0.7-(-10)}{5k\Omega+5k\Omega} = 1.43mA$$

$$I_2 = \frac{0-0.7-(-5)}{5k\Omega} = 0.86mA$$

The direction of both currents I_1 and I_2 agree with the direction, the diodes D_1 and D_3 allow the current to flow.
The diodes D_1 and D_3 are, in deed, on and
$V_1 = 5-5\times1.43 = -2.15V$ and $V_2 = -0.7$

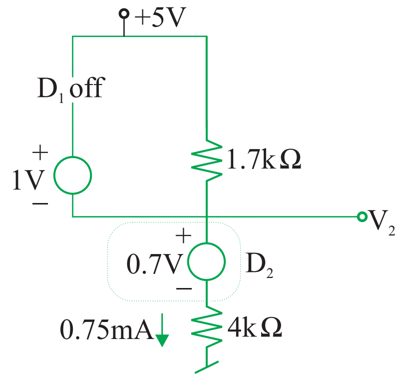
Q12(d). The circuit is sketched below for $V_1 = 5V$ and assuming that both diodes D_1 and D_2 are on.
Note that 1.7V across 1.7kΩ resistance gives



$I = 1mA$, $V_2 = 5-1.7 = 3.3V$ and $I_2 = \frac{3.3-0.7}{4k\Omega} = 0.65mA$

Then, $I_1 = I - I_2 = 1 - 0.65 = 0.35mA$.
But, the direction of I_1 is disallowed by diode D_1. In fact, D_1 is off.

The circuit with only D_2 on, is again sketched below.

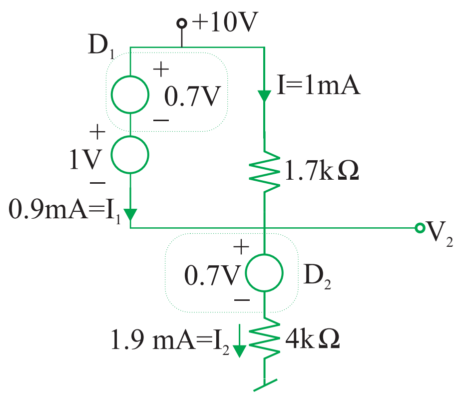


$$\frac{5-V_2}{1.7k\Omega} = \frac{V_2-0.7}{4k\Omega} \Rightarrow V_2 = 3.72V$$

The current through the diode is $\frac{V_2-0.7}{4k\Omega}$ =0.75mA,

the direction of which agrees with the direction in which the diode allows the current to flow.

For $V_2 = 10V$ assuming diodes D_1 and D_2 on, the circuit is sketched below.
Again 1.7V across 1.7kΩ resistance gives I=1mA



$V_2 = 10-1.7 = 8.3V$ and $I_2 = \frac{8.3-0.7}{4k\Omega} = 1.9mA$

$I_1 = I_2 - I = 1.9 - 1 = 0.9$ mA, the direction of which agrees with the direction, the diode D_1 allows the current to flow.
Thus, for $V_2 = 10V$, both diodes D_1 and D_2 are, in deed, on.

Q13(c) On varying V_1, the node voltage V_2 will remain constant equal to 4.8 V only when the transistor is in saturation and $V_{EC} = 5 - 4.8 = 0.2V$.

$$I_{C,sat} = \frac{V_2}{4k\Omega} = \frac{4.8}{4k\Omega} = 1.2mA \text{ and } I_{B,min} = \frac{1.2mA}{80} = 0.015mA$$

$$\text{Base current}, I_B \frac{5 - 0.8 - V_1}{180k\Omega} A = \frac{4.2 - V_1}{180} mA$$

$$\text{For the transistor to be in saturation}, I_B \geq I_{Bmin}, \text{ that is}, \frac{4.2 - V_1}{180} \geq 0.015 \Rightarrow V_1 \leq 1.5V$$

$$\text{Thus } V_2 = 4.8V \text{ for } 0 \leq V_1 \leq 1.5V$$

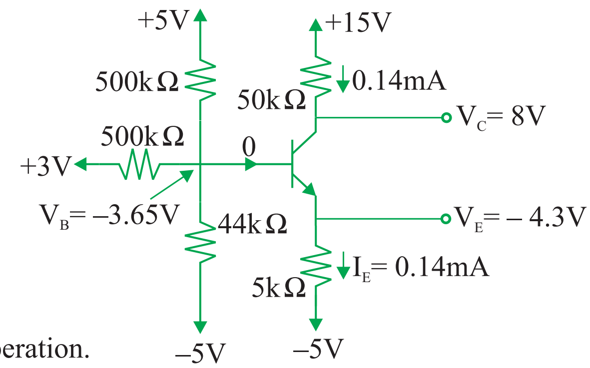
Q14. Assume transistor in active mode of operation.

$$\beta = \infty \Rightarrow I_B = 0$$

$$\frac{5 - V_B}{500k\Omega} + \frac{3 - V_B}{500k\Omega} + \frac{-5 - V_B}{44k\Omega} = 0$$

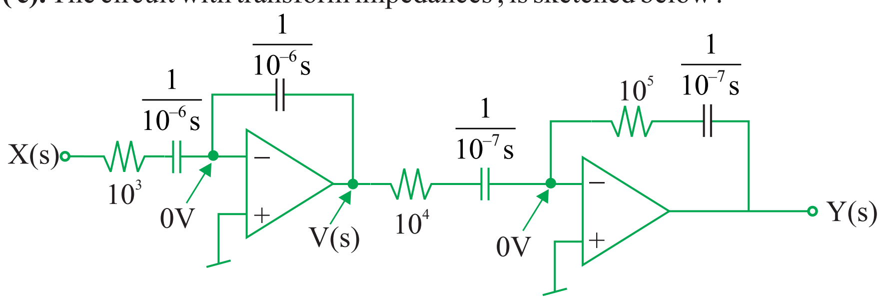
gives $V_B = -3.65V$ and $V_E = -3.65 - 0.65 = 4.3V$

$$I_E = I_C = \frac{-4.3 - (-5)}{5k\Omega} = 0.14mA$$



$V_C = 15 - (0.14 \times 50) = 8V$
$V_{CE} = V_C - V_E = 8 - (-4.3) = 12.3V$
and power dissipation $= V_{CE} \times I_C = 12.3 \times 0.14 = 1.7mW$
Since, $V_{CE} > V_{CE,sat}$, the transistor is ,indeed, in active mode of operation.

Q15 (c). The circuit with transform impedances , is sketched below .



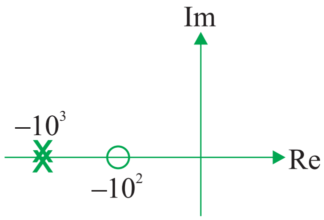
$$\frac{X(s) - 0}{10^3 + \frac{1}{10^{-6}s}} = \frac{0 - V(s)}{\frac{1}{10^{-6}s}} \Rightarrow V(s) = \frac{-X(s)}{10^{-3}s + 1}$$

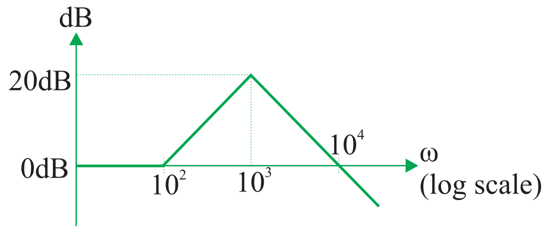
$$\frac{V(s) - 0}{10^4 + \frac{1}{10^{-7}s}} = \frac{0 - Y(s)}{10^5 + \frac{1}{10^{-7}s}} \Rightarrow V(s) = \frac{-Y(s)(10^{-3}s + 1)}{10^{-2}s + 1}$$

$$\text{Now}, \frac{-X(s)}{10^{-3}s + 1} = \frac{-Y(s)(10^{-3}s + 1)}{(10^{-2}s + 1)} \Rightarrow H(s) = \frac{Y(s)}{X(s)} = \frac{10^{-2}s + 1}{(10^{-3}s + 1)^2} = \frac{s + 10^2}{(s + 10^3)^2}$$

$$\text{and } H(j\omega) = \frac{10^{-2}(j\omega) + 1}{\left[10^{-3}(j\omega) + 1\right]^2}$$

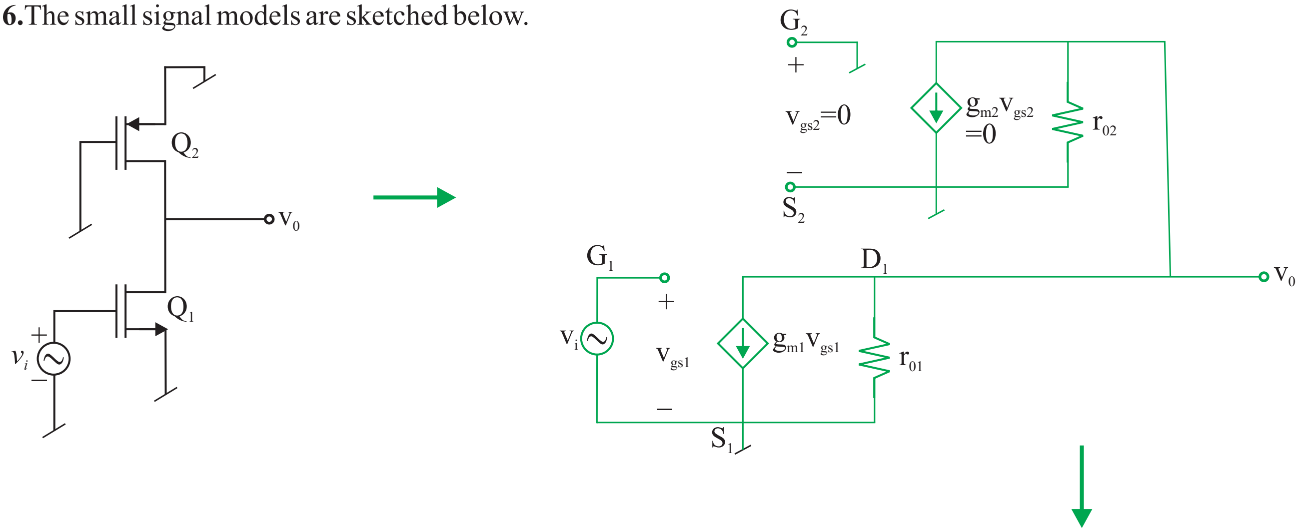
The Bode dB plot and pole-zero plot, both are depicted below.





It is obvious that the component of frequency 10^3 rad/sec , is the most amplified with the gain of 20dB in the output. The components of 100 rad / sec and 10^4 rad/sec , are treated with 0dB (unity)gain .

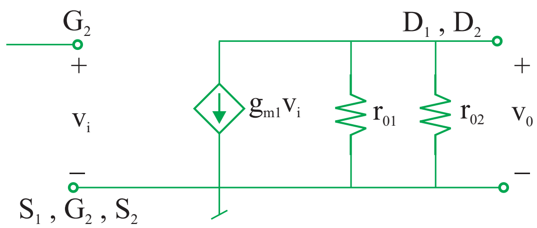
Q16. The small signal models are sketched below.



$$v_0 = -g_{m1}\ v_i\,(r_{01} \| r_{02})$$

$$\left|\frac{v_0}{v_i}\right| = g_{m1}\,(r_{01} \| r_{02})$$

$$g_{m1} = \frac{\partial I_{D1}}{\partial V_{GS1}} = \mu_n C_{ox}\frac{W}{L}\left(V_{GS1} - V_{tn}\right) = 2\times10^{-3}(4-2) = 4\,mA/V$$



$$r_{01} = (\lambda_1\ I_{D1})^{-1}\ \text{where}\ I_{D1} = \frac{1}{2}\mu_n C_{ox}\frac{W}{L}\left(V_{GS1} - V_{tn}\right)^2 = \frac{1}{2}\times 2\times10^{-3}(4-2)^2 = 4mA$$

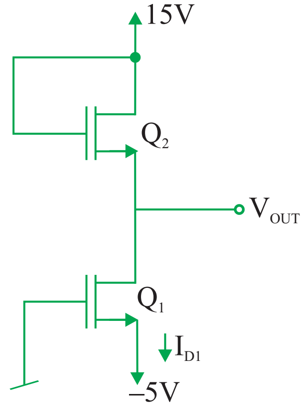
$$r_{01} = (0.01\times 4mA)^{-1} = 25k\Omega$$

$$r_{02} = (\lambda_2\ I_{D2})^{-1} = (\lambda_2\ I_{D1})^{-1} = (0.025\times 4mA) = 10k\Omega$$

$$\left|\frac{v_0}{v_i}\right| = 4\times10^{-3}\times\frac{25\times10}{25\times10}\times10^3 = \mathit{28.6}$$

Q17(b). Assume Q1 in saturation mode.

dc model



$$I_{D1} = \frac{1}{2}\mu_e C_{ox}\left(\frac{W}{L}\right)_1 (V_{GS1} - V_{t1})^2 \; ; \quad V_{GS1} = 5V$$

$$= \frac{1}{2} \times 3.2 \times 10^{-3} (5-3)^2 = 6.4mA$$

$$I_{D2} = I_{D1} = \frac{1}{2}\mu_e C_{ox}\left(\frac{W}{L}\right)_2 (V_{GS2} - V_{t2})^2$$

$$6.4 \times 10^{-3} = \frac{1}{2} \times 0.4 \times 10^{-3} (V_{GS2} - 3)^2$$

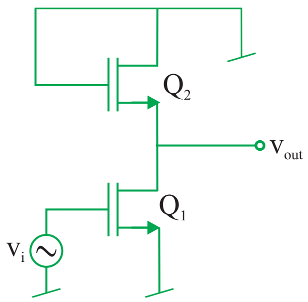
$(V_{GS2} - 3) = \pm 5.66 \;\Rightarrow V_{GS2} = 8.66V$ or $-2.66V$

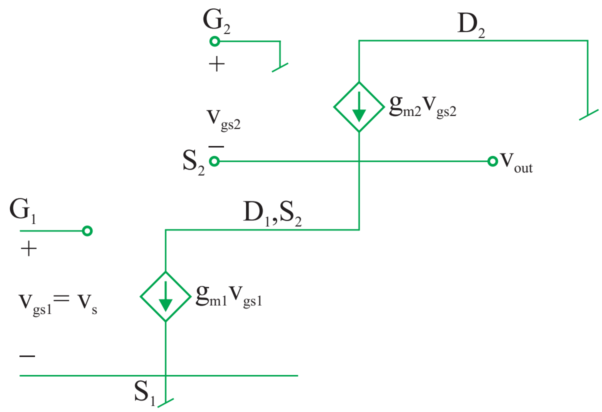
V_{GS2} can not be $-2.66V$. Thus, $V_{GS2} = 8.66V$

$V_{GS2} = 15 - V_{OUT} \Rightarrow V_{OUT} = 6.34V = \lambda$

$V_{GD1} = 0 - V_{OUT} = -6.34V < V_{t1}$ and therefore, Q_1 is, in deed, in saturation.

ac model





$$\frac{v_0}{v_s} = \frac{-v_{gs2}}{v_{gs1}} = -\frac{g_{m1}}{g_{m2}} \; ; \; i_{d1} = i_{d2} \Rightarrow g_{m1}v_{gs1} = g_{m2}v_{gs2}$$ under no load condtion.

$$I_{D1} = \frac{1}{2}\mu_e C_{ox}\left(\frac{W}{L}\right)_1 (V_{GS} - V_{t1})^2 \text{ and } g_{m1} = \frac{\partial I_{D1}}{\partial V_{GS1}} = \mu_e C_{ox}\left(\frac{W}{L}\right)_1 (V_{GS} - V_{t1}) = \sqrt{2I_{D1}\mu_e C_{OX}\left(\frac{W}{L}\right)_1}$$

Similarly, $g_{m2} = \sqrt{2I_{D2}\mu_e C_{OX}\left(\frac{W}{L}\right)_2}$

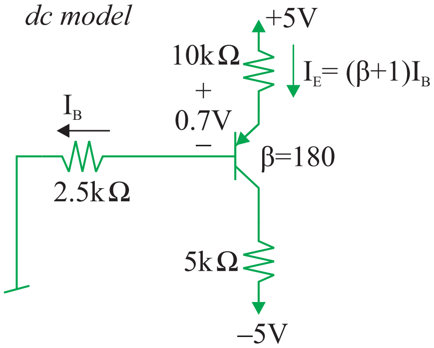
$$\frac{v_0}{v_s} = -\frac{\sqrt{2I_{D1}\mu_e C_{OX}\left(\frac{W}{L}\right)_1}}{\sqrt{2I_{D2}\mu_e C_{OX}\left(\frac{W}{L}\right)_2}} = -\sqrt{\left(\frac{3.2}{0.4}\right)} = -2.8$$

$v0 = -2.8 \times 0.5 \sin \omega t = -1.4 \sin \omega t \Rightarrow \mu = -1.4$

Thus, $\lambda = 6.34$ and $\mu = -1.4$

Q18(a).

dc model

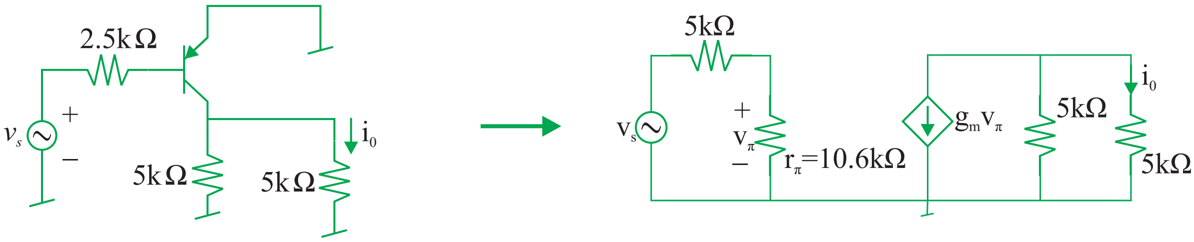


$$I_{BQ} = \frac{5-0.7}{(180+1)\times 10k\Omega + 2.5k\Omega} = 2.37\mu A$$

$$I_{CQ} = \beta I_{BQ} = 180\times 2.37\mu A = 0.427mA$$

$$g_m = \frac{I_{CQ}}{V_T} = \frac{0.427mA}{25mV} = 0.017A/V$$

$$r_\pi = \frac{\beta}{g_m} = \frac{180}{0.017} = 10.6k\Omega$$



$$i_0 = -\frac{1}{2} g_m v_\pi = -0.5\times 0.017\times \frac{10.6}{10.6+2.5} v_s = -6.88\times 10^{-3} v_s$$

$$i_0 = -6.88\times 10^{-3}\times (4\sin\,\omega t)\times 10^{-3} A = -27.52\ \sin\omega t\ \mu A$$

$$\lambda = -27.52$$

Q19(b).

$$\frac{V_X(s)-V(s)}{1k\Omega} = \frac{V(s)-V_Y(s)}{1k\Omega}$$

$$V(s) = 0.5V_X(s) + 0.5V_Y(s)$$

$$\text{and } \frac{V_X(s)-V(s)}{R} = \frac{V(s)-0}{1/Cs}$$

$$V_X(s) = V(s)\ (1+s\ RC)$$

$$V_X(s) = [0.5V_X(s) + 0.5V_Y(s)](1+sRC)$$

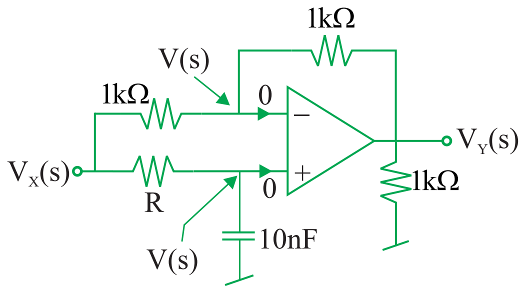
$$V_X\ (s)\ [1-0.5-0.5s\ RC] = 0.5(1+s\ RC)\,V_Y(s)$$

$$\frac{V_Y(s)}{V_X(s)} = H(s) = \frac{1-sRC}{1+sRC} \text{ and } H(j\omega) = \frac{1-j\omega RC}{1+j\omega RC}$$

$$|H(j\omega)| = 1 \text{ and } \angle H(j\omega) = -2\tan^{-1}\omega RC$$

$$-2\tan^{-1}\ \omega RC = -\frac{\pi}{6} \Rightarrow 10^4\times R\times 10\times 10^{-9} = \tan\left(\frac{\pi}{12}\right) \Rightarrow R = 2.68k\Omega$$

$$|H(j\omega)| = -1 \text{ regardless of } \omega \text{ and therefore}, \lambda = 0.1$$

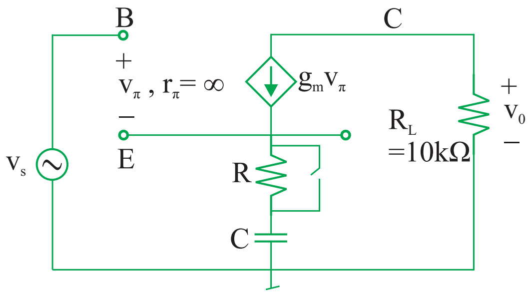


Q20.

$$g_m = \frac{I_C}{V_T} = \frac{1mA}{25mV} = 0.4\,A/V\ ,\ \alpha = 1 \Rightarrow r_\pi = \infty \text{ and } V_A = \infty \Rightarrow r_0 = \infty$$

SW closed implies $R = 0$ and $v_0 = -g_m v_\pi R_L$

KVL around input loop gives



$$v_s - v_\pi - g_m v_\pi \times \frac{1}{j\omega C} = 0$$

$$v_\pi = \frac{v_s \times j\omega C}{g_m + j\omega C}$$

$$v_0 = (-g_m R_L)\ v_s \left[\frac{j\omega C}{g_m + j\omega C}\right]$$

$$\frac{v_0}{v_s} = \frac{-g_m R_L}{1 - j\frac{g_m}{\omega C}} \Rightarrow \omega_L = \frac{g_m}{C} \text{ on comparing with general form of gain } |A_v| = \left|\frac{v_0}{v_s}\right| = \frac{A_0}{1 - j\frac{\omega_L}{\omega}}$$

With SW open , again $v_0 = -g_m v_\pi R_L$ and $v_s - v_\pi - g_m v_\pi \left(R + \frac{1}{j\omega C}\right) = 0$

$$v_\pi = \frac{v_s \times j\omega C}{g_m + j\omega C(1 + g_m R)} \text{ and } v_0 = -g_m R_L v_s \left[\frac{j\omega C}{g_m + j\omega C(1 + g_m R)}\right]$$

$$\left|\frac{v_0}{v_s}\right| = \frac{g_m R_L}{(1 + g_m R) + \frac{g_m}{j\omega C}} = \frac{\frac{g_m R_L}{1 + g_m R}}{1 - \frac{j}{\omega} \times \left[\frac{g_m}{(1 + g_m R)C}\right]} \Rightarrow \omega^*_L = \frac{g_m}{(1 + g_m R)C}$$

$$\omega^*_L = 0.2\omega_L \Rightarrow \frac{g_m}{(1 + g_m R)C} = 0.2\frac{g_m}{C} \Rightarrow 1 + g_m R = 5 \text{ and } R = \frac{4}{g_m} = \frac{4}{0.04} = 100\Omega$$

Q21(c). *Fig.(1)* ; Let the input signal to block with gain $A_1 = 10^3$ be v_E.

$$v_0^* = A_1 A_1 v_E + A_2 v_{ni}\ ,\ v_E = v_i - \beta v^*_0$$

$$v_0^* = A_1 A_2 v_i - A_1 A_2 \beta v^*_0 + A_2 v_{ni}$$

$$v_0^* = \frac{A_1 A_2}{1 + A_1 A_2 \beta} v_i + \frac{A_2}{1 + A_1 A_2 \beta} v_{ni} = \frac{10^4}{1 + 10^2} v_i + \frac{10}{1 + 10^2} v_{ni} \cong 100 v_i + 0.1 v_{ni}$$

$$(SNR)_o = \frac{100}{0.1} \times \frac{v_i}{v_{ni}} = 1000(SNR)_i$$

Fig.(2); $v^*_0 = A_1 A_2 v_E = A_1 A_2 \left[v_i + v_{ni} - \beta v^*_0\right]$

$$v^*_0 = \frac{A_1 A_2}{1 + A_1 A_2 \beta} v_i + \frac{A_1 A_2}{1 + A_1 A_2 \beta} v_{ni} = \frac{10^4}{1 + 10^4 \times 0.01} v_i + \frac{10^4}{1 + 10^4 \times 0.01} v_i \cong 100 v_i + 100 v_{ni}$$

$$(SNR)_o = \frac{100}{100} \times \frac{v_i}{v_{ni}} = (SNR)_i$$

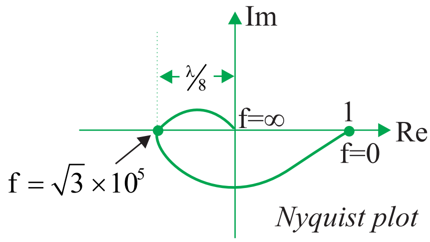
Amplifier configuration of Fig(1) has better noise immunity.

Q22(d). $T(f) = |T(f)| \angle T(f) = \dfrac{\lambda}{(1+10^{-10}f^2)^{3/2}} \angle -3\tan^{-1}10^{-5}f$

$-3\tan^{-1}10^{-5}f = -180^\circ$ gives $f = 10^5 \tan 60^\circ = \sqrt{3}\times 10^5\,\text{Hz}$

$$|T(f)|_{f=\sqrt{3}\times10^5} = \frac{\lambda}{\left[1+10^{-10}\times\left(\sqrt{3}\times10^5\right)^2\right]^{\frac{3}{2}}} = \frac{\lambda}{8}$$

For the amplifier to be stable $\dfrac{\lambda}{8} < 1$ or $\lambda < 8$.



Nyquist plot

Q23. For $v_0 = 0$, $I_{D3} = 2\text{mA} = \dfrac{1}{2}\mu_n C_{ox}\dfrac{W}{L}(V_{GS3} - V_T)^2$

$2\times10^{-3} = \dfrac{1}{2}\times 2\times10^{-3}(V_{GS3}-1)^2 \Rightarrow V_{GS3} = -0.414\text{V or } 2.414\text{V}$

V_{GS3} must be greater than $V_T = 1\text{V}$. Thus, $V_{GS3} = 2.414\text{V}$

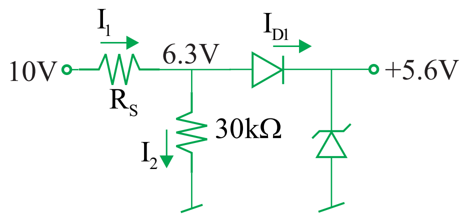
$V_{G3} = 2.414\text{V}$ and current I_{D2} in M_2 is 0.5mA.

$R = \dfrac{12 - V_{G3}}{0.5\text{mA}} = \dfrac{12-2.414}{0.5\text{mA}} = 19.2k\Omega$

Note that $V_{GD3} = V_{G3} - V_{D3} = 2.414 - 12 = -9.586\text{ V} < V_T$.

M_3 is , indeed, in saturation.

Q24(c). $V_0 = V_Z\left[1 + \dfrac{32k\Omega}{40k\Omega}\right] = 5.6\times1.8 \cong 10\text{V}$



Set I_F for minimum bias current of 1mA to get

$R_F = \dfrac{10-5.6}{1\text{mA}} = 4.4k\Omega$

The maximum Zener current should be no more than 1.25mA.

Set $I_{D1} = 0.25\text{mA}$

$I_2 = \dfrac{5.6+0.7}{30k\Omega} = 0.21\text{mA}$

$I_1 = \dfrac{10-6.3}{R_S} = (0.21+0.25)\text{ mA} \Rightarrow R_S \cong 8k\Omega$

Q25. $I_X = \dfrac{V_1 - V_2}{R} \Rightarrow \dfrac{0.25-(-0.25)}{R} = 5\text{mA} \Rightarrow R = 100\Omega$

$\dfrac{V_{01}-V_1}{R_2} = I_X \Rightarrow V_{01} = V_1 + I_X R_2 = 0.25 + 5\times10^{-3}\times1000 = 5.25\text{V}$

$V_{02} = -0.25\text{V}$ and $V_{01} - V_{02} = 5.25 - (-0.25) = 5.5V$