$$I_C = \frac{V_{CC} - V_{BE}}{R}$$

J.S.
02/07/11

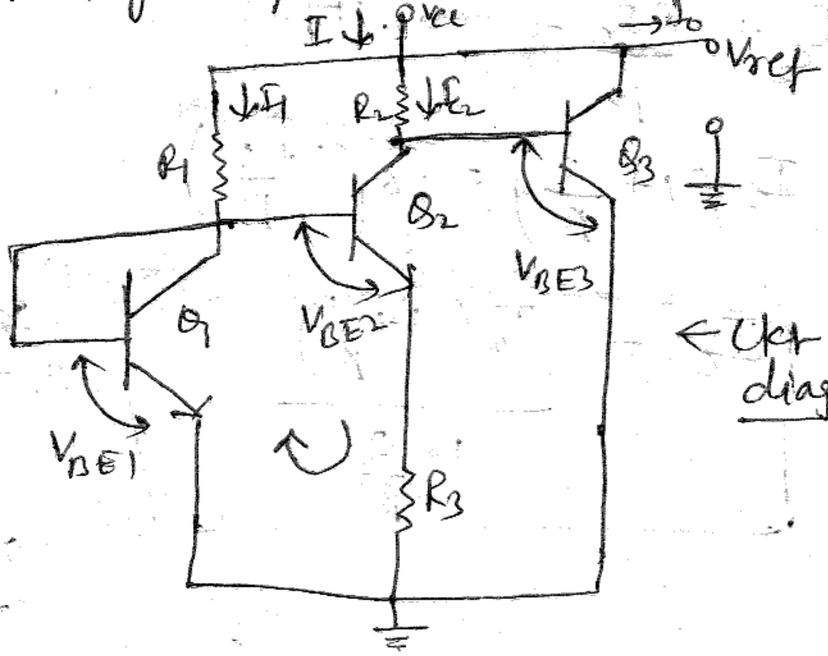
6/7/11

BANDGAP VOLTAGE REFERENCE.

→ It is used for circuit operating supply voltage below 5 volt or less.

Bandgap voltage $\begin{cases} Ge \rightarrow 1.1 \text{ volt} \\ Si \rightarrow 0.78 \text{ volt.} \end{cases}$

Since zener diode and temperature compensated avalanchee diode have breakdown voltage of 6 to 7V. So the supply voltage required will be low



← Ckt diagram

Applying KVL through R_3, Considering

~~At~~

$V_{BE1} + V_{BE2}$

$$-V_{R_3} - V_{BE1} + V_{BE2} = 0$$

$$\Rightarrow \boxed{V_{R_3} = V_{BE1} - V_{BE2}}$$

$$V_{R_3} = \Delta V_{BE}$$

Eber Moll's Equation :-

$$I_{C_1} = I_s e^{V_{BE1}/V_T} \quad \text{— (1)}$$

$$I_{C_2} = I_s e^{V_{BE2}/V_T} \quad \text{— (2)}$$

I_s = Collector saturation current.

$$\boxed{V_T = KT}$$

K = Boltzman Constant

$$\frac{I_{C_1}}{I_{C_2}} = e^{(V_{BE1} - V_{BE2})/V_T}$$

$$\Rightarrow \boxed{\ln \frac{I_{C_1}}{I_{C_2}} = \frac{V_{BE1} - V_{BE2}}{V_T}}$$

$$\Rightarrow V_{BE1} - V_{BE2} = V_T \ln\left(\frac{I_{C_1}}{I_{C_2}}\right)$$

$$\Rightarrow \boxed{V_{R_3} = V_T \ln\left(\frac{I_{C_1}}{I_{C_2}}\right)} \quad \text{— Eq}^n \text{ (1)'}$$

We know,

$$I_E = I_B + I_C$$

for transistor Q_2

also $I_{E_2} = I_{C_2}$ (neglecting base current)

I_{E_2} = Current through R_3

$$I_{E_2} = I_{R_3}$$

$$\Rightarrow \boxed{I_{R_3} = I_{C_2}}$$

Apply KVL through R_2,

taking V_{BE3} & V_{ref}

$$-V_{BE_3} - I_{C_2} R_2 + V_{ref} = 0$$

$$\Rightarrow V_{ref} = V_{BE3} + (I_{C_2}) R_2$$

$$V_{R_3} \cancel{V_{ref}} = \cancel{I_{R_3}} \; I_{R_3} \cdot R_3$$

$$\Rightarrow \frac{V_{R_3}}{R_3} = I_{R_3}$$

$$\Rightarrow \quad V_{ref} = V_{BE_3} + \left(V_T \ln \frac{I_{C_4}}{I_{C_2}}\right) \frac{R_2}{R_3}$$

Differentiating above eqn w.r.t. T.

$$\frac{V_{ref}}{dT} = \frac{dV_{BE3}}{dT} + \frac{d}{dT}\left(kT \ln \frac{I_4}{I_{C2}} \cdot \frac{R_2}{R_3}\right)$$

rent)

Diff of volt. w.r.to Temp -

$$\Rightarrow = \frac{dV_{BE3}}{dT} + \frac{R_2}{R_3} \cdot k \ln \frac{I_4}{I_{C2}}$$

$$\Rightarrow \boxed{\frac{V_{ref}}{dT} = \frac{dV_{BE3}}{dT} + \frac{R_2}{R_3} \cdot k \ln \frac{I_4}{I_{C2}}}$$

$$\Rightarrow \frac{dV_{ref}}{dT} = TC(V_{BE})$$

Temp Coefficient of V_{BE}.

Acording to PN junction Theory :-

$$TC(V_{BE}) = \frac{dV_{BE}}{dT}$$

$$\boxed{TC(V_{BE}) = \frac{V_{BE} - (V_{G0} + 3kT)}{T}}$$

V_{G0} = Bandgap voltage

$$TC(V_{BE}) = -\left[\frac{V_{G0} - V_{BE} + 3k}{T}\right] \quad (A)$$

$$V_{ref} = V_{BE} + \frac{R_2}{R_3} \ln\left(\frac{I_4}{I_{C2}}\right)$$

$$\frac{dV_{ref}}{dT} = \frac{dV_{BE}}{dT} + \frac{R_2}{R_3} k \ln\left(\frac{I_4}{I_{C2}}\right)$$

$$= TC(V_{BE}) + \frac{R_2}{R_3} k \ln\left(\frac{I_4}{I_{C2}}\right) \quad (3)$$

Sub (A) in (3)

$$\frac{dV_{ref}}{dT} = -\left[\frac{V_{G0} - V_{BE}}{T} + 3k\right] + \frac{R_2}{R_3} k \ln\left(\frac{I_4}{I_{C2}}\right)$$

Always, ~~$TC(V_{BE}) = 0$~~ . $\frac{dV_{ref}}{dT} = 0$

$$\Rightarrow \cancel{\frac{dV_{ref}}{dT} = \frac{R_2}{R_3} k \ln\left(\frac{I_4}{I_{C2}}\right)}$$

$$-\left[\frac{V_{G0} - V_{BE}}{T} + 3k\right] = -\frac{R_2}{R_3} k \ln \frac{I_4}{I_{C2}}$$

$$\Rightarrow V_{G0} - V_{BE} + 3kT = \frac{R_2}{R_3} kT \ln \frac{I_{C2}}{I_4}$$

$$\Rightarrow \boxed{V_{G0} - V_{BE} = \frac{R_2}{R_3} kT \ln \frac{I_{C2}}{I} - 3kT}$$

Monolithic IC op-amp :-

↑ manufacturers ↓ specification

MOTOROLA

- MC 741
- SE 741
- NE 741
- μA 741

(3) Manufacturers design

μA — Fairchild Semicond^r — manufacturers name

741 — last three digits ~~its~~ is 741 and it represent op-amp

Ideal Char of op-amp :-

$A_{OL} = \infty$ $\qquad R_i$ = i/p impedance

$R_i = \infty$

$R_o = \cancel{\infty}\ 0$

$BW = \infty$

Non Ideal Characteristics of op-amp

D.C Characteristic :-

(1) I/p biased current :- The average of the current entering into +ve & -ve terminal, of an op-amp. is known as i/p biased current.

2) I/P offset Current :- The algebraic difference between the current entering $ into the inverting & non-inverting terminal is called I/P offset current

3) I/P offset voltage :-
The voltage that must be applied betn the I/P to nullify the O/P .

4) Total O/P offset Voltage :- The O/P voltage produced at the O/P due to I/P biased current, or I/P offset voltage.

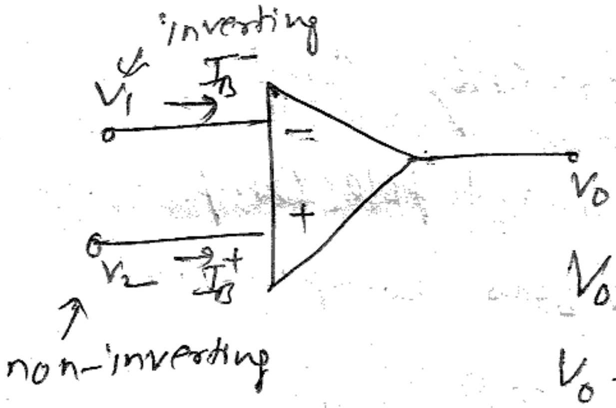
5) Thermal drift :- The average rate of change of I/P offset voltage per unit change in temperature.

A.C Characteristics :-

(i) Frequency Response

(ii) Band width

(iii) Slew Rate



$V_0 = -V_i$ -ve ~~std~~ sign shows phase change.

$V_0 = V_2$

for ideal,

$V_1 = V_2 = 0$,

$V_0 = 0$.

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FREQUENCY COMPENSⁿ

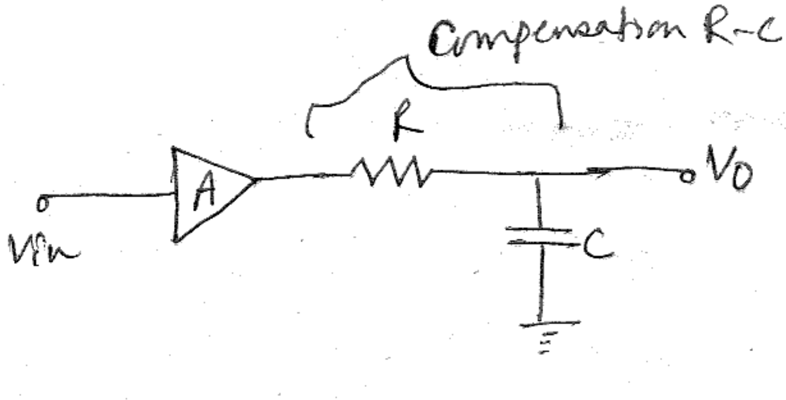
↑ BW

↓ open loop gain

(1) External frequency comp

- → Dominant Pole Comp.
- → Pole zero Compensation
- → Miller Effect "

Dominant Pole Compensation :-



$$A = \frac{A_{OL}}{(1+jf/f_1)(1+jf/f_2)(1+jf/f_3)} \quad \text{— (1) eqn.}$$

where

A = uncompensated gain

$$\frac{V_o}{V_{in}} = A \cdot \frac{Z_c}{Z_R + Z_c}$$

$$Z_c = \frac{1}{j\omega C}$$

$$Z_R = R$$

$$\frac{V_o}{V_{in}} = A \cdot \frac{1/j\omega C}{R + \frac{1}{j\omega C}}$$

$$= \frac{A}{1 + j\omega RC}$$

$\because \boxed{f_d = \frac{1}{2\pi RC}}$

dominant frequency

$$= \frac{A}{1 + j\, f/f_d} \quad \text{— (2) eq.}$$

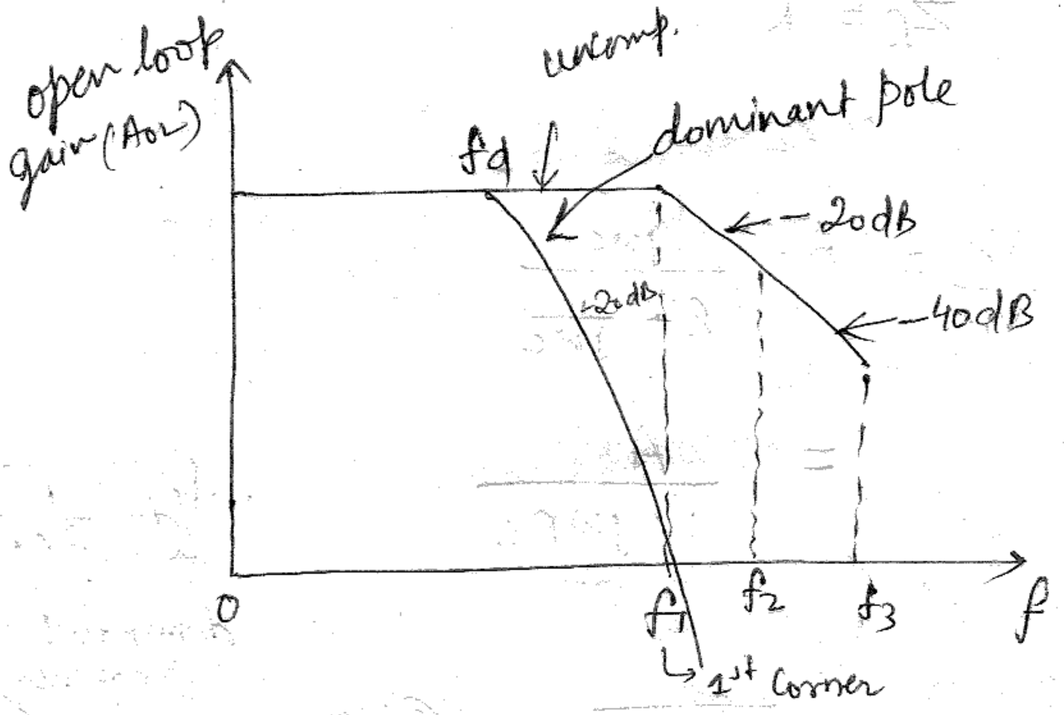
Sub (1) in (2)

$$\frac{V_o}{V_{in}} \Rightarrow \frac{A}{1 + j\, f/f_d} = \frac{A_{OL}}{(1 + j f/f_1)(1 + j f/f_2)(1 + j f/f_3)}$$

$$\Rightarrow \boxed{\frac{V_o}{V_{in}} = \frac{A_{OL}}{(1 + j f/f_d)(1 + j f/f_1)(1 + j f/f_2) \cdots}}$$

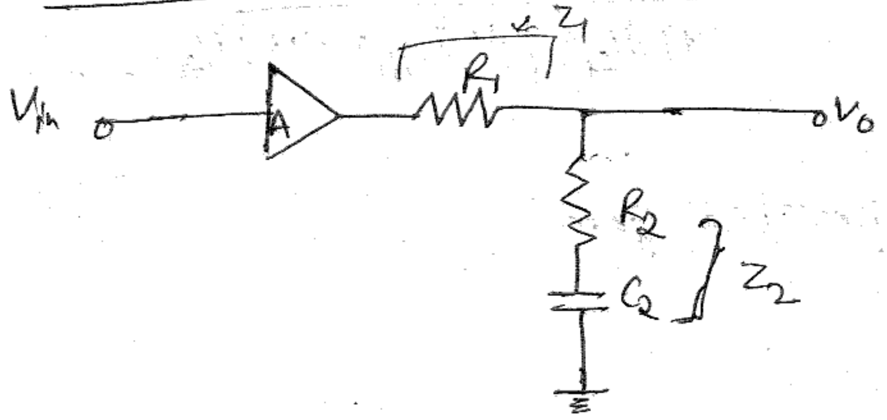
Compensated gain

The capacitance 'C' is Choosen so that ~~mof~~ modify loop gain drops to 0 dB with a slope of − 20dB.



The dominant pole is selected so that the Componsated transfer function goes to 0 dB ~~and~~ at 1st Corner frequency with a slope of -20dB.

Pole Zero Compensation :-



$$\frac{V_o}{V_{in}} = A \frac{Z_2}{Z_1 + Z_2}$$

$$A = \frac{A_{OL}}{\left(1+jf/f_1\right)\cancel{\left(1+jf/f_2\right)}\left(1+jf/f_3\right)\cdots}$$

$$\frac{V_o}{V_{in}} = A \frac{R_2 + \frac{1}{j\omega C_2}}{R_1 + R_2 + \frac{1}{j\omega C_2}}$$

$$= A \frac{1 + j\omega R_2 C_2}{1 + j\omega C_2 (R_1 + R_2)}$$

$$= A \cdot \frac{1 + j(f/f_2)}{1 + j(f/f_0)}$$

$$= \frac{A_{OL}\cancel{(1+jf/f_2)}}{(1+jf/f_0)(1+jf/f_1)\cancel{(1+jf/f_2)}(1+jf/f_3)}$$

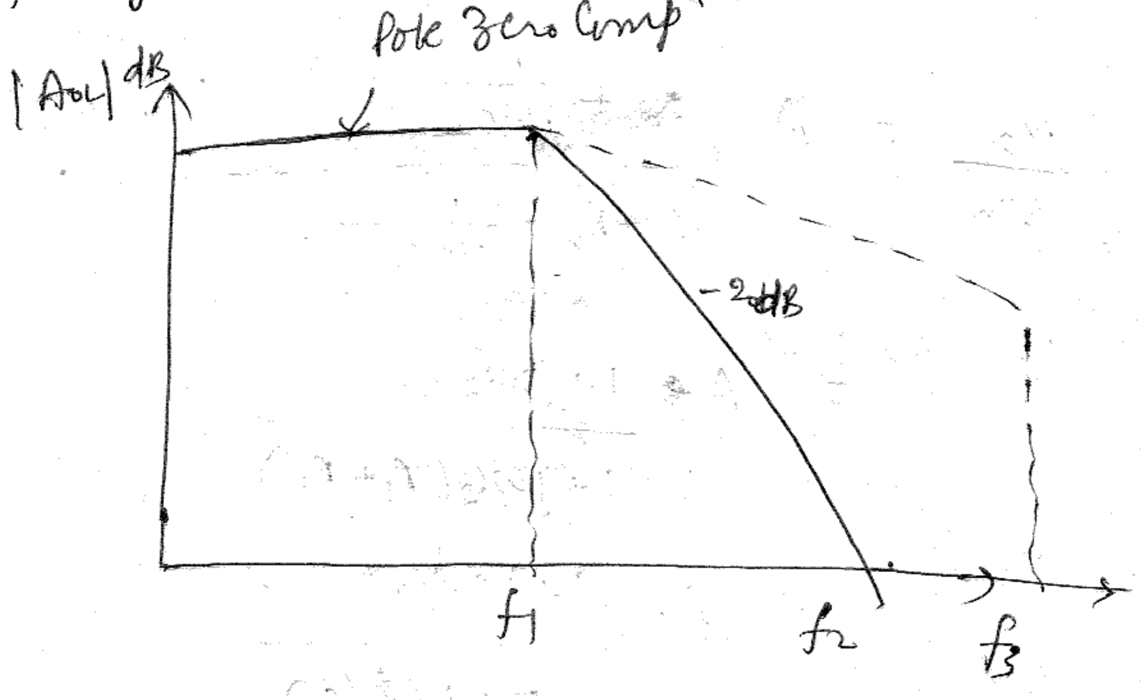
$$f_2 = \frac{1}{2\pi R_2 C_2}$$

$$f_0 = \frac{1}{2\pi C_2 (R_1 + R_2)}$$

$$\boxed{\frac{V_o}{V_{in}} = \frac{A_{OL}}{(1+jf/f_0)(1+jf/f_1)(1+jf/f_3)}}$$

$$0 < f_0 < f_1 < f_3$$

The Componsating n/wk is designed to produce a zero at 1st Corner frequency and a pole at 2nd Corner frequency



Pole at f_2

zero at f_1

Internal Compensation

To ↑ Bandwidth, Componsation techniques are used in such Cases internally Componsated op-amp called Compansated op-amp Can be employed.

μA 741

↳ internally Componsated op-amp.

Op-amp 741 internaly Contain Capacitors of 30 pf. This internally Componsating Capacitor has open loop gain at -20dB that gives the stable characteristics of op-amp

SLEW RATE :- It is the rate of Change of o/p voltage with respect to time

$$\boxed{S = \frac{\Delta V_o}{\Delta t}}$$

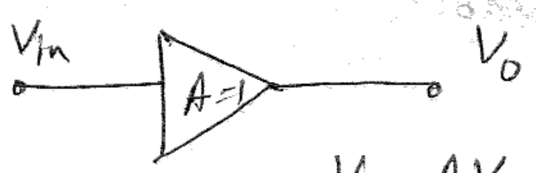
unit → volt/μsec

~~It~~ Slew rate is Caused due to limiting Changing rate of Componsating Capacitor.

$$\boxed{C = \frac{I}{V}}$$

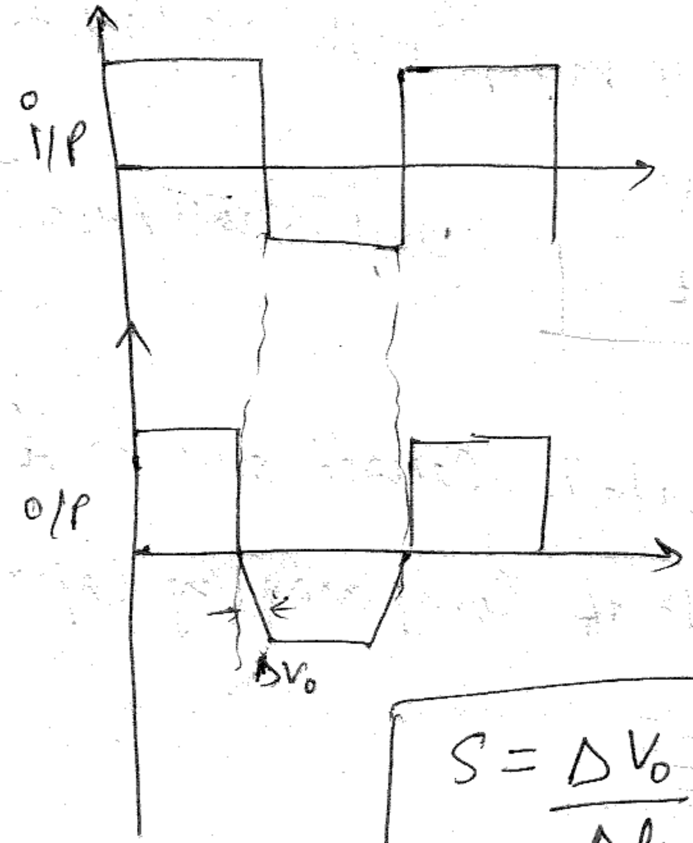
The slew rate is maximum internal Capacitor Charging Current is ~~known~~ more then, $\dfrac{dV_c}{dt} = \dfrac{I}{C}$.

$$\boxed{\frac{dV_c}{dt} = \frac{I_{max}}{C}}$$



$V_0 = A V_{in}$ $\quad \boxed{A=1}$

$V_0 = V_{in}$

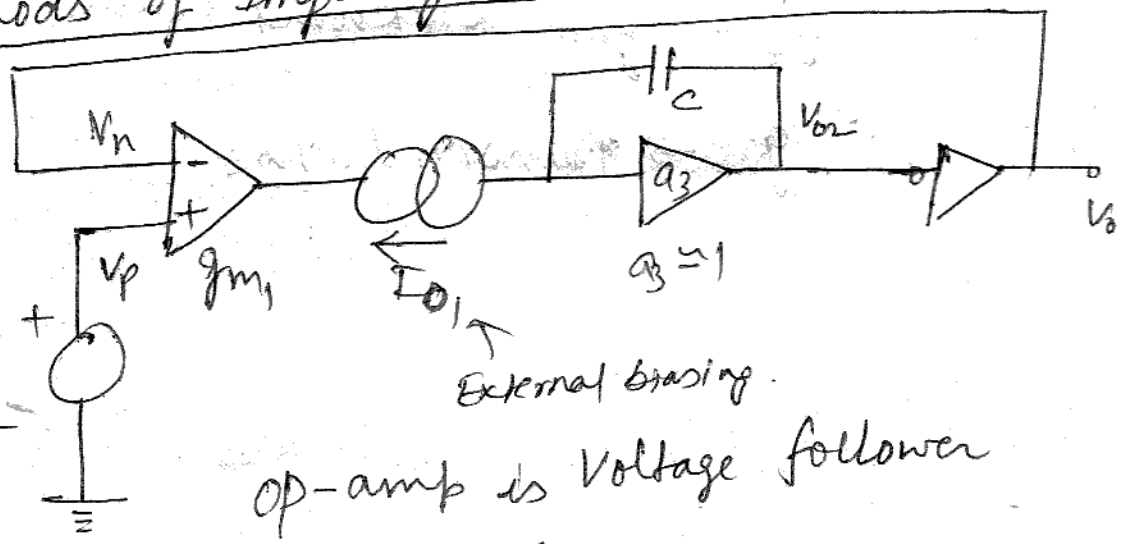


$$\boxed{S = \frac{\Delta V_0}{\Delta t}}$$

Ideally skew rate should be infinite for better performance of op-amp.

Bakshi

Methods of Improving slew rate :-



op-amp is voltage follower

when ~~let~~ i/p over drives, the i/p stage,

$I_{max} = I_{o1}\ (sat)$

The saturation of i/p stage remains ~~skew~~ slew rate bcoz under saturatⁿ condⁿ the rate at which capacitor charges & discharges is maxm.

$$\frac{I_{o1}\ (sat)}{C} = \frac{dV_{o2}}{dt}$$

$$\boxed{S = \frac{2\pi\ I_{o1}\ (sat)}{g_m}\ f_t}$$

I_{01} (sat) $\uparrow$ or $g_m \downarrow$

~~fct~~ $f_t \uparrow$

~~If f represents~~

f_t → gain backward product

g_m → Transconductance

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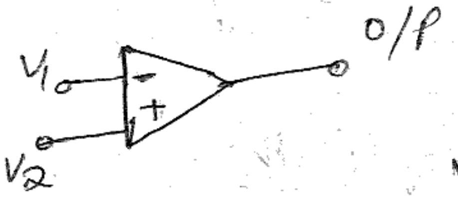
UNIT 2

APPLICATIONS OF OP-AMP

→ (i) Differentiator
(ii) Integrator

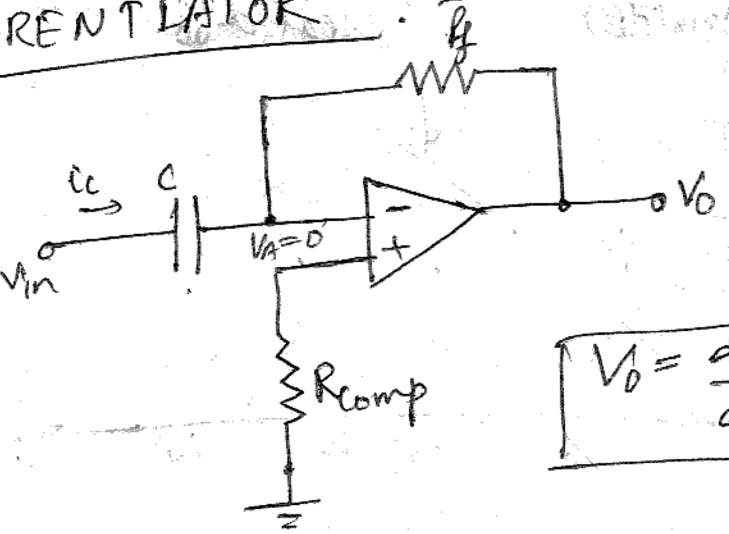


$V_0 = -V_1$

$V_2 = V_1$

$V_1 \rightarrow$ Inverting
$V_2 \rightarrow$ non-inverting

DIFFERENTIATOR :



$$\boxed{V_0 = \frac{dV_i}{dt}}$$

Analysis :-

$I_B = 0$
$V_A = 0$

I_B = Biased Current

At node A, $V_A = 0$
KCL at node A

$$\longrightarrow \; C_1 \frac{d(V_i - V_A)}{dt} + R_f V_0 = 0$$

$$C_1 \frac{dv_i}{dt} + \cancel{R_f} \frac{V_0}{R_f} = 0$$

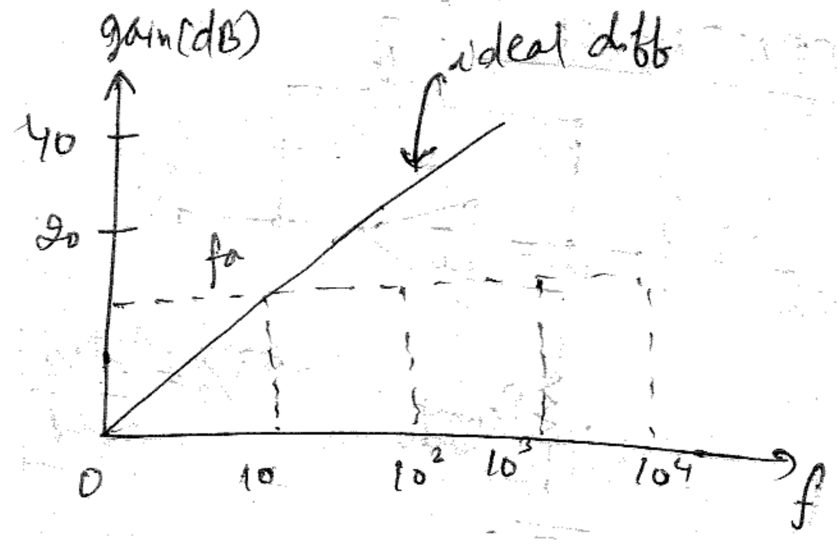
$$\cancel{R_f} \frac{V_0}{R_0} = -C_1 \frac{dv_i}{dt}$$

$$\cancel{V_0 = \frac{-C_1 R_f}{R_f} \frac{dv_i}{dt}}$$

$$\boxed{V_0 = -R_f C_1 \frac{dv_i}{dt}}$$

$$\boxed{V_0 = (-R_f C_1) \frac{dv_i}{dt}}$$

<u>frequency Response :-</u>



~~$V_0(t)=$~~

$$V_0(t) = -R_f C_1 \left(\frac{dV_1}{dt}\right)$$

Apply Laplace transform!

$$V_0(S) = -R_f C_1 S V_i(S)$$

$$V_0(j\omega) = -R_f C_1 j\omega V_i(j\omega)$$

$$\frac{V_0(j\omega)}{V_i(j\omega)} = \cancel{-R_f C_1} - jR_f C_1 2\pi f$$

$$\boxed{G = -jf/f_a}$$

Substitute $f_a = \frac{1}{2\pi R_f C_1}$

$$\frac{V_o(j\omega)}{V_i(j\omega)} = -jf/f_a$$

$$|A| = |-jf/f_a|$$

$$\boxed{|A| = \frac{f}{f_a}}$$

$f < f_a \Rightarrow$ gain ($-dB$)

$f > f_a \rightarrow$ gain ($+dB$)

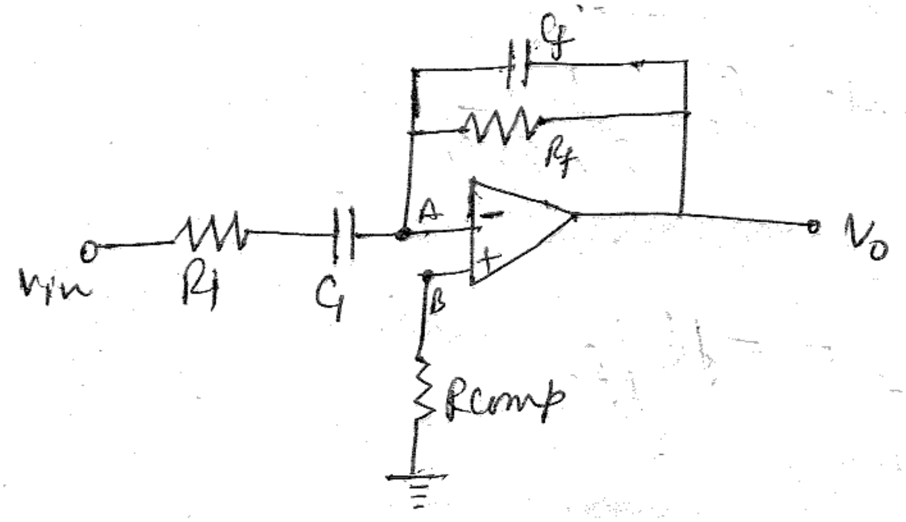
f_a = Corner frequency.

Disadvantage of Ideal Differentiator

(i) As ~~gain~~ freq $\uparrow$, gain $\uparrow$, for high frequency differentiator becomes unstable and goes into oscillation

(ii) I/P impedance $X_c \downarrow$, as frequency $\uparrow$, this makes the circuit, very sensitive to noise.

Practical Differentiator



$V_A = V_B = 0$

Apply KCL at node 'A'.

$$\frac{V_{in}}{R_1} + C_1 \frac{dv_i}{dt} + (C_f \parallel R_f)\, v_o = 0$$

$$\Rightarrow \boxed{\frac{V_o(s)}{V_i(s)} = \frac{sR_f C_1}{(1+sR_f C_f)(1+sR_1 C_1)}}$$

Take $R_f C_f = R_1 C_1$

$$\frac{V_o(s)}{V_i(s)} = \frac{sR_F C_F}{(1+sR_1 C_1)^2}$$

$$\Rightarrow \frac{V_o(s)}{V_i(s)} = \frac{j\omega R_F C_F}{(1+j\omega R_1 C_1)^2}$$

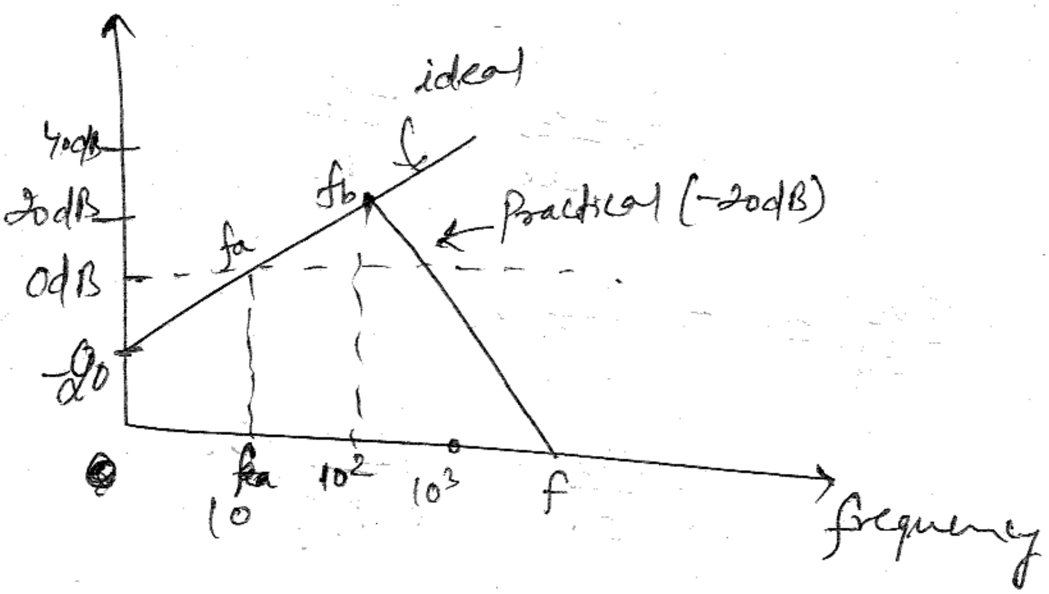
$$= \frac{j2\pi f R_1 C_1}{(1+j2\pi f R_1 C_1)^2}$$

$$\frac{V_o(s)}{V_i(s)} = \frac{j\, f/f_a}{\left(1 + j\, f/f_b\right)^2}$$

$$|A| = \frac{f/f_a}{\cancel{\left(1 + f/f_b\right)^2}}$$

$$\boxed{|A| = \frac{f/f_a}{1 + \left(f/f_b\right)^2}}$$

Frequency Response



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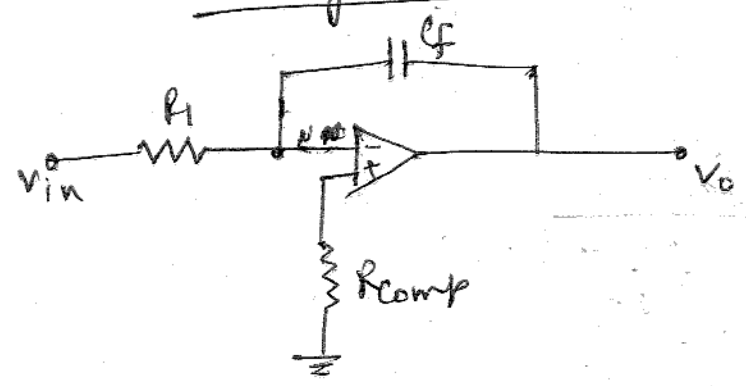
Integrator



Apply KCL at node 'A',

$$\frac{V_i - V_A}{R_1} + C_f \frac{dv_o}{dt} = 0$$

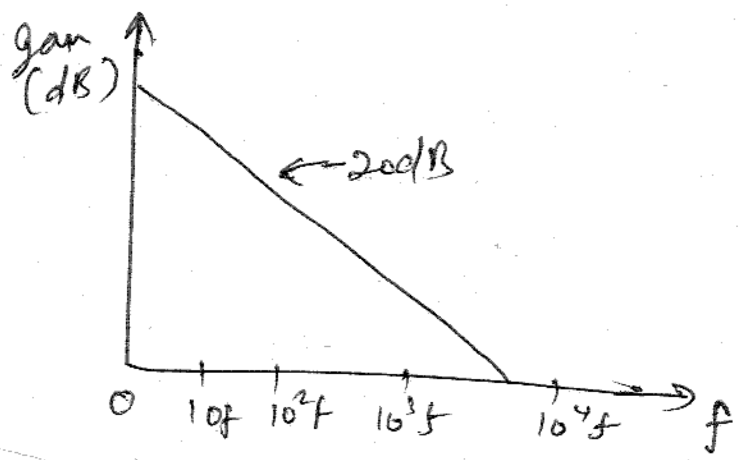
$$\frac{V_i}{R_1} + C_f \frac{dv_o}{dt} = 0$$

$$C_f \frac{dv_o}{dt} = \frac{-V_i}{R_1}$$

$$\frac{dv_o}{dt} = \frac{-1}{R_1 C_f} V_i$$

$$\int \frac{dv_o}{dt} = \int \frac{-1}{R_1 C_f} V_i$$

Freq. Response



i) As the gain of integrator ↓, with freq ↑, the integrator ckt will not have frequency as differentiator

ii) At low frequency, gain becomes ∞,