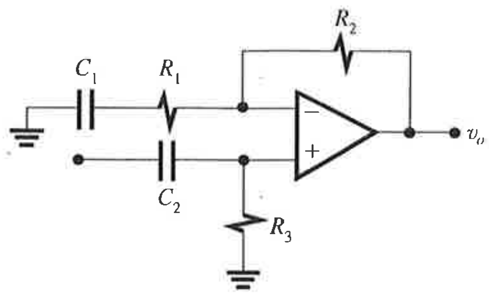
WEEK 13

2.100



$R_2 = R_3 = 100\ \text{k}\Omega$

$1 + \frac{R_2}{R_1} = 200$

$R_1 = \frac{100\ \text{k}}{199} = 502\ \Omega$

$\frac{1}{R_1 C_1} = 2\pi \times 100 \Rightarrow C_1 = \frac{1}{500 \times 2\pi \times 100}$

$= 3.18\ \mu\text{F}$

$\frac{1}{R_3 C_2} = 2\pi \times 10 \Rightarrow C_2 = \frac{1}{100\ \text{K} \times 2\pi \times 100}$

$= 0.16\ \mu\text{F}$

2.101

$v_O = 4\ \text{mV}$

The output component due to v_{OS} is

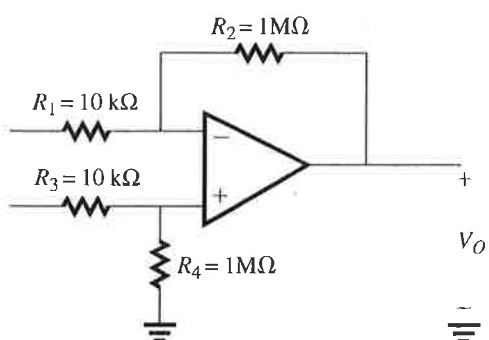
$v_{01} = v_{OS}\left(1 + \frac{1\ \text{M}\Omega}{10\ \text{k}\Omega}\right) = 101\ v_{OS}$

$= 101 \times 4\ \text{mV}$

$= 404\ \text{mV}$

The output component due to input bias current I_B is:

$I_{B1} = I_B + \frac{I_{OS}}{2}$



$= \left(0.5 + \frac{0.1}{2}\right)\mu\text{A}$

$= 0.55\ \mu\text{A}$

$I_{B2} = I_B - \frac{I_{OS}}{2}$

$= \left(0.5 - \frac{0.1}{2}\right)$

$= 0.45\ \mu\text{A}$

$v_+ = -I_{B2} \times (10\ \text{k}\Omega \,\|\, 1\ \text{M}\Omega) = -0.45\ \mu\text{A} \times 9.9\ \text{k}\Omega$

$= -4.46\ \text{mV}$

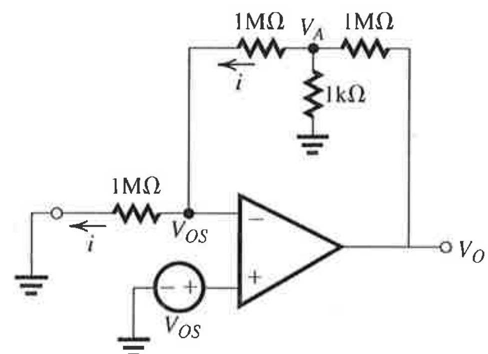
$v_{02} = \text{V}_+ + \left[1\ \text{M}\Omega \times \left(I_{B1} + \frac{v_+}{10\ \text{k}}\right)\right]$

$= -4.46 + 1\ \text{M}\Omega \times \left(0.55\ \mu\text{A} + \frac{-4.46\ \text{mA}}{10\ \text{k}\Omega}\right)$

$= 99.5\ \text{mV}$

The worst case dc offset Voltage at the output is $(99.5 + 404)\text{mV} = 503.5\ \text{mV}$

2.102



$v_- = v_+ = v_{os}$

$V_A = 2v_{os} = 8\ \text{mV}$

$i = \frac{V_{OS}}{1\ \text{M}\Omega} = V_{OS}(\text{in}\ \mu\text{A})$

$V_O = V_A + 1\ \text{M}\Omega \times \left(i + \frac{V_A}{1\ \text{k}}\right)$

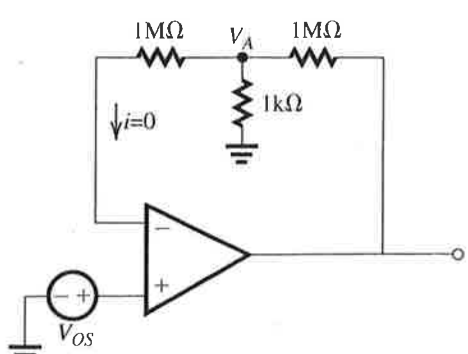
$= 2V_{os} + 1\ \text{M}\Omega \times \left(\frac{V_{OS}}{1\ \text{M}} + \frac{2V_{OS}}{1\ \text{k}}\right)$

$= 2003\ V_{OS}$

$= 2003 \times 4\ \text{mV}$

$\cong 8\ \text{V}$

For capacitively coupled input



$V_+ = V_- = V_{OS}$

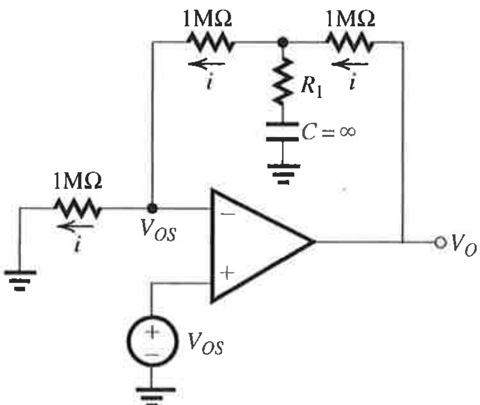
$V_A = V_{OS} \because i = 0$

$V_O = V_A + 1\ \text{M}\Omega \times \dfrac{V_{OS}}{1\ \text{k}\Omega} = V_{OS} + 1000\ V_{OS}$

$= 1001 V_{OS}$

$= 1001 \times 4\ \text{mV} = 4.004\text{V}$

A large capacitor placed in series with 1 kΩ resistor



$V_+ = V_- = V_{OS}$

No dc current flows through R_1, C branch

$\therefore V_O = V_A + V_{OS}$

$= 2V_{OS} + V_{OS}$

$= 3V_{OS}$

$= 3 \times 4\ \text{mV}$

$= 12\ \text{mV}$

2.103

At 0°C, we expect

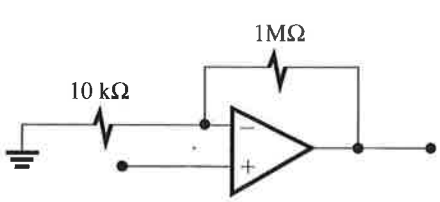
$\pm 10 \times 25 \times 1000\ \mu = \pm 250\ \text{mV}$

At 75°C, we expect

$\pm 10 \times 50 \times 1000\ \mu = \pm 500\ \text{mV}$

We expect these quantities to have opposite polarities.

2.104



$100 = 1 + \dfrac{R_2}{R_1} \Rightarrow R_1 = 10.1\ \text{k}\Omega$

a) $V_O = 100 \times 10^{-9} \times 1 \times 10^6 = 0.1\ \text{V}$

b) Largest output offset is:

$V_O = 1\ \text{mV} \times 100 + 0.1\ \text{V} = 200\ \text{mV} = 0.2\ \text{V}$

c) For bias current compensation we connect a resistor R_3 in series with the positive input terminal of the op-amp, with: $R_3 = R_1 \| R_2$

$I_{OS} = \dfrac{100}{10} = 10\ \text{nA}$

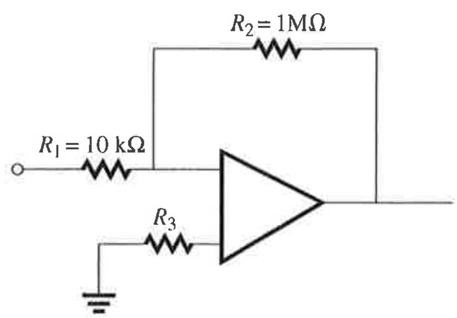
$R_3 = 10\ \text{k}\Omega \| 1\ \text{M}\Omega = 10\ \text{k}\Omega$

The offset current alone result in an output offset voltage of

$I_{OS} \times R_2 = 10 \times 10^{-9} \times 1 \times 10^6 = 10\ \text{mV}$

d) $V_O = 100\ \text{mV} + 10\ \text{mV} = 110\ \text{mV}$

2.105

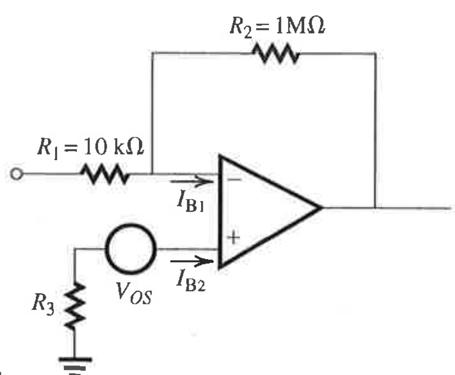


See equation 2.39

$R_3 = R_1 \| R_2 = 10\ \text{k}\Omega \| 1\ \text{M}\Omega = 9.9\ \text{k}\Omega$

From equation 2.40

$V_O = I_{OS}R_2$ and $V_O = 0.21\ \text{V}$



If $V_{OS} = 1\ \text{mV}$

$V_+ = -I_{B2}R_3 \pm V_{OS}$

$I_{B1} = \dfrac{I_{B2}R_3 \pm V_{OS}}{R_1} + \dfrac{I_{B3}R_3 \pm V_{OS}}{R_2}$

$= I_{B2}R_3\left(\dfrac{1}{R_1} + \dfrac{1}{R_2}\right) \pm V_{OS}\left(\dfrac{1}{R_1} + \dfrac{1}{R_2}\right)$

But $\dfrac{1}{R_1} + \dfrac{1}{R_2} = \dfrac{1}{R_3}$

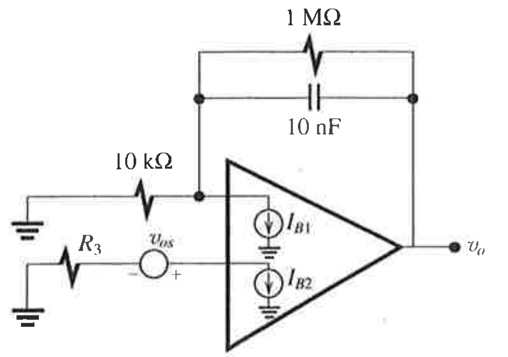
$$I_{B1} = I_{B2} \pm \frac{V_{OS}}{R_3}$$

$$(I_{B1} - I_{B2}) = \pm\frac{V_{OS}}{R_3} = \pm\frac{1\ \text{mV}}{9.9\ \text{K}} = \pm 0.1\ \mu\text{A}$$

so the offset current is $\pm 0.1\ \mu$A

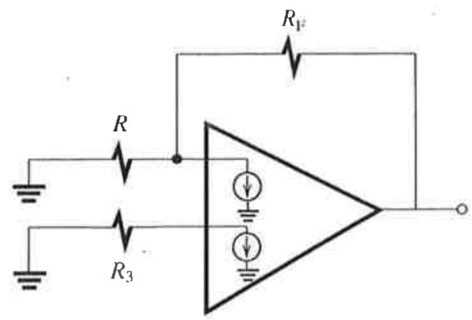
2.106

a) To compensate for the effect of dc bias current I_B, we can consider the following model



Similar to the discussion leading to equation (2.46) we have:

$R_3 = R \| R_F = 10\ \text{k}\Omega \| 1\ \text{M}\Omega \Rightarrow R_3 = 9.9\ \text{k}\Omega$



b) As discussed in Section 2.8.2 the dc output voltage of the integrator when the input is grounded is: $V_O = V_{OS}\left(1 + \frac{R_F}{R}\right) + I_{DS}R_F$

$$V_O = 3\ \text{mV}\left(1 + \frac{1\ \text{M}\Omega}{10\ \text{k}\Omega}\right) + 10\ \text{nA} \times 1\ \text{M}\Omega$$

$$= 0.303\ \text{V} + 0.01\ \text{V}$$

$$V_O = 0.313\ \text{V}$$

2.107

eq.2.28:

$w_t = A_O w_b$

$\Rightarrow f_t = A_O f_b$

A_O	f_b(Hz)	f_t(Hz)
10^5	10^2	10^7
10^6	1	10^6
10^5	10^3	10^8
10^7	10^{-1}	10^6
2×10^5	10	2×10^6

2.108

Eq. 2.25:

$$A = \frac{A_O}{1 + jw/w_b} \Rightarrow |A| = \frac{|A_O|}{\sqrt{1 + \left(\frac{f}{f_b}\right)^2}}$$

$A_O = 80$ dB, $A = 40$ db @ $f = 100$ kHz

$$20\log\sqrt{1 + \left(\frac{f}{f_b}\right)^2} = 20\log\frac{|A_O|}{|A|} = 20\log A_O - 20\log A$$

$$= 86 - 40 = 46\ \text{dB}$$

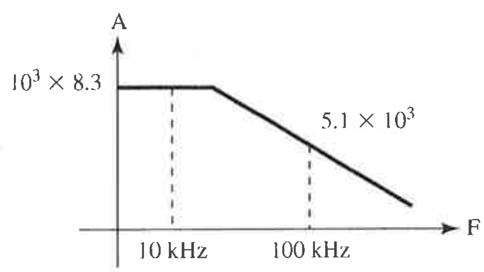
$$1 + \left(\frac{100\ \text{kHz}}{f_b}\right)^2 = (199.5)^2 \Rightarrow f_b = 0.501\ \text{kHz}$$

$f_b = 501$ Hz

$$f_t = A_O f_b = \underbrace{1.995 \times 10^4}_{86\ \text{dB}} \times 501$$

$$= 9.998\ \text{MHz} \simeq 10\ \text{MHz}$$

2.109



$A_O = 8.3 \times 10^3$ V/V

Eq. 2.25: $A = \dfrac{A_O}{1 + j\dfrac{f}{f_b}}$

$f_t = A_O f_b$

c) $1 + \frac{R_2}{R_1} = 2$ V/V, $f_{3db} = 10$ kHz

$f_t = 10$ MHz $\times 2 = 20$ MHz

d) $-\frac{R_2}{R_1} = -2$ V/V, $f_{3db} = 10$ kHz

$f_t = 10$ MHz$(1+2) = 30$ MHz

e) $-\frac{R_2}{R_1} = -1000$ V/V, $f_{3db} = 20$ kHz

$f_t = 20$ kHz$(1+100) = 20.02$ MHz

f) $1 + \frac{R_2}{R_1} = 1$ V/V, $f_{3db} = 1$ MHz

$f_t = 1\text{M} \times 1 = 1\text{MHz}$

g) $-\frac{R_2}{R_1} = -1$, $f_{3db} = 1$ MHz

$f_t = 1\,\text{M}(1+1) = 2$ MHz

2.114

$$\text{Gain} = 1 + \frac{R_2}{R_1} = 96 \text{ V/V}$$

$f_{3dB} = 8$ kHz

$f_t = 96 \times 8 = 768$ kHz

for $f_{3dB} = 24$ kHz

$$\text{Gain} = \frac{768}{24} = 32 \text{ V/V}$$

2.115

$f_{3db} = f_t = 1$ MHz

$$|G| = \frac{1}{\sqrt{1 + \left(\frac{f}{f_{3db}}\right)^2}} = \frac{1}{\sqrt{1+f^2}} \quad f_{in} \text{ MHz}$$

$|G| = 0.99 \Rightarrow f = 0.142$ MHz

The follower behaves like a low-pass STC circuit with a time constant $\tau = \frac{1}{2\pi \times 10^6} = \frac{1}{2\pi}$ μs

$t_r = 2.2\tau = 0.35$ μs (Refer to Appendix F)

2.116

$1 + \frac{R_2}{R_1} = 10$ V/V, $R_1 = 1$ kΩ, $R_2 = 9$ kΩ

If we consider 5τ the time that it takes for the output voltage to reach 99% of its final value, then: $5\tau = 100 \text{ ns} \Rightarrow \tau = 20$ ns

$$\tau = \frac{1}{w_{3db}} \Rightarrow w_{3db} = 50 \times 10^6 \Rightarrow f_{3db} = 7.96 \text{ MHz}$$

$$f_t = \left(1 + \frac{R_2}{R_1}\right) f_{3db} = 10 \times 7.96 = 79.6 \text{ MHz}$$

2.117

a) Assume two identical stages, each with a gain function: $G = \frac{G_O}{1 + j\frac{w}{w_1}} = \frac{G_O}{1 + jf/f_1}$

$$G = \frac{G_O}{\sqrt{1 + \left(\frac{f}{f_1}\right)^2}}$$

overall gain of the cascade is $\frac{G_O^2}{\sqrt{1 + \left(\frac{f}{f_1}\right)^2}}$

The gain will drop by 3db when:

$1 + \left(\frac{f_{3db}}{f_1}\right)^2 = \sqrt{2}$, Note $3\text{db} = 20\log\sqrt{2}$

$f_{3db} = F_1\sqrt{\sqrt{2}-1}$

b) 40 db = 20 log $G_O \Rightarrow G_O = 100 = 1 + \frac{R_2}{R_1}$

$$f_{3db} = \frac{f_t}{1 + \frac{R_2}{R_1}} = \frac{1 \text{ MHz}}{100} = 10 \text{ kHz}$$

c) Each stage should have 20db gain or

$1 + \frac{R_2}{R_1} = 10$ and therefore a 3db frequency of:

$$f_1 = \frac{10^6}{10} = 10^5 \text{ Hz}.$$

The overall $f_{3db} = 10^5\sqrt{\sqrt{2}-1} = 64.35$ kHz

which is 6 time greater than the bandwidth achieved using single op amp.
(case b above)

2.118

$f_t = 100 \times 5 = 500$ MHz if single op-amp is used.

with op-amp that has only $f_t = 40$ MHz,

the possible closed 100 p gain at 5 MHz is:

$$|A| = \frac{40}{5} = 8 \text{ V/V}$$

To obtain a overall gain of 100, three such amplifier cascaded, would be required. Now, if each of the 3 stages, has a low-frequency (d) closed loop gain K, then its 3-db frequency will $\frac{40}{k}$ MHz.

$v_P = \frac{2}{100} = 0.02\text{ V} = 20\text{ mV}$

c) $R_L = ?,\ i_{omax} = 20\text{ mA} = \frac{10\text{ V}}{R_{Lmin}} + \frac{10\text{ V}}{100\text{ K}}$

$20 - 0.1 = \frac{10}{R_{Lmin}} \Rightarrow R_{Lmin} = 502\ \Omega$

2.123

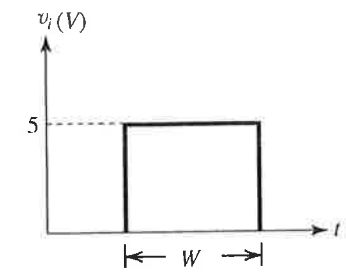
Op Amp slew rate = 10 v/μs

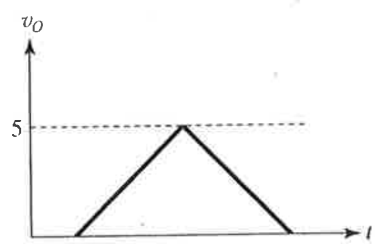
For the input pulse to rise $5V_1$, it will take

$\frac{5}{10} = 0.5\ \mu s$

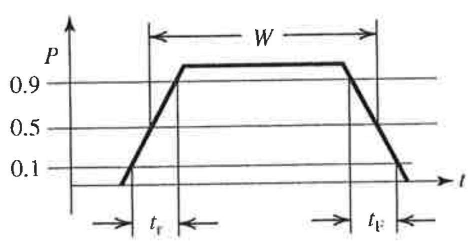
∴ The minimum pulse width = $W = 0.5\ \mu s$

The output will be a triangular with 10 V/μs slew rate





2.124



$W = 2\ \mu s$

$t_r + t_F = 0.2\text{ W} = 0.4\ \mu s$

$t_r = t_F = 0.2\ \mu s$

$\text{SR} = \frac{(0.9 - 0.1)P}{t_r} = \frac{0.8 \times 10}{0.2} = 40\text{ V}/\mu s$

2.125

Slope of the triangle wave $= \frac{20\text{ V}}{T/2} = \text{SR}$

Thus $\frac{20}{T} \times 2 = 10\text{ V}/\mu s$

$\Rightarrow T = 4\ \mu s$ or $f = \frac{1}{T} = 250\text{ kHz}$

For a sine wave $v_o = v_o \sin(2\pi \times 250 \times 10^3 t)$

$\left.\frac{dv_o}{dt}\right|_{max} = 2\pi \times 250 \times 10^3\ \hat{v}_o = \text{SR}$

$\Rightarrow \hat{v}_o = \frac{10 \times 10^6}{2\pi \times 10^3 \times 250} = 6.37\,j\text{V}$

2.126

$v_o = 10\sin\omega t \Rightarrow \frac{dv_o}{dt} = 10\omega\cos\omega t \Rightarrow \left.\frac{dv_o}{dt}\right|_{max}$

$= 10\,\omega$

The highest frequency at which this output is possible is that for which:

$\left.\frac{dv_o}{dt}\right|_{max} = \text{SR} \Rightarrow 10\omega_{max} = 60 \times 10^{+6} \Rightarrow \omega_{max}$

$= 6 \times 10^5$

$\Rightarrow f_{max} = 45.5\text{ kHz}$

2.127

a) $v_i = 0.5,\ v_o = 10 \times 0.5 = 5\text{ V}$

Output distortion will be due to slew-Rate limitation and will occur at the frequency for which

$\left.\frac{dv_o}{dt}\right|_{max} = \text{SR}$

$\omega_{max} \times 5 = \frac{1}{10^{-6}} = 2 \times 10^5\text{ rad/s} \Rightarrow f_{max}$

$= 31.8\text{ kHz}$

b) The output will distort at the value of V_i that results in $\left.\frac{dv_o}{dt}\right|_{max} = \text{SR}$.

$v_o = 10\ v_i \sin 2\pi \times 20 \times 10^3$

$\left.\frac{dv_o}{dt}\right|_{max} = 10v_i \times 2\pi \times 20 \times 10^3$

Thus $v_i = \frac{1/10^{-6}}{10 \times 2\pi \times 20 \times 10^3} = 0.795\text{ V}$

c) $v_i = 50\text{ mV}$ $\quad v_o = 500\text{ mV} = 0.5\text{ V}$

Slew rate begins at the frequency for which ωx 0.5 = SR which gives $\omega_i = \frac{1/10^{-6}}{0.5} = 2 \times 10^6$ rad/s or

$f = 318.3$ kHz. However the small signal 3 dB frequency is

$$f_{3dB} = \frac{f_t}{1 + \frac{R_2}{R_1}} = \frac{2 \times 10^6}{10} = 200 \text{ kHz}$$

Thus the useful frequency range is limited at 200 kHz.

d) for $f = 5$ kHz, the slew Rate limitation occurs at the value of v_i given by

$$\omega_i \times 10 v_i = \text{SR} \Rightarrow v_i = \frac{1/10^{-6}}{2\pi \times 5 \times 10^3 \times 10}$$

$$= 3.18 \text{ V}$$

Such an input voltage, however would ideally result in an output of 31.8V which exceeds V_{omax}.

Thus $V_{imax} = \frac{V_{omax}}{10} = 1$ V peak.