Topic: Op-Amp

1. Determine the expressions/values of v_o (V_0) in the following circuits:

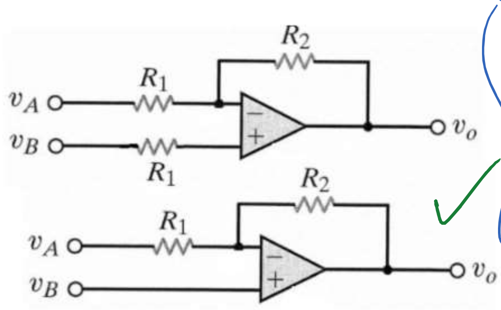


Fig. 1a (i & ii)

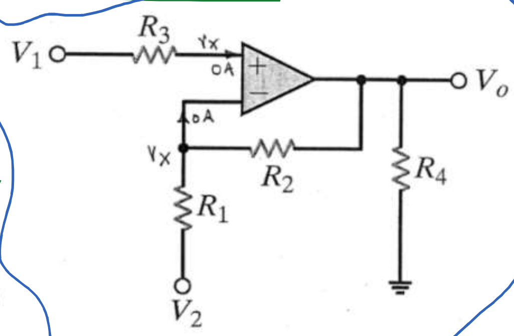


Fig. 1b

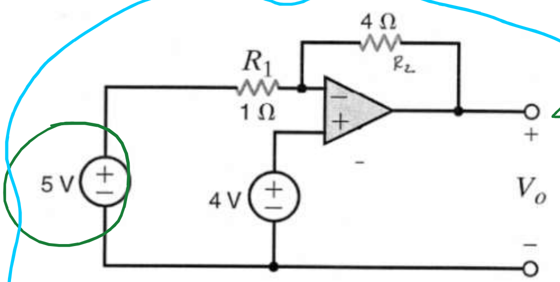


Fig. 1c

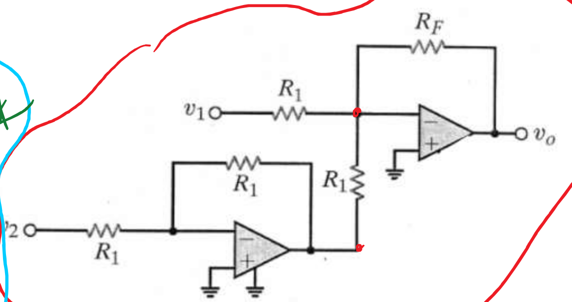


Fig. 1d

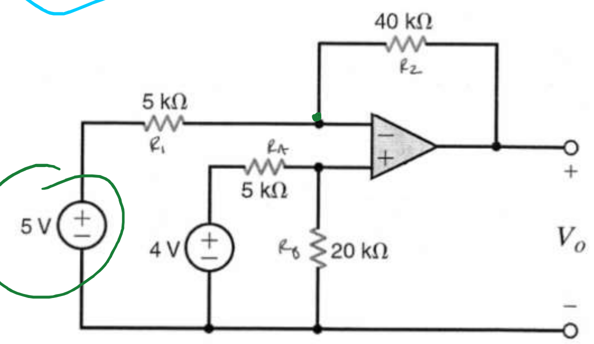


Fig. 1e

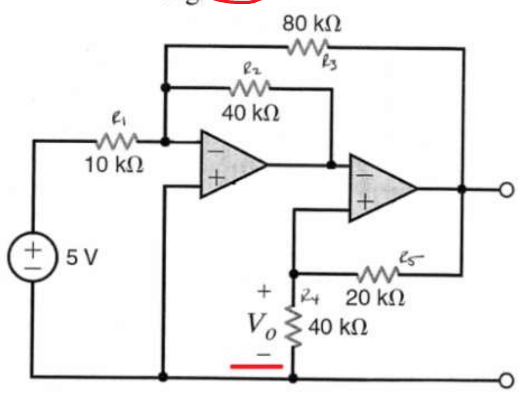
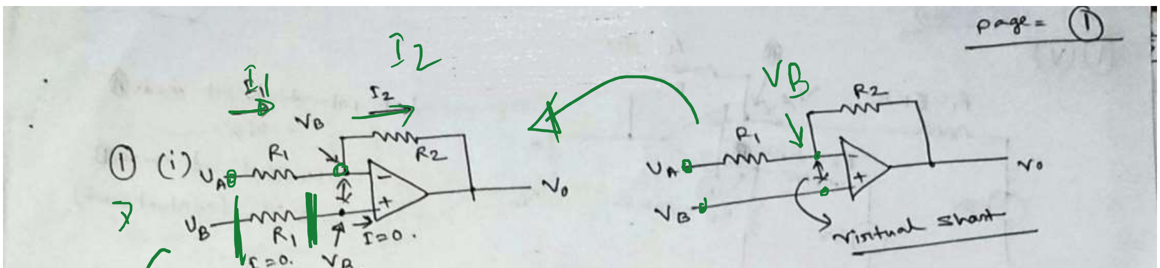


Fig. 1f



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① (i)

virtual short

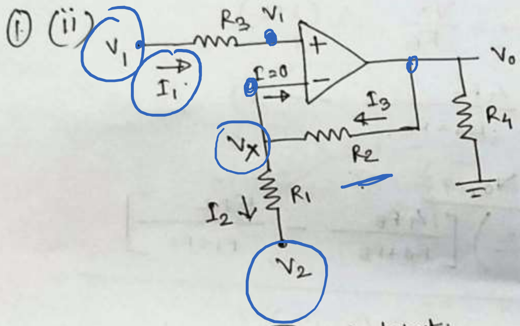
Same as

$$\frac{V_A - V_B}{R_1} = \frac{V_B - V_0}{R_2} \; ; \; (\text{as } I_1 = I_2)$$

$$V_0 = \left(1 + \frac{R_2}{R_1}\right) V_B - \frac{R_2}{R_1} V_A$$

$V_0 = \left(1 + \frac{\;}{R_1}\right) \ldots \frac{\;}{R_1} \ldots$

1 (ii)



as, $I_1 = I = 0$.

$V_x = V_1$ (virtual short).

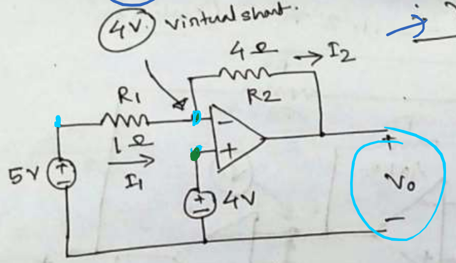
$I_2 = I_3$

$$\therefore \frac{V_x - V_2}{R_1} = \frac{V_0 - V_x}{R_2}$$

$$V_0 = \frac{V_x R_2 - V_2 R_2 + V_x R_1}{R_1}$$

$$\therefore V_0 = \left(1 + \frac{R_2}{R_1}\right) V_1 - \frac{R_2}{R_1} V_1$$

1 (iii)

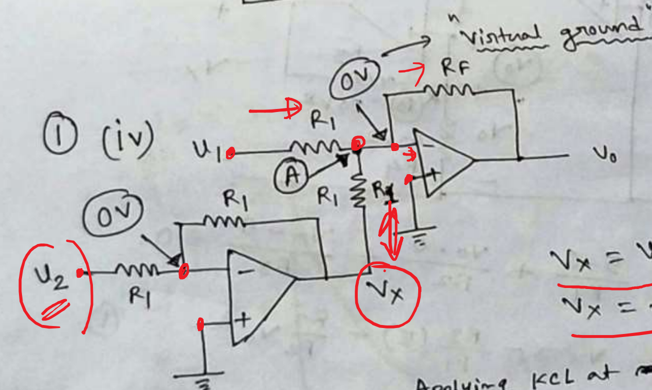


as, $I_1 = I_2$.

$$\therefore \frac{5-4}{1} = \frac{4 - V_0}{4}$$

$$\therefore V_0 = 0.$$

1 (iv)



$$V_x = V_2 \times \left(-\frac{R_1}{R_1}\right)$$

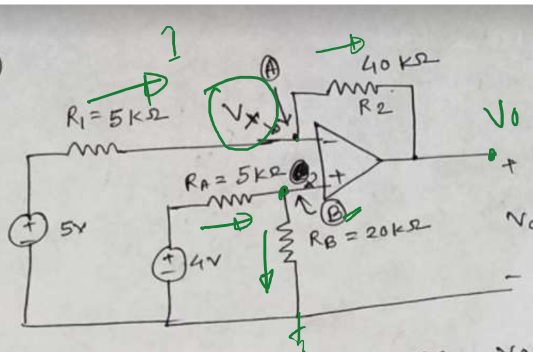
$$V_x = -V_2$$

Applying KCL at node A,

$$\frac{V_1 - 0}{R_1} + \frac{V_x - 0}{R_1} = \frac{0 - V_0}{R_F}$$

$$\therefore V_0 = -\frac{R_F}{R_1}(V_1 - V_2)$$

1 (v)



Let potential at node (A) $= V_x$

So, potential at node (B) $= V_x$ (virtual short)

At, node (A), $\dfrac{5-V_x}{R_1} = \dfrac{V_x - V_0}{R_2}$ (KCL)

$\therefore V_x = \left(\dfrac{R_2}{R_1+R_2}\right)\cdot 5 + \left(\dfrac{R_1}{R_1+R_2}\right) V_0$ — (1)

At, node (B), $\dfrac{4-V_x}{R_A} = \dfrac{V_x}{R_B}$; (KCL)

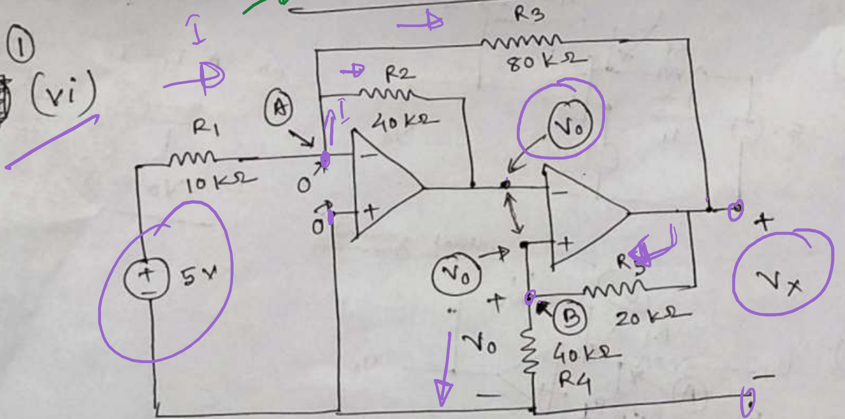
$\therefore V_x = \dfrac{4R_B}{R_A+R_B}$ — (2)

From, (1) & (2), Find V_0.

$$V_0 = \left(\frac{R_1+R_2}{R_1}\right)\left[\frac{4R_B}{R_A+R_B} - \frac{5R_2}{R_1+R_2}\right]$$

$V_0 = -11.2$ V. (value).

1 (vi)



At node (A), $\dfrac{5-0}{R_1} + \dfrac{V_0 - 0}{R_2} + \dfrac{V_x - 0}{R_3} = 0.$

$\therefore V_x = -\dfrac{R_3}{R_1}(5) - \dfrac{R_3}{R_2} V_0$ ----- (1)

At node (B), $\dfrac{V_0}{R_4} + \dfrac{V_0 - V_x}{R_5} = 0.$

$V_x = V_0\left(1 + \dfrac{R_5}{R_4}\right)$ --- (2)

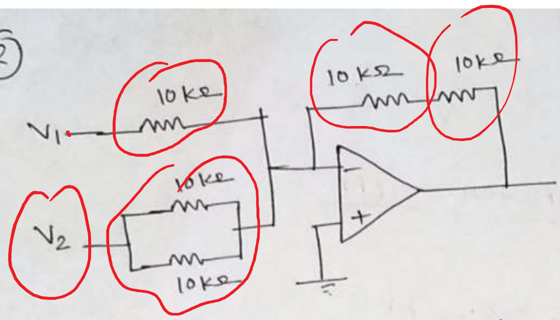
From (1) and (2), find V_0.

$V_0 = -11.43$ V.

2. You have given a bunch of 10 kΩ resistors and an Op-Amp. Design a circuit that will produce the following output (V_0). $V_0 = -2V_1 - 4V_2$

$V_0 = -(2V_1 + 4V_2)$

(2)



$V_o = -20\left(\frac{V_1}{10} + \frac{V_2}{10 \| 10}\right)$

$V_o = -2V_1 - 4V_2$.

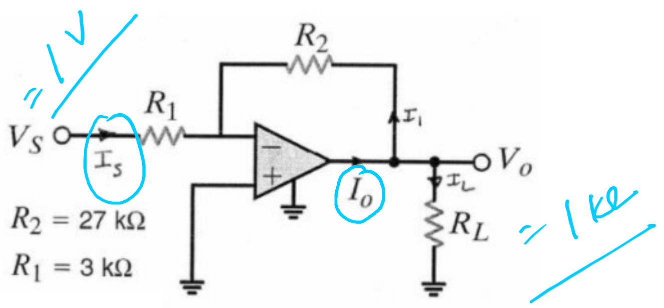
$V_o = -2(V_1 + 2V_2)$

4

$\left(-\frac{R_f}{R_1} V_1\right)$

(small correction in the question)

3. In the Op-Amp circuit shown in Fig. 2, find I_0 and I_S if V_S = 1 V and R_L = 1 kΩ. Also, plot the variation of I_0 with R_L.



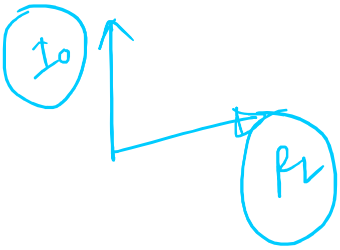
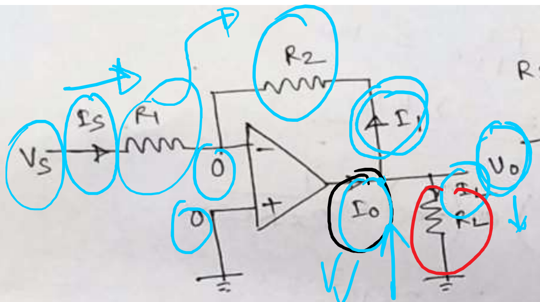


Fig. 2

(3)



$R_2 = 27k\Omega$
$R_1 = 3k\Omega$.

$R_L = 1k\Omega$.

$V_s = 1V$.

R_L

$V_o = -\frac{R_2}{R_1} V_s = -\left(\frac{27}{3}\right) \cdot 1 = -9V$

$I_L = -\frac{9V}{1k\Omega} = -9 mA$.

$I_1 = \frac{-9-0}{R_2} = \left(-\frac{9V}{27k}\right) = -0.33 mA$.

$-\frac{9}{R_L}$

$I_o = I_1 + I_L = -9.33 mA$.

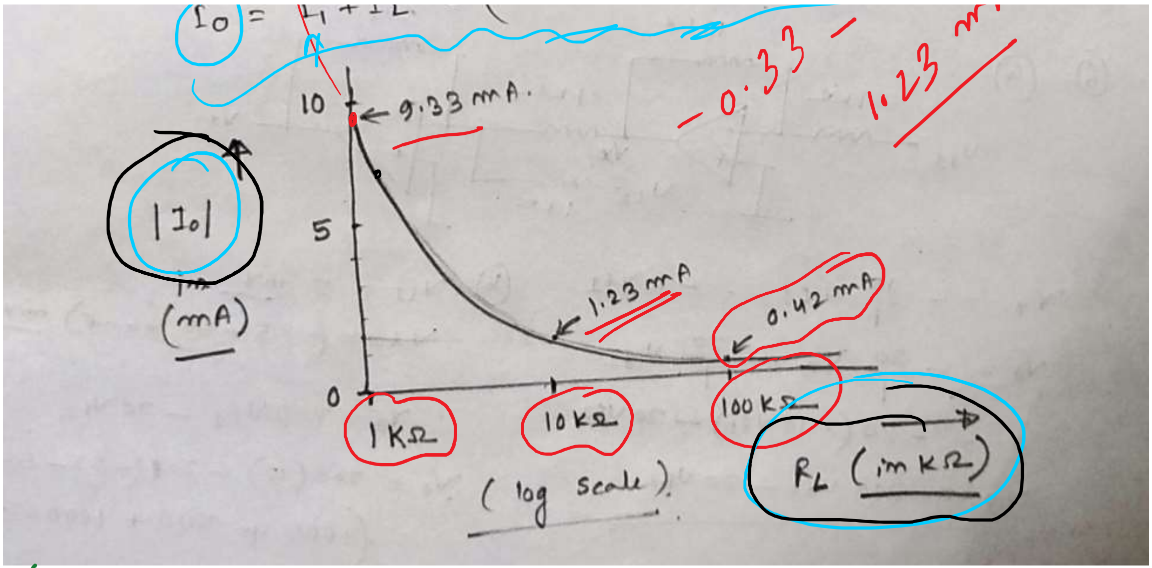
$I_s = -I_1 = 0.33 mA$.

$I_o = I_1 + I_L = \left(-0.33 - \frac{9}{R_L}\right)$ in mA.

0.9

0.33 –

1.23 mA



4. Fig. 3 shows a low-pass filter. Estimate the value of feedback resistor R_2 such that the 'pass-band' gain of the total circuit is 100. Given that $C = 0.2$ µF and $R_1 = 1$ kΩ. Also calculate the value of resistor R for realizing a cut-off frequency of 2 kHz.

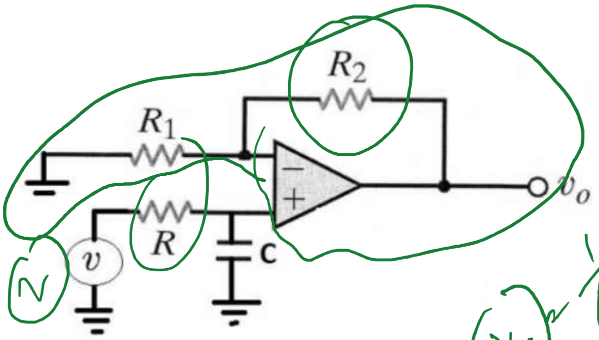
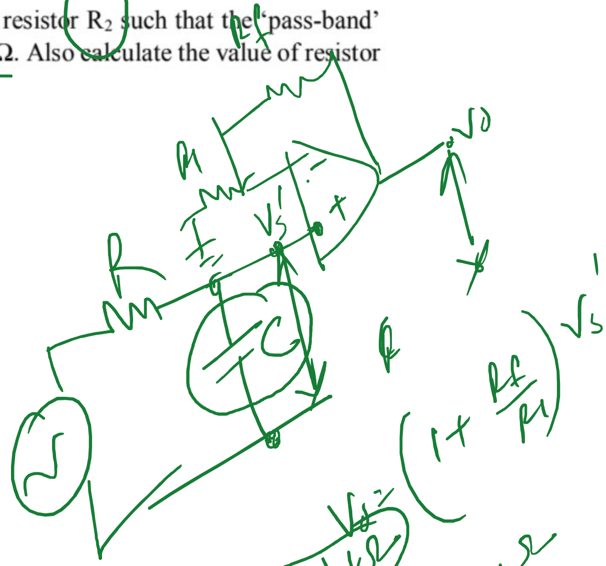
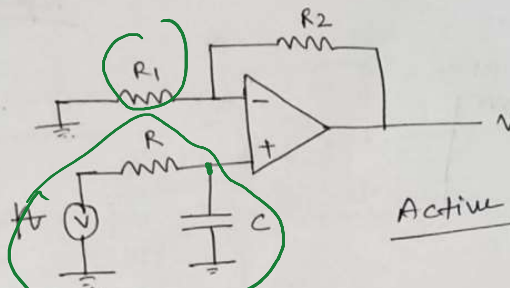


Fig. 3



④



Active 'LPF'

$R_1 = 1\ \text{k}\Omega$, $C = 0.2\ \mu F$

pass-band gain = 100 = gain of the non-inverting amplifier.

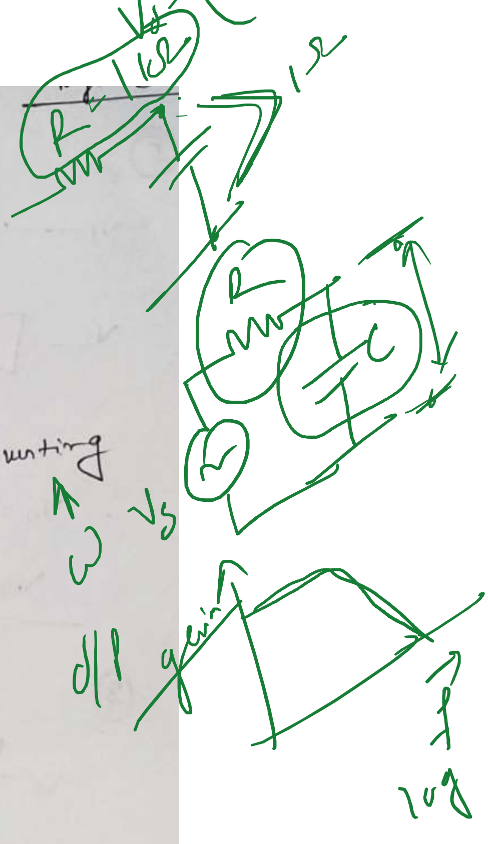
$$A = \left(1 + \frac{R_2}{R_1}\right) = 100$$

$$\therefore 1 + \frac{R_2}{1\,\text{k}\Omega} = 100$$

$$R_2 = 99\ \text{k}\Omega.$$

Cut-off frequency (f_T) or $(f_c) = \dfrac{1}{2\pi RC}$

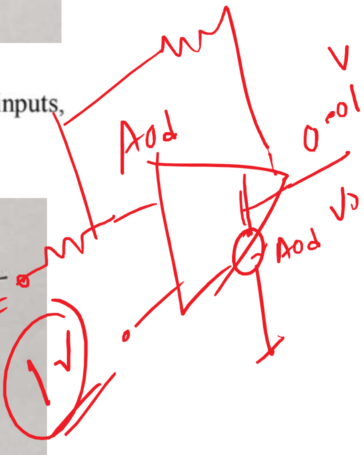
$$\therefore \frac{1}{2\pi RC} = 2 \times 10^3$$



$\therefore \frac{1}{2\pi RC} = 2\times10^{3}$

$\therefore R = 398\ \Omega.$

5. For an Op-Amp, the differential gain (A_d) is 100. When 1 V is applied (common) to both the inputs, the output voltage measured is 0.01 V. Calculate the CMRR of the Op-Amp in dB.



(5) Differential gain $= 100 = A_d$

Common mode gain $(A_c) = \frac{V_{out}}{V_{in}} = \frac{0.01}{1} = 10^{-2}$

$\therefore$ So, $CMRR = \left|\frac{A_d}{A_c}\right| = \frac{100}{10^{-2}} = 10^{4}$

$\therefore (CMRR)_{dB} = 20\log\left|\frac{A_d}{A_c}\right| = 80\ dB.$

6. Consider the circuit in Fig. 4, (a) Derive the expression for the output voltage v_O in terms of v_{I1} and v_{I2}. (b) Determine v_O for v_{I1} = +5 mV and v_{I2} = (−25 − 50 sinωt) mV.

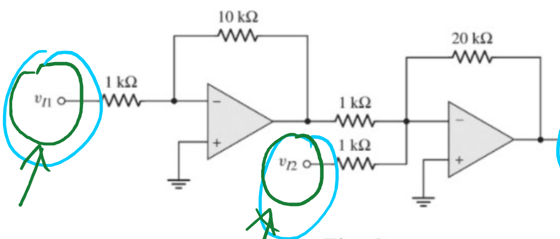


Fig. 4

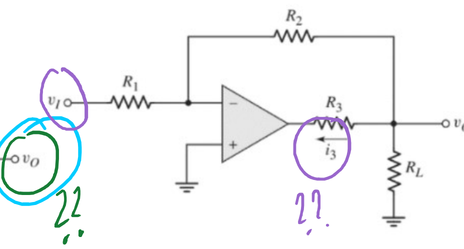


Fig. 5

7. In the circuit shown in Fig. 5, derive the expression for i_3 in terms of v_I.

$V_0 = -\frac{20}{R_1}V_x - \frac{20}{R_2}V_{i2}$

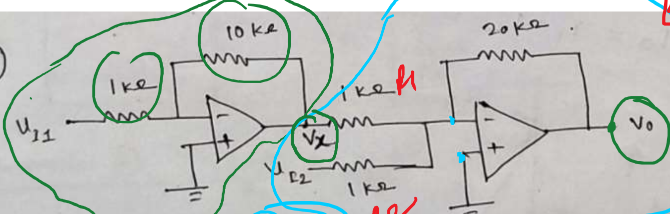
$V_0 = -\frac{20}{1}(V_x + V_{I2})$

$V_0 = -20V_x - 20V_{I2}$

$V_0 = -20(-10V_{i1}) - 20V_{i2}$

$V_0 = -200V_{i1} - 20V_{i2}$

(6) (a)



$V_x = -\frac{10}{1}V_{I1} = -10V_{I1}$

$V_0 = -\frac{20}{1}V_x - \frac{20}{1}V_{I2}$

$= -20(-10V_{I1}) - 20V_{I2}$

$\therefore V_0 = 200V_{I1} - 20V_{I2}$

(b) $V_{I1} = 5$ mV.

$V_{I2} = (-25 - 50\sin\omega t)$ mV

$\therefore V_0 = 200V_{I1} - 20V_{I2}$

$V_0 = 200(5) - 20(-25 - 50\sin\omega t)$

$= (1000 + 500 + 1000\sin\omega t)$ mV

$V_0 = (1.5 + \sin\omega t)$ V.

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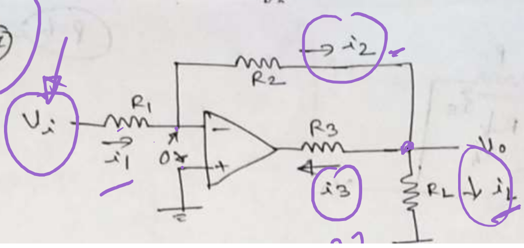
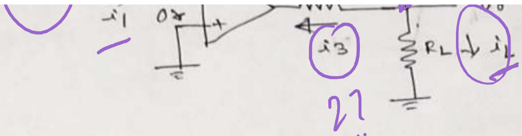
(7) (P-5)



$i_1 = \frac{V_i}{R_1}$; $i_2 = \frac{0 - V_0}{R_2}$

$i_1 = i_2$

$\therefore \frac{V_i}{R_1} = -\frac{V_0}{R_2}$



$\therefore \frac{V_i}{R_1} = -\frac{V_o}{R_2}$

$\therefore V_o = -\frac{R_2}{R_1} V_i$

$i_L = \frac{V_o}{R_L}$

again, $i_2 = i_3 + i_L$

$\therefore \frac{V_i}{R_1} = i_3 + \frac{V_o}{R_L}$

$\therefore \frac{V_i}{R_1} = i_3 - \frac{R_2}{R_1 R_L} V_i$

$\therefore i_3 = \frac{V_i}{R_1}\left(1 + \frac{R_2}{R_L}\right)$

$\boxed{20\,mA}$

8. Consider the circuit shown in Fig. 6. (a) Determine the ideal voltage gain. (b) Find the actual gain if the open-loop gain (A_{od}) of the op-amp is $A_{od} = 5 \times 10^3$. (c) Determine the required value of A_{od} in order that the actual voltage gain be within 0.2 percent of the ideal value.

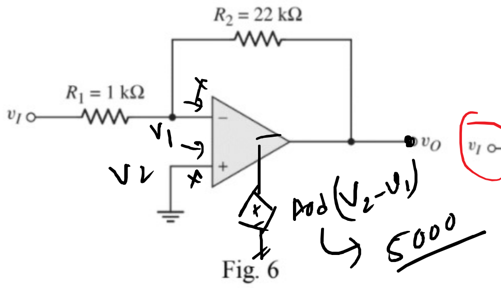


Fig. 6

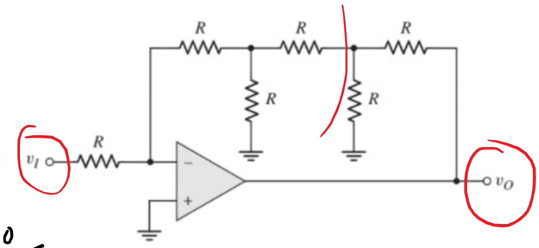
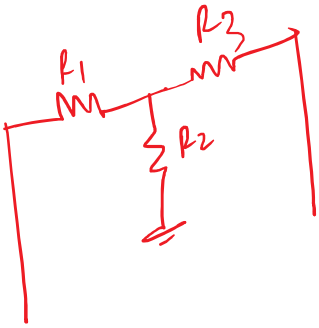
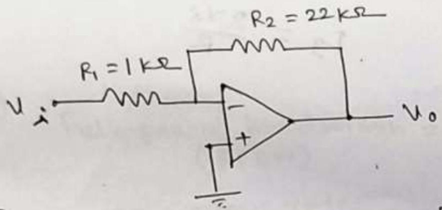


Fig. 7



9. For the inverting op-amp amplifier shown in Fig. 7, determine the gain $A_v = v_O/v_I$.

(8)



(a) Considering the op-amp as ideal, the gain is $= \left(-\frac{R_2}{R_1}\right)$

$= -\frac{22}{1} = -22$

(b) Actual gain $= -\frac{R_2}{R_1} \times \frac{1}{\left[1 + \frac{1}{A_{od}}\left(1 + \frac{R_2}{R_1}\right)\right]}$; [we have derive this in the class]

where, A_{od} = open-loop gain.

$= -22 \times \frac{1}{1 + \frac{1}{5 \times 10^3}(1 + 22)}$

$= -21.9$

(c) Gain $= -22 \pm 0.2\%$ $= -22 \pm 0.044$ $= \begin{matrix} -21.956 \\ -22.044\ (x) \end{matrix}$

$\therefore -21.956 = -22 \times \frac{1}{1 + \frac{1}{A_{od}} \times 23}$

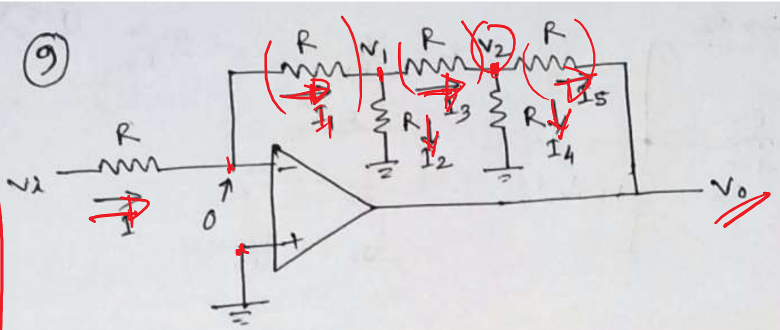
$\therefore 23/A_{od} = 1.002 - 1$

$\therefore A_{od} = 11.4 \times 10^3$

(P-6)

P-6

(9)



$I = \frac{v_i - 0}{R} = \frac{v_i}{R} = I_1$

$\therefore V_1 = 0 - I_1 R$

$V_1 = -\frac{v_i}{R} \times R = -v_i$

$\therefore I_2 = \frac{V_1}{R} = -\frac{v_i}{R}$; again, $I_1 = I_2 + I_3$

$\therefore I_3 = I_1 - I_2$

$= \frac{v_i}{R} - \left(-\frac{v_i}{R}\right)$

$I_3 = \frac{2v_i}{R}$

$\therefore V_2 = V_1 - I_3 R$

$= -v_i - \frac{2v_i}{R} \times R$

$\therefore V_2 = -3v_i$

So, $I_4 = \frac{V_2}{R} = -\frac{3v_i}{R}$

$I_5 = I_3 - I_4 = \frac{2v_i}{R} - \left(-\frac{3v_i}{R}\right) = \frac{5v_i}{R}$

$V_o = V_2 - I_5 R = -3v_i - \frac{5v_i}{R} \cdot R = -8v_i$

$\therefore \frac{v_o}{v_i} = -8 = A_v$

10. The circuit shown in Fig. 8 is a first-order high-pass active filter. Determine how the gain of this circuit [$A_v = v_O/v_I$] is dependent on frequency i.e. find the voltage transfer function.

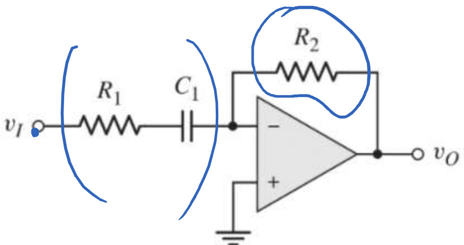


Fig. 8

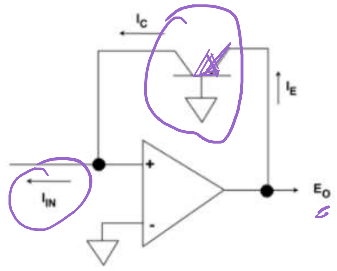
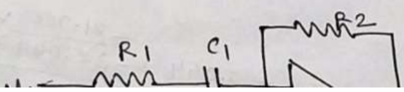


Fig. 9

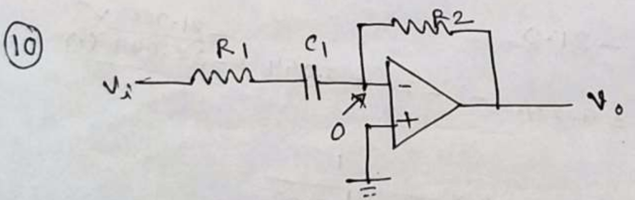
$I_E = I_{ES} \exp\left(\frac{|V_{BE}|}{V_T}\right)$

11. In Fig. 9, show that $E_0 = \frac{kT}{q}\ln\left(\frac{I_{IN}}{I_{ES}}\right)$, where, I_{ES} is the reverse saturation current.

(10)



(10)



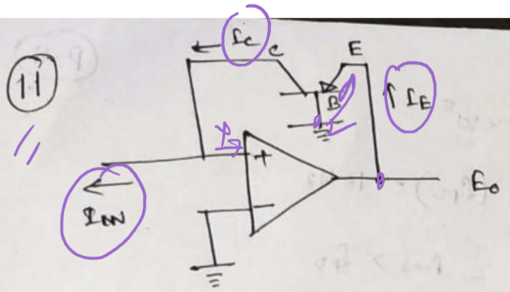
Non-inverting amplifier, gain $= \dfrac{V_o}{V_i} = -\dfrac{Z_2}{Z_1}$

$$= -\frac{R_2}{R_1 + \frac{1}{j\omega C_1}}$$

$$\text{Gain} = -\frac{R_2(j\omega C_1)}{R_1 j\omega C_1 + 1}$$

$|\text{Gain}|^2$

(11) (P-7)



$V_{EB} = E_o$.

$I_E = I_{ES} \exp\left(\dfrac{V_{EB}}{V_T}\right)$

$I_E \approx I_C$ (β very high)

$\therefore I_C = I_{IN}$

$\therefore I_{IN} = I_{ES} \exp\left(\dfrac{V_{EB}}{V_T}\right)$

$\dfrac{I_{IN}}{I_{ES}} = \exp\left(\dfrac{E_o}{V_T}\right)$

$\therefore E_o = \dfrac{KT}{q} \ln\left(\dfrac{I_{IN}}{I_{ES}}\right)$; $\left[V_T = \dfrac{KT}{q}\right]$

12. If an op-amp has a slew-rate of 5 V/μs, find the full-power bandwidth for a peak output voltage of (a) 5 V, (b) 1.5 V, and (c) 0.4 V

(12) Full power bandwidth (FPBW) $= \dfrac{SR}{2\pi V_{o,max}}$

SR = slew rate

$V_{o,max}$ = peak output voltage

(a) FPBW $= \dfrac{5\ V/\mu s}{2\pi(5)} = \dfrac{\cancel{5}\times 10^6\ V/S}{2\pi \times \cancel{5}} = 159.2$ kHz.

(b) FPBW = 530.78 kHz.

(c) FPBW = 1.99 MHz.

13. An amplifier system is to be designed to provide an undistorted 10 V peak sinusoidal signal at a frequency of f = 12 kHz. Determine the minimum slew rate required for the amplifier.

13. An amplifier system is to be designed to provide an undistorted 10 V peak sinusoidal signal at a frequency of f = 12 kHz. Determine the minimum slew rate required for the amplifier.

(13) output peak = 10 V. max. frequency = 12 KHz.

∴ FPBW = 12 KHz.

If the max. operating freq. is limited by the slew rate, then,

$$FPBW = \frac{SR}{2\pi V_{omax}}$$

$$\therefore SR = FPBW \times 2\pi V_{omax}$$

$$= 12\times10^3 \times 2\pi \times 10$$

$$SR = 0.75\ V/\mu s.$$

14. An audio amplifier system is to use an op-amp with an open-loop gain of $A_{Od} = 2 \times 10^5$ and a dominant-pole frequency of 10 Hz. The maximum closed-loop gain for the audio amplifier is 100. Determine the closed loop bandwidth of the amplifier.

(14) open-loop gain $(A_{od}) = 2\times10^5$

Dominant pole frequency (f_{PD}) = 10 Hz.

∴ unity-gain bandwidth $= A_{od} \times f_{PD}$

$= 2\times10^6$

Closed loop gain (A_{cd}) = 100

∴ so, closed loop frequency $= \frac{2\times10^6}{100} = 2\times10^4$

= 20 KHz.

15. For Fig. 10, neatly sketch the output voltage V_0 when V_{in} is a sine wave of amplitude 2 V (zero to peak). Consider the op-amp as ideal and zero voltage drop across the diode in forward bias.

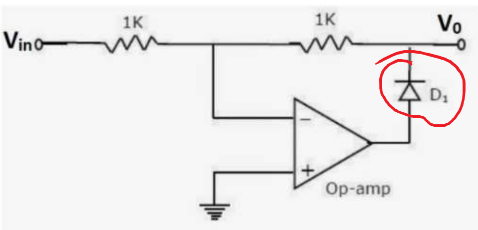
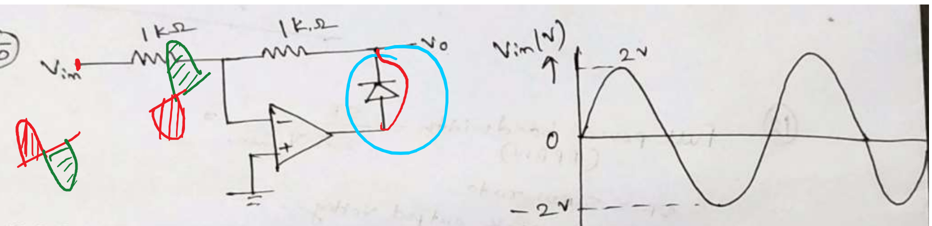


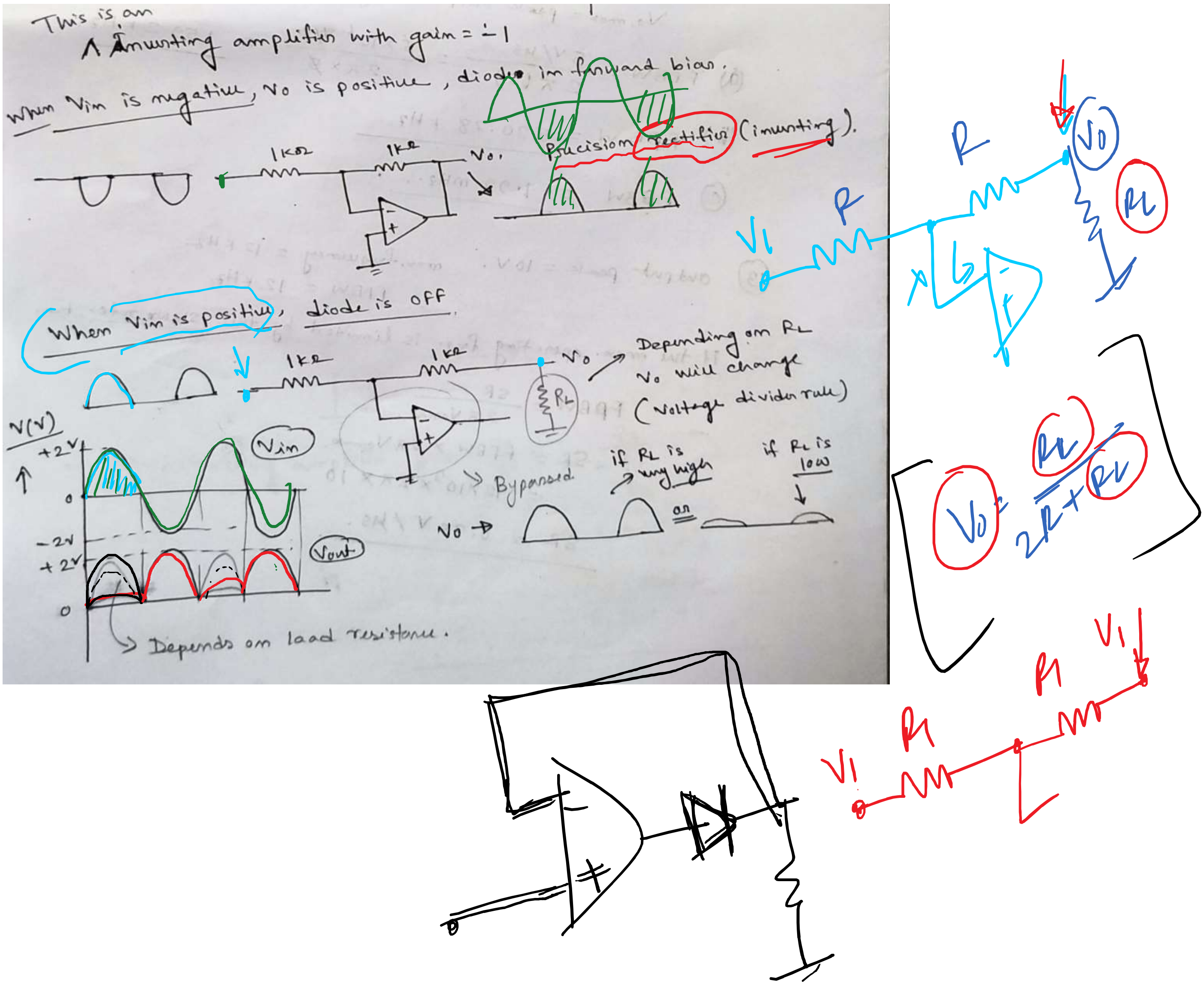
Fig. 10

(15)



This is an Inverting amplifier with gain = −1

... is positive, diode in forward bias.


This is an Inverting amplifier with gain = -1
When Vin is negative, Vo is positive, diode in forward bias.
Precision rectifier (inverting).
1KΩ
1KΩ
Vo
When Vin is positive, diode is off
1KΩ
1KΩ
Vo
RL
Depending on RL Vo will change (Voltage divider rule)
Bypassed
if RL is very high
if RL is low
No
V(V)
+2V
0
-2V
+2V
0
Vin
Vout
Depends on load resistance.
R
R
Vi
Vo
RL
Vo = RL / (2R + RL)
V1
R1
R1
V1