Microelectronic Circuits Analysis and Design 3rd edition Rashid Solutions Manual

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Chapter 2

2.1

(a) $v_d = v_O/A_o = \pm 15\text{ V}/2 \times 10^5 = \pm 75\ \mu\text{V}$

(b) $i_i = v_d/R_i = \pm 75\ \mu\text{V}/2 \times 10^6 = \pm 37.5 \times 10^{-12}\text{ A}$

2.2

$$v_O = (v_+ - v_-) = A_o v_S = 10^5 \times 50 \times 10^{-6} = 5\text{ V}$$

2.3

$$v_O = -A_o v_d = -A_v v_S = -10^5 \times 10 \times 10^{-6} = -1\text{ V}$$

2.4

$$v_O = A_o\,(v_+ - v_-) = 2 \times 10^5\,(0 - 2\sin 377t)$$

Output saturates at ±14 V.

2.5

$$v_O = A_o\,(v_+ - v_-) = 2 \times 10^5\,(75 + 25)10^{-6} = +20\text{ V; at saturation, } v_O = +14\text{ V}$$

2.6

(a) $v_d = v_1 - v_2 = (120 - 80)\ \mu\text{V} = 40\ \mu\text{V}$

(b) $v_c = \dfrac{v_1 + v_2}{2} = \dfrac{200}{2} = 100\ \mu\text{V}$

(c) 20 log CMMR = 90

log CMMR = 90/20 or $|A_d/A_c| = 31{,}622$

$$|A_c| = |A_d|/31{,}622 = \frac{2 \times 10^5}{31{,}622} = \pm 6.32$$

(d) $v_O = A_d v_d \pm A_c v_c = 2 \times 10^5 \times 40 \times 10^{-6} \pm 6.32 \times 80 \times 10^{-6}$

$= 8 \pm 50.56 \times 10^{-6}\text{ V}$

2.7

(a) $v_d = v_2 - v_1 = 60\ \mu\text{V} - 100\ \mu\text{V} = -40\ \mu\text{V}$

(b) $v_c = \dfrac{v_1 + v_2}{2} = \dfrac{60 + 100}{2}\ \mu\text{V} = 80\ \mu\text{V}$

(c) 20 log CMRR = 90 dB

log CMRR = 4.5

$$\left|\frac{A_d}{A_c}\right| = 3.1622 \times 10^4$$

$$A_c = \frac{A_d}{3.1622 \times 10^4} = \frac{2 \times 10^5}{3.1622 \times 10^4} = 6.3247$$

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(d) $v_O = A_d\, v_d + A_c\, v_c$

$= 2 \times 10^5\,(-40 \times 10^{-6}) + 6.3247 \times 80 \times 10^{-6}$

$= -8 \pm 5.05976 \times 10^{-4} = -7.9994$ V or -8.00050 V

2.8

Choose 1 kΩ < R_1 < 10 MΩ; let R_1 = 10 kΩ.

$$A_f = 100 = 1 + R_F/R_1,\ R_F = 900\ \text{k}\Omega$$

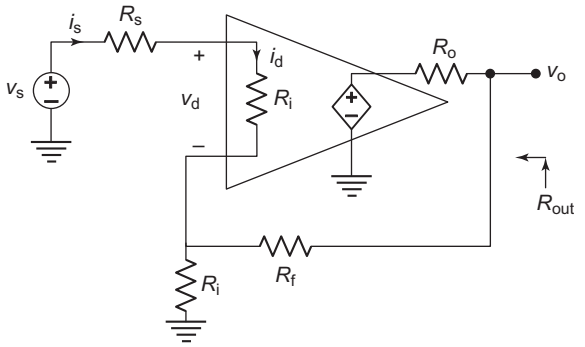
$$v_O = v_S\,(1 + R_F/R_1) = 100 \times 10^{-3} \times 100 = 10\ \text{V}$$

Problem 2.8

```
VS    1     0     DC    100MV
RS    1     2     1K
RF    4     3     990K
R1    3     0     10K
VCC   5     0     15V
VEE   0     6     15V
XA1   2     3     4     0     OPAMP
. SUBCKT OPAMP    1     2     3     4
RI    1     2     1E12
RO    5     3     50
EA    5     4     1     2     5E5
. ENDS OPAMP
. PROBE
. TF V(4) VS
. END
```

2.9

$$i_S = i_d = \frac{v_d}{R_i},\ v_d = \frac{v_O}{A_d}$$



Then

$$i_S = i_d = \frac{v_O}{A_o R_i},\ R_i >> R_s$$

Substituting for $v_O = \left(1 + \frac{R_f}{R_1}\right) v_S$

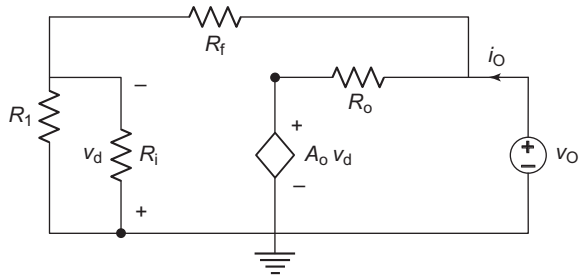
$$i_S = \frac{(1 + R_f/R_1)}{A_o\ R_i} v_S,\quad R_{in} = \frac{v_S}{i_S} = \frac{A_o\ R_i}{1 + R_f/R_1} \qquad \text{(i)}$$

i_O from the circuit

$$i_O = \frac{v_O - A_o v_d}{R_o} + \frac{v_O}{R_i + R_f} \qquad \text{(ii)}$$

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Also $-v_d = \dfrac{R_1}{R_1 + R_f} v_O$ Assuming $R_i >> R_1$ (iii)

From (ii) and (iii),

$$\frac{1}{R_{out}} = \frac{i_O}{V_o} = \frac{1 + R_1 A_o/(R_1 + R_f)}{R_o} + \frac{1}{R_1 + R_f}$$

Assuming $(R_1 + R_f) >> \dfrac{R_o}{1 + A_o R_1/(R_1 + R_f)}$ (iv)

$$R_{out} = \frac{R_o}{1 + A_o R_1/(R_1 + R_f)}$$

(a) From (i)

$$R_{in} = \frac{A_o\ R_i}{1 + R_f/R_1} = \frac{25 \times 10^3 \times 10^{12}}{1 + 990\text{ k}/10\text{ k}} = 250 \times 10^{12}\ \Omega$$

$$R_{out} = \frac{50}{1 + 25 \times 10^3 \times 10^4/(10\text{ k} + 990\text{ k})} = \frac{50}{1 + 250} = 0.2\ \Omega$$

(b) $R_{in} = 5 \times 10^5 \times 10^{12}/100 = 5 \times 10^{15}\ \Omega$

$$R_{out} = \frac{50}{1 + 5 \times 10^5 \times 10^4/1000 \times 10^3} = 0.01\ \Omega$$

2.10

Let $R_1 =$ 10 kΩ. Then

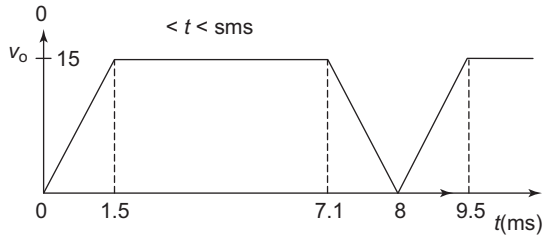
$$A_v = 10 = \left(1 + \frac{R_F}{R_1}\right),\ R_F = 90\ \text{k}\Omega$$

$$v_O = 500\text{ mV} \times 10 = 5\text{ V}$$

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2.11



v_S needed for $v_O = \pm 15$ V

$$\pm 15 = v_S\left(1+\frac{R_F}{R_1}\right) = v_S\left(1+\frac{20}{5}\right),\ v_S = \pm 3 \text{ V}$$

$$v_S = 2t,\ t = \frac{3}{2} = 1.5 \text{ ms} \qquad 0 < t < 5 \text{ ms}$$

$$3 = -\frac{10}{3\times 10^{-3}}t + \frac{80}{3}$$

$$t = \frac{71}{10} \text{ ms}$$

2.12

$$v_- = \frac{v_O R_1}{R_1 + R_F} \tag{i}$$

$$v_O = A_o v_d = A_d (v_S - v_-)$$

$$v_- = v_S - \frac{v_O}{A_d} \tag{ii}$$

From (i) and (ii)

$$v_S = v_O\left(\frac{1}{A_o} + \frac{R_1}{R_1 + R_f}\right)$$

$$A_f = \frac{v_O}{v_S} = \frac{A_o(R_1 + R_f)}{R_1 + R_F + A_o R_1} \tag{iii}$$

(a) $A_f = \dfrac{5\times 10^5 \times 40\times 10^3}{40\times 10^3 \times 5\text{ k} \times 10^5 \times 10^4} = 3.999968$

(b) $v_O = A_f v_S = 3.999968\, v_S$

(c) For $A_o \to \infty$, $A_f = \left(1+\dfrac{R_F}{R_1}\right) = 1 + \dfrac{30\text{ k}}{10\text{ k}} = 4$, $v_O = 4\, v_S$ Error insignificant

2.13

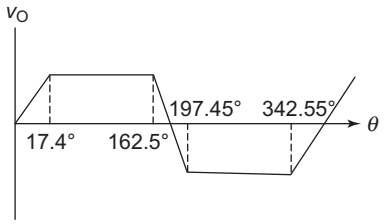
$$v_O = v_S\left(1+\frac{R_F}{R_1}\right) = 5\, v_S$$

$$v_O = \pm 15 \text{ V}$$

$$v_O = 50 \sin 2000\,\pi t = \pm 15 \text{ V},\ \theta = \sin^{-1}\frac{15}{50},\ \theta = 17.45°$$

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2.14

Assuming v_d to be negligible, $v_O \simeq v_+ = v_S$. Hence,

$$v_O = v_S = 5 \text{ V}$$

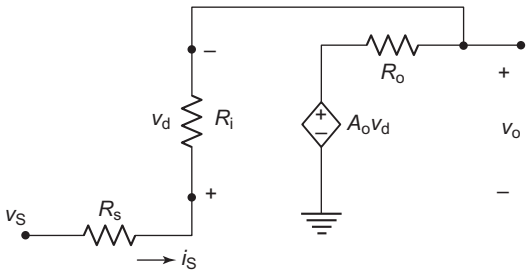
$$i_S = i_i = v_d/R_i \quad \text{and}$$

$$v_d = v_O/A_o$$

$$i_S = i_i = \frac{v_O}{A_o R_i} \simeq \frac{v_+}{A_o R_i}, \quad \frac{v_S}{i_S} = R_s + A_o R_i$$

$$= 10 \text{ k} + 5 \times 10^5 \times 10^5 \times 2 \times 10^6 \simeq 10^{12}\ \Omega$$

$$i_O = \frac{v_O - A_o v_d}{R_o} + \frac{v_O}{R_i + R_s} \tag{i}$$



Also

$$v_d = -\frac{v_O R_i}{R_i + R_s} \tag{ii}$$

(i) and (ii) give

$$i_O = \frac{v_O + A_o v_O R_i/(R_i + R_s)}{R_o} + \frac{v_O}{R_i + R_s}$$

$$\frac{1}{R_{out}} = \frac{i_O}{v_O} = \frac{1 + A_o\ R_i/(R_i + R_s)}{R_o} + \frac{1}{R_i + R_s}$$

$$\frac{R_o}{1 + A_o\ R_i/(R_i + R_s)} << (R_i + R_s)$$

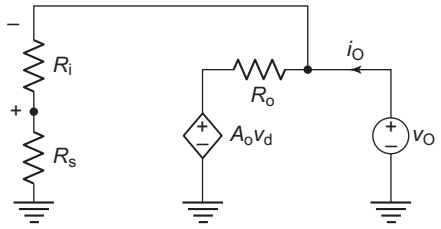
Hence

$$R_{out} = \frac{R_o}{1 + A_o\ R_i/(R_i + R_s)}$$

$$= \frac{75}{1 + 5 \times 10^5 \times 2 \times 10^6/(2 \times 10^6 + 10^4)} \simeq 15 \times 10^{-5}\ \Omega$$

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2.15

(a) From Eq. (2.13)

$$f_{bw} = A_o f_b = 2 \times 10^5 \times 10 = 2 \text{ MHz}$$

From Eq. (2.31) we get

$$A_f(j\omega) = \frac{1 + R_F / R_1}{1 + jf\,(1 + R_F/R_1)/f_{bw}}$$

$$R_F = 50\ \text{k}\Omega,\ R_1 = 15\ \text{k}\Omega$$

$$\therefore \quad A_f(j\omega) = \frac{1 + 50\,\text{k}/15\,\text{k}}{1 + jf\,(1 + 50\,\text{k}/15\,\text{k})/2 \times 10^6}$$

$$= \frac{4.333}{1 + j\,100 \times 10^3\,(4.333)/2 \times 10^6}$$

$$= \frac{4.333}{1 + j\,0.2167} = 4.235\ \angle -12.23°$$

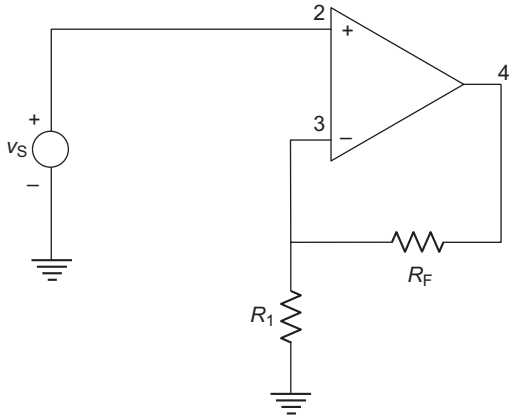
From Eq. (2.32)

$$f_c = \beta A_o f_b = \frac{R_1}{R_1 + R_F} A_o f_b$$

$$= \frac{15\,\text{k}}{15\,\text{k} + 50\,\text{k}} \times 2 \times 10^5 \times 10\ \text{Hz}$$

$$= 461.54\ \text{kHz}$$

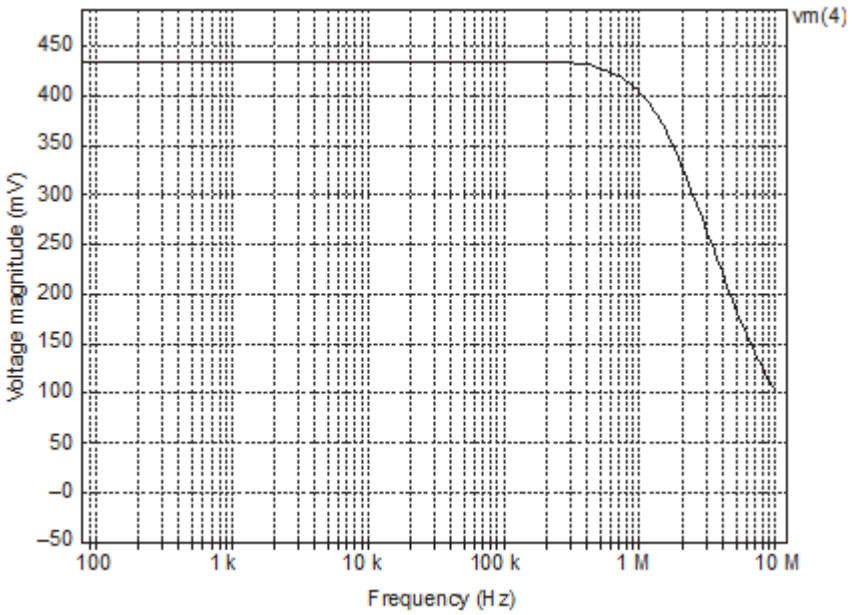
(b)



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```
VS    2     0     AC    0.1V
RF    4     3     50K
R1    3     0     15K
XA1   2     3     4     0
* Vi+Vi-   Vo+   Vo-
* Subcircuit definition for UA741-AC
. SUBCKT UA741-AC     1     2     3     4
* Subcircuit name    Vi+   Vi-   Vo+   Vo-
RI    1     2     2MEG
RO    6     3     75
GB    4     5     1     2     0.5M
R1    5     4     10K
C1    5     4     1.5619UF
EA    4     6     54    2E+5
D1    3     7     DMOD
D2    4     7     DMOD
. MODEL DMOD D (BV = 14V)
. ENDS UA741-AC
. AC DEC 10 100 HZ 1 MEGHZ
. PRINT AC VM(4)
. PROBE
. END
```



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2.16

(a) $R_1 = R_F = 15\ \text{k}\Omega$

$f_{bw} = A_o f_b = 2 \times 10^5 \times 10 = 2\ \text{MHz}$

From Eq. (2.31)

$$A_f(j\omega) = \frac{1 + R_F/R_1}{1 + jf\,(1 + R_F/R_1)/f_{bw}}$$

$$= \frac{1+1}{1 + jf\,(1+1)/2\times10^6} = \frac{2}{1 + j\,100 \times 10^3 \times 10^{-6}}$$

$$= \frac{2}{1 + j\,0.1} = 1.998\ \angle -5.71°$$

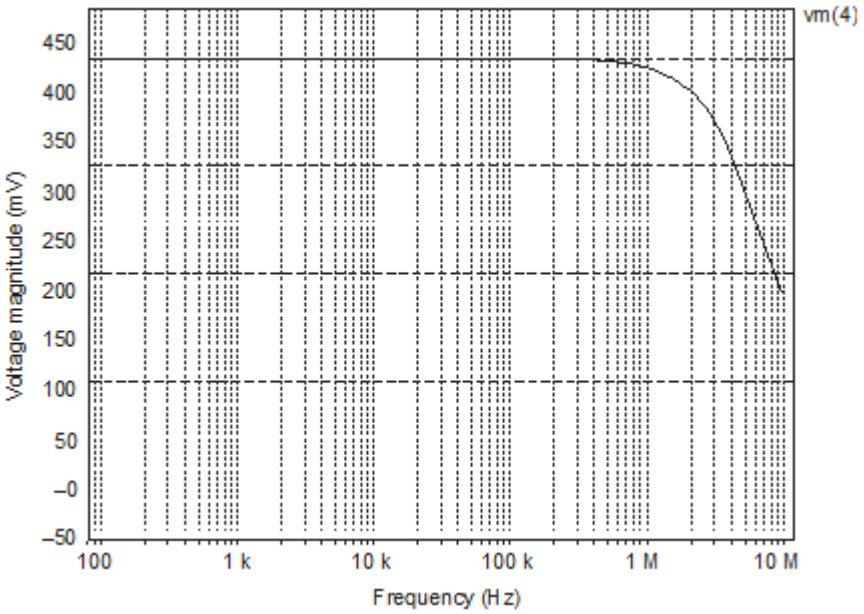
(b) From Eq. (2.32)

$$f_c = \beta A_o f_b = \frac{15\ \text{k}}{15\ \text{k} + 15\ \text{k}} \times 2 \times 10^5 \times 10 = 1\ \text{MHz}$$

```
VS    2     0     AC    0.1V
RF    4     3     15K
R1    3     0     15K
XA1   2     3     4     0
* Vi+Vi-   Vo+   Vo-
* Subcircuit definition for UA741-AC
* SUBCKT UA741-AC   1     2     3     4
* Subcircuit name  Vi+   Vi-   Vo+   Vo-
RI    1     2     2MEG
RO    6     3     75
GB    4     5     1     2     0.5M
R1    5     4     10K
C1    5     4     1.5619UF
EA    4     6     5     4     2E+5
D1    3     7     DMOD
D2    4     7     DMOD
. MODEL DMOD D (BV = 14V)
. ENDS UA741-AC
. AC DEC 10 100HZ 1MEGHZ
. PRINT AC VM(4)
. PROBE
. END
```


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2.17

From Eq. (2.35)

$$v_O = \left(1 + \frac{R_F}{R_B}\right)\left(\frac{R_A}{R_a}v_a + \frac{R_A}{R_b}v_b + \frac{R_A}{R_c}v_c\right)$$

$$R_A = R_a \parallel R_b \parallel R_c = \frac{20}{3}\ \text{k}\Omega$$

$$v_O = \left(1 + \frac{40\ \text{k}}{20\ \text{k}}\right)\left(\frac{20 \times 2}{3 \times 20} + \frac{20(-3)}{3 \times 20} + \frac{20(-2)}{3 \times 20}\right)$$

$$= 3\left(\frac{2}{3} - 1 - \frac{2}{3}\right) = -3\ \text{V}$$

2.18

$$i_S = \frac{v_S}{R_s} = \frac{50\ \text{mV}}{5\ \text{k}\Omega} = 10\ \mu\text{A}\ (R_1 = R_s)$$

$$v_O = -A_f v_S, \frac{5\ \text{V}}{50\ \text{mV}} = 100 = A_f$$

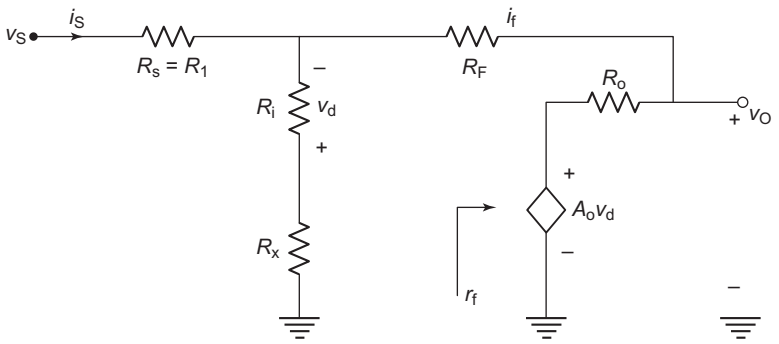
$$\frac{R_F}{R_1} = 100, R_F = 100 \times 5\ \text{k} = 500\ \text{k}\Omega$$

$$R_x = R_1 \parallel R_F = 5\ \text{k} \parallel 500\ \text{k} = 4.95\ \text{k}\Omega$$

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2.19



Assume $R_i >> R_x$

$$R_{in} = \frac{v_S}{i_S} = R_1 + R_i \parallel r_f \tag{i}$$

where $$r_f = -\frac{v_d}{i_f}$$

$$-v_d = i_f R_F + R_o i_f + A_o v_d$$

or $$r_f = \frac{-v_d}{i_f}, \frac{-v_d}{i_f}(1 + A_o) = R_F + R_o$$

$$r_f = \frac{R_F + R_o}{1 + A_o} \tag{ii}$$

The expression for R_{out} is the same as in Problem 2.14.

(a) $$R_{in} = 5\text{ k} + 10^{12} \parallel \frac{500 \times 10^3 \times 50}{1 + 25 \times 10^3}$$

$$\simeq 5\text{ k} + 10^{12} \parallel 20 \simeq 5020\ \Omega$$

$$R_{out} = \frac{R_o}{1 + A_o\, R_i/(R_i + R_s)} = \frac{50}{1 + 25 \times 10^3 \times 10^{12}/(10^{12} + 5\text{ k})}$$

$$\cong \frac{50 \times 10^{-3}}{25} \simeq 2 \times 10^{-3}\ \Omega$$

From Eq. (2.45)

$$A_f = -\frac{R_F/R_1}{1 + (1 + R_F/R_1)/A_o}$$

$$= \frac{-500\text{ k}/5\text{ k}}{1 + (1 + 500\text{ k}/5\text{ k})/25 \times 10^3} = -99.60$$

$$v_O = -50 \times 10^{-3} \times 99.6 = -4.98\text{ V}$$

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(b) $R_{in} = 5\text{ k} + 10^{12} \,||\, \dfrac{500 \times 10^3 + 50}{1 + 5 \times 10^5}$

$= 5\text{ k} + 10^{12} \,||\, 1 \simeq 5001\ \Omega$

$$R_{out} = \frac{R_o}{1 + A_o\, R_i/(R_i + R_s)} = \frac{50}{1 + 5 \times 10^5 \times 10^{12}/(10^{12} + 5\text{ k})}$$

$$\simeq 100 \times 10^{-6}\ \Omega = 10^{-4}\ \Omega$$

(c) From Eq. (2.45)

$$A_f = -\frac{R_F/R_1}{1 + (1 + R_E/R_1)/A_o}$$

$$= \frac{-500\text{ k}/5\text{ k}}{1 + (1 + 500\text{ k}/5\text{ k})/5 \times 10^5} \cong -99.98$$

Problem 2.19

```
VIN   4    0    DC   10MV
R1    4    2    5K
RF    2    3    500K
RX    1    0    4.95K
XA1   1    2    3    0   LF411-DC
. SUBCKT LF411-DC  1   2   3   4
RI    1    2    1E12
RO    5    3    50
EA    4    5    1    2   25E3
. ENDS LF411-DC
. TF V(3) VIN
. PROBE
. END
```

2.20

$$A_f = -\frac{R_F}{R_1} = \infty,\ v_O = A_f v_S = \infty \rightarrow \text{Saturation}$$

$$v_O = -14\text{ V}$$

2.21

(a) From Eq. (2.46)

$$x = \frac{1}{A_o}\left(1 + \frac{R_F}{R_1}\right) = \frac{1}{2 \times 10^5}\left(1 + \frac{50\text{ k}}{10\text{ k}}\right) = 3 \times 10^{-5}$$

From Eq. (2.45)

$$A_f = -\frac{R_F}{R_1(1 + x)} = -\frac{50\text{ k}}{10\text{ k}\ (1 + 3 \times 10^{-5})} = -4.9998$$

(b) $v_O = A_f\, v_S = -4.9998 \times 100 \times 10^{-3} = -0.4998\text{ V}$

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(c) From Eq. (2.47)

$$\Delta V_o = x\,\frac{R_F}{R_1} = 3 \times 10^{-5} \times 5 = 15 \times 10^{-5}$$

$$= 0.15 \text{ mV} = 0.03\%$$

2.22

(a) From Eq. (2.13)

$$f_{bw} = A_o f_b = 2 \times 10^5 \times 10 = 2 \text{ MHz}$$

From Eq. (2.56)

$$A_f = -\frac{R_F/R_1}{1 + jf\,(1 + R_F/R_1)/f_{bw}} = \frac{-50\text{ k}/15\text{ k}}{1 + jf\,(1 + 150\text{ k}/15\text{ k})/2 \times 10^6}$$

$$= \frac{-3.333}{1 + j\,(100 \times 10^3)(1 + 3.333)/2 \times 10^6}$$

$$= \frac{-3.333}{1 + j\,0.216} = -3.258\,\angle -12.19°$$

$$\beta = \frac{R_1}{R_1 + R_F} = \frac{15\text{ k}}{15\text{ k} + 50\text{ k}} = 0.230$$

$$f_c = \beta f_{bw} = 0.23 \times 2 \times 10^6 = 460 \text{ kHz}$$

(b) Problem 2.22

```
VS    1    0    AC   0.1V
R1    1    3    15K
RF    3    4    50K
RX    2    0    10K
XA1   2    3    4    0   UA741-AC
. SUBCKT UA741-AC  1   2   3   4
RI    1    2    2MEG
RO    6    3    75
GB    4    5    1    2   0.5
R1    5    4    10K
C4    5    4    1.5619UF
EA    4    6    5    4   2E5
D1    3    7    DMOD
D2    4    7    DMOD
. MODEL DMOD D (BV = 14V)
. ENDS UA741-AC
. PRINT AC VM(4)
. AC DEC  10   100  1MEGHZ
. PROBE
. END
```


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2.23

(a) $R_1 = R_F = 15\ \text{k}\Omega$

$$f_{bw} = A_o f_b = 2 \times 10^5 \times 10 = 2\ \text{MHz}$$

From Eq. (2.56)

$$A_f = -\frac{R_F/R_1}{1 + jf\,(1 + R_F/R_1)/f_{bw}} = \frac{-1}{1 + j\,100 \times 10^3\,(1+1)/2 \times 10^6}$$

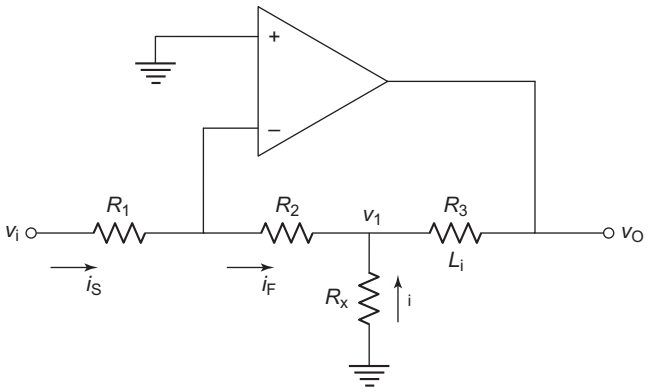
$$= -\frac{1}{1 + j\,0.1} = -0.99\,\angle -5.71°$$

$$f_c = \beta f_{bw}, \quad \beta = 0.5$$

$\therefore$ $f_c = 0.5 \times 2 \times 10^6 = 1\ \text{MHz}$

2.24

(a)



Ignoring v_d (virtual ground)

$$i_S = \frac{v_i}{R_1} = i_F,\ v_1 = -i_F R_2 = -\frac{v_i}{R_1} R_2 = -v_i \frac{R_2}{R_1}$$

$$i = -\frac{v_1}{R_x} = +\ v_1 \frac{R_2}{R_1 R_x}$$

$$i_1 = i_F + i = \frac{v_i}{R_1} + v_i \frac{R_2}{R_1 R_x}$$

Also $$v_O = v_1 - i_1 R_3 = -\ v_i \frac{R_2}{R_1} - R_3 \left(\frac{1}{R_1} + \frac{R_2}{R_1\ R_x}\right) v_i$$

$$\frac{v_O}{v_i} = -\frac{R_2}{R_1}\left(1 + \frac{R_3}{R_2} + \frac{R_3}{R_x}\right)$$

$$-10 = -\frac{20\ \text{k}}{50\ \text{k}}\left(1 + \frac{20\ \text{k}}{20\ \text{k}} + \frac{20\ \text{k}}{R_x}\right)$$

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$$10 = \frac{2}{5}\left(2 + \frac{20\text{ k}}{R_x}\right), 25 = 2 + \frac{20\text{ k}}{R_x}$$

$$R_x = \frac{20\text{ k}}{23} = 869.5\ \Omega$$

(b) SR = 6 V/μs, $f_{s(max)} = \dfrac{SR}{2\pi V_m}$

$$f_{s(max)} = \frac{6 \times 10^6}{2\pi \times 10} = 95\text{ kHz}$$

(c)

```
VS    5    0    AC 10MV
R1    5    3    50K
R2    2    0    1K
R3    3    6    20K
RX    6    0    869.5
R4    4    6    20K
XA1   2    3    4   0   UA741-AC
. SUBCKT UA741-AC1   2   3   4
RI    1    2    2MEG
RO    6    3    75
GB    4    5    1   2   0.5 M
R1    5    4    10K
C1    5    4    1.5619UF
EA    4    6    5   4   1E5
D1    3    7    DMOD
D2    4    7    DMOD
. MODEL DMOD D (BV = 14V)
. ENDS UA741-AC
. AC DEC 10 100 20MEGHZ
. PRINT AC VM(4) VP(4)
. PROBE
. END
```

2.25

From Eq. (2.60)

$$v_O = -\left(\frac{R_F}{R_1}v_1 + \frac{R_F}{R_2}v_2 + \frac{R_F}{R_3}v_3\right)$$

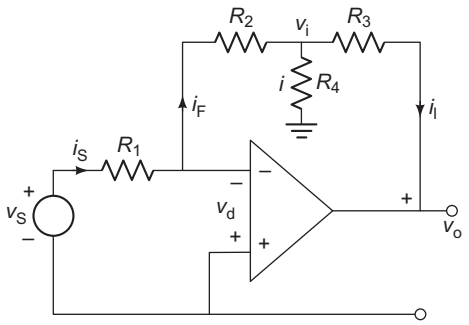
$$= -\left(\frac{40\text{ k}}{20\text{ k}} \times 2 + \frac{40\text{ k}}{20\text{ k}}(-3) + \frac{40\text{ k}}{20\text{ k}}(-2)\right)$$

$$= -(4 - 6 - 4) = +6\text{ V}$$

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2.26



$$i_S = i_F = \frac{v_S}{R_1}, \quad v_1 = -i_F R_2 = -\frac{v_S}{R_1} R_2$$

$$\therefore \qquad i = -\frac{v_1}{R_4} = +v_S \frac{R_2}{R_1 R_4}$$

$$i_1 = i_F + i = \frac{v_S}{R_1} + v_S \frac{R_2}{R_1 R_4}$$

Also $$v_O = v_1 - i R_3 = -\frac{v_S}{R_1} R_2 - v_S \frac{R_2}{R_1 R_4} R_3 + \frac{v_S}{R_1} R_3$$

$$= -v_S \frac{R_2}{R_1} - R_3 \left(\frac{1}{R_1} + \frac{R_2}{R_1 R_4} \right) v_S$$

$$\frac{v_O}{v_S} = -\frac{R_2}{R_1} - R_3 \left(\frac{1}{R_1} + \frac{R_2}{R_1 R_4} \right)$$

$$= -\frac{R_2}{R_1} \left(1 + \frac{R_3}{R_2} + \frac{R_3}{R_4} \right), \qquad \text{Given } \frac{v_O}{v_S} = \frac{-12}{0.05} = -240$$

Taking $R_2 = 6\,R_1$ and $R_3 = 9\,R_4$

$$\therefore \qquad 240 = 6 \left(1 + 9 + \frac{R_3}{R_2} \right) = 6 \left(10 + \frac{R_3}{R_2} \right)$$

$$\frac{R_3}{R_2} = 30$$

Let $R_2 = 10$ kΩ and $R_3 = 300$ kΩ. Then

$$R_4 = \frac{300\text{ k}}{9} = \frac{100}{3}\text{ k} = 33.33\text{ kΩ}$$

$$R_1 = \frac{10}{6}\text{ kΩ}$$

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2.27

From Eq. (2.67)

$$v_O = (v_a - v_b)\,\frac{R_F}{R_1}, \quad 5 = (220 - 200)\text{ mV} \times \frac{R_F}{R_1}$$

$$\frac{R_F}{R_1} = 250$$

Let $R_a = R_1 = 2\ \text{k}\Omega$; then

$$R_F = 0.5\ \text{M}\Omega = R_x$$

2.28

$$v_O = -A_o\,(v_+ - v_-) \tag{i}$$

$$R_i = 10^{12}$$

Ignoring current through R_i

$$v_+ = \frac{v_a\ R_x}{R_a + R_x} \text{ and } v_- = \frac{R_F}{R_1 + R_F} \cdot v_b + \frac{R_1}{R_1 + R_F} \cdot v_O$$

Substitution in (i) gives

$$v_O = -\frac{A_o\ v_a\ R_x}{R_a + R_x} + \frac{A_o\ R_F\ v_b}{R_1 + R_F} + \frac{A_o\ R_1\ v_O}{R_1 + R_F}$$

For $R_a = R_1$ and $R_F = R_x$

$$v_O = -\frac{A_o\ v_a\ R_F}{R_1 + R_F} + A_o\,\frac{R_F\ v_b}{R_1 + R_F} + \frac{A_o\ R_1\ v_O}{R_1 + R_F}$$

$$= -A_o \frac{R_F}{R_1 + R_F}\,(v_a - v_b) + A_o\,\frac{R_1\ v_O}{R_1 + R_F} \tag{ii}$$

or

$$v_O = \frac{A_o\ R_F/(R_1 + R_F)}{1 - A_o R_1/(R_1 + R_F)}\,(v_b - v_a)$$

$$= \frac{A_o\ R_F\,(v_b - v_a)}{R_1(1 - A_o) + R_F}$$

(a) $$v_O = \frac{25 \times 10^3 \times 0.5 \times 10^6 (200 - 220) \times 10^{-3}}{2 \times 10^3 (1 - 25 \times 10^3) + 0.5 \times 10^6} = \frac{-250 \times 10^6}{2 \times 10^3 - 50 \times 10^6 + 0.5 \times 10^6} \simeq 5.05\ \text{V}$$

(b) $$v_O = \frac{-5 \times 10^5 \times 0.5 \times 10^6 \times 20 \times 10^{-3}}{2 \times 10^3 (1 - 5 \times 10^5) + 0.5 \times 10^6} \simeq 5\ \text{V}$$

2.29

(a) $A_o \to \infty$, Eq. (ii) from the last problem reduces to

$$|A_f| = v_O/v_b - v_a = \frac{R_F}{R_1}, \quad 200 = \frac{R_F}{R_1}$$

Let $R_1 = 2.5\ \text{k}\Omega$. Then $R_F = 0.5\ \text{M}\Omega$.

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(b) For $A_o = 5 \times 10^5$

$$v_O = \frac{A_o R_F}{R_1 - R_1 A_o + R_F}(v_b - v_a)$$

$$= \frac{5 \times 10^5 \times 0.5 \times 10^6 \times 20 \times 10^{-3}}{2.5 \times 10^3 - 2.5 \times 10^3 \times 5 \times 10^5 + 0.5 \times 10^6} = 4 \text{ V}$$

$$A_f \Big|_{\infty} = 200 \times 20 \times 10^{-3} = 4 \text{ V}$$

Hardly any error.

2.30

From Problem 2.28

$$v_O = -\frac{A_o v_a R_x}{R_a + R_x} + \frac{A_o R_F v_b}{R_1 + R_F} + \frac{A_o R_1 v_b}{R_1 + R_F}$$

$$\therefore \quad v_O = \frac{+5 \times 10^5 \times 15 \times 10^{-3} \times 20 \times 10^3}{2 \times 10^3 + 20 \times 10^3} + \frac{5 \times 10^5 \times 50 \times 10^3 \times 5 \times 10^{-3}}{5 \times 10^3 + 50 \times 10^3}$$

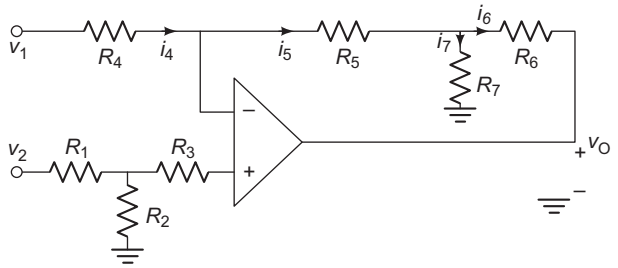
$$+ \frac{5 \times 10^5 \times 5 \times 10^3 v_O}{5 \times 10^3 + 50 \times 10^3}$$

$$= 6.818 \times 10^3 + 2.777 \times 10^3 + 4545 \times 10^3 \, v_O$$

$$v_O \simeq -0.2 \text{ V}$$

2.31

(a)



$$v_+ = \frac{R_2}{R_1 + R_2} v_2, \qquad i_4 = \frac{v_1 - v_-}{R_4}, \qquad i_5 = \frac{v_- - v_1}{R_5}$$

$$i_7 = \frac{v_3}{R_7}, \qquad i_6 = \frac{v_3 - v_O}{R_6}$$

$$i_4 = i_5$$

$$\frac{v_1 - v_-}{R_4} = \frac{v_- - v_3}{R_5} \tag{i}$$

$$i_5 = i_6 + i_7, \quad \frac{v_- - v_3}{R_5} = \frac{v_3 - v_O}{R_6} + \frac{v_3}{R_7}$$

$$\therefore \quad -\frac{v_3}{R_5} - \frac{v_3}{R_6} - \frac{v_3}{R_7} = -\frac{v_-}{R_5} - \frac{v_O}{R_6}$$

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$$-v_3\left(\frac{1}{R_5}+\frac{1}{R_6}+\frac{1}{R_7}\right)=-\frac{v_-}{R_5}-\frac{v_O}{R_6} \qquad \text{(ii)}$$

From (i)

$$\frac{v_1}{R_4}-\frac{v_-}{R_4}=\frac{v_-}{R_5}-\frac{v_3}{R_5}$$

$$\frac{v_1}{R_4}-v_-\left(\frac{1}{R_4}+\frac{1}{R_5}\right)=-\frac{v_3}{R_5}$$

$$\frac{v_1}{R_4}-v_-\left(\frac{R_4+R_5}{R_4\,R_5}\right)=-\frac{v_3}{R_5} \qquad \text{(iii)}$$

From (ii)

$$-v_3\left(\frac{R_5\,R_6+R_6\,R_7+R_5\,R_7}{R_5\,R_6\,R_7}\right)=-\frac{v_-}{R_5}-\frac{v_O}{R_6} \qquad \text{(iv)}$$

From (iii) using (iv)

$$\frac{v_1}{R_4}-v_-\frac{(R_4+R_5)}{R_4\,R_5}=\frac{1}{R_5}\frac{R_5\,R_6\,R_7}{R_5\,R_6+R_6\,R_7+R_5\,R_7}\times\left[-\frac{v_-}{R_5}-\frac{v_O}{R_6}\right]$$

Let $$X=\frac{R_5\,R_6\,R_7}{R_5\,R_6+R_6\,R_7+R_5\,R_7}$$

$$\frac{v_1}{R_4}-v_-\frac{R_4+R_5}{R_4\,R_5}=-\frac{1}{R_5}X\frac{v_-}{R_5}-\frac{1}{R_5}X\frac{v_O}{R_6}$$

$\therefore$

$$-v_-\frac{R_4+R_5}{R_4\,R_5}+\frac{1}{R_5}X\frac{v_-}{R_5}=-\frac{v_1}{R_4}-\frac{1}{R_5}X\frac{v_O}{R_6}$$

$$-v_-\left[\frac{R_4+R_5}{R_4\,R_5}+\frac{1}{R_5}X\frac{1}{R_5}\right]=-\frac{v_1}{R_4}-\frac{1}{R_5}X\frac{v_O}{R_6}$$

$$v_-=\frac{v_1/R_4+\left(\frac{1}{R_5}\right)X(v_O/R_6)}{(R_4+R_5)/R_4\,R_5-\left(\frac{1}{R_5}\right)X(1/R_5)}$$

Also $(v_+ - v_-)A_o = v_O$. Substituting for v_+ and v_-

$$\frac{R_2}{R_1+R_2}v_2-\frac{\frac{v_1}{R_4}+\left(\frac{1}{R_5}\right)X\left(\frac{v_O}{R_6}\right)}{\frac{(R_4+R_5)}{R_4\,R_5}-\left(\frac{1}{R_5}\right)X\left(\frac{1}{R_5}\right)}=\frac{v_O}{A_o}$$

$$\frac{R_2}{R_1+R_2}v_2-\frac{\frac{v_1}{R_4}}{\frac{(R_4+R_5)}{R_4\,R_5}-\left(\frac{1}{R_5}\right)X\left(\frac{1}{R_5}\right)}-\frac{\left(\frac{1}{R_5}\right)X\left(\frac{v_O}{R_6}\right)}{\frac{(R_4+R_5)}{R_4\,R_5}-\left(\frac{X}{R_5}\right)\cdot\left(\frac{1}{R_5}\right)}=\frac{v_O}{A_o}$$

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$$\frac{R_2}{R_1+R_2}v_2-\frac{v_1}{R_1\left[\frac{(R_4+R_5)}{R_4\ R_5}-\left(\frac{1}{R_5}\right)X\left(\frac{1}{R_5}\right)\right]}=\frac{1}{R_5}\cdot\frac{X}{\frac{(R_4+R_5)}{R_4\ R_5}-\left(\frac{X}{R_5}\right)\cdot\left(\frac{1}{R_5}\right)}v_o/R_6+\frac{v_O}{A_o}$$

$$v_O=\frac{\left[\frac{R_2}{(R_1+R_2)}\right]\cdot v_2-\frac{v_1}{R_4\left[\frac{(R_4+R_5)}{R_4\ R_5}-\left(\frac{1}{R_5}\right)X\left(\frac{1}{R_5}\right)\right]}}{\left(\frac{1}{R_5}\right)\frac{X}{\left[\frac{(R_4+R_5)}{R_4\ R_5}-\left(\frac{X}{R_5}\right)\cdot\left(\frac{1}{R_5}\right)\right]}\cdot\left(\frac{1}{R_6}\right)+\frac{1}{A_o}}$$

Assume A_o is large

$$V_O=\frac{\left[\frac{R_2}{(R_1+R_2)}\right]v_2-\frac{v_1}{R_4\left[\frac{(R_4+R_5)}{R_4\ R_5}-\left(\frac{1}{R_5}\right)X\left(\frac{1}{R_5}\right)\right]}}{\left(\frac{1}{R_5}\right)\frac{X}{\left[\frac{(R_4+R_5)}{R_4\ R_5}-\left(\frac{1}{R_5}\right)X\left(\frac{1}{R_5}\right)\right]}}$$

Given $R_4=R_5=R_6=R_7=50\ \text{k}\Omega$

$$V_O=\frac{\left[\frac{R_2}{(R_1+R_2)}\right]v_2-\frac{v_1}{\left[\frac{(R_4+R_5)}{R_4}-\frac{X}{R_5}\right]}}{\frac{X}{(R_4+R_5-X)}}$$

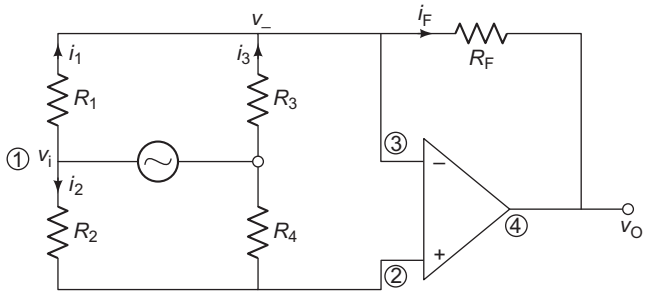
$$X=\frac{50\ \text{k}\times 50\ \text{k}\times 50\ \text{k}}{3(50\ \text{k}\times 50\ \text{k})}=\frac{50\ \text{k}}{3}$$

$$\therefore\qquad v_O=\frac{(150\ \text{k}/250\ \text{k})\,v_2-\frac{v_1}{(100\ \text{k}/50\ \text{k}-50\ \text{k}/3\times 50\ \text{k})}}{50\ \text{k}/3(100\ \text{k}-50\ \text{k}/3)}$$

$$=\frac{0.6\,v_2-0.6\,v_1}{50\ \text{k}/250\ \text{k}}\approx 3(v_2-v_1)$$

2.32

(a)



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$$i_1 = \frac{v_i - v_-}{R_1}, \quad i_3 = \frac{v_-}{R_3}, \quad i_F = i_1 + i_3$$

$$i_F = \frac{v_i}{R_1} - \frac{v_-}{R_1} - \frac{v_-}{R_3}$$

Also $$i_F = \frac{v_- - v_O}{R_F} = \frac{v_i}{R_1} - \frac{v_-}{R_1} - \frac{v_-}{R_3}$$

$$-\frac{v_O}{R_F} = \frac{v_i}{R_1} - v_- \left(\frac{1}{R_1} + \frac{1}{R_3} + \frac{1}{R_F}\right) \qquad \text{(i)}$$

$$i_2 = \frac{v_i - v_+}{R_2} = \frac{v_+}{R_4}, \qquad \frac{v_i}{R_2} - \frac{v_+}{R_2} = \frac{v_+}{R_4}$$

$$\frac{v_i}{R_2} = v_+ \left(\frac{1}{R_2} + \frac{1}{R_4}\right)$$

$$v_i = v_+ \frac{(R_2 + R_4)}{R_4}, \qquad v_+ = v_i \frac{R_4}{R_2 + R_4}$$

Also $$v_O = A_o (v_+ - v_-)$$

$$\frac{v_O}{A_o} = v_+ - v_-, \qquad v_- = v_+ - \frac{v_O}{A_o}$$

$$v_- = \frac{v_i R_4}{R_2 + R_4} - \frac{v_O}{A_o} \qquad \text{(ii)}$$

Substituting in (i)

$$-\frac{v_O}{R_F} = \frac{v_i}{R_1} - \frac{R_4}{R_2 + R_4} v_i \left(\frac{1}{R_1} + \frac{1}{R_3} + \frac{1}{R_F}\right) + \frac{v_O}{A_o}\left(\frac{1}{R_1} + \frac{1}{R_3} + \frac{1}{R_F}\right)$$

$$\frac{v_O}{R_F} - \frac{v_O}{A_o}\left(\frac{1}{R_1} + \frac{1}{R_3} + \frac{1}{R_F}\right) = \frac{v_i}{R_1} - \frac{R_4}{R_2 + R_4} v_i \left(\frac{1}{R_1} + \frac{1}{R_3} + \frac{1}{R_F}\right)$$

$$\frac{v_O}{v_i} = -\frac{1/R_1 - R_4/(R_2 + R_4)(1/R_1 + 1/R_3 + 1/R_F)}{1/R_F + 1/A_o\,(1/R_1 + 1/R_3 + 1/R_F)}$$

For large A_o

$$\frac{v_O}{v_i} = -\frac{1/R_1 - R_4/R_2 + R_4\,(1/R_1 + 1/R_3 + 1/R_F)}{1/R_F}$$

$$= -\frac{R_F}{R_1} + \frac{R_F R_4}{R_2 + R_4}\left(\frac{1}{R_1} + \frac{1}{R_3} + \frac{1}{R_F}\right)$$

$$\frac{v_O}{v_i} = \frac{-500\text{ k}}{40\text{ k}} + \frac{500\text{ k} \times 100\text{ k}}{80\text{ k} + 100\text{ k}}\left(\frac{1}{40\text{ k}} + \frac{1}{50\text{ k}} + \frac{1}{500\text{ k}}\right)$$

$$= -12.5 + 277\text{ k}\,(20 \times 10^{-6} + 20 \times 10^{-6} + 2 \times 10^{-6})$$

$$= -12.5 + 13.0 = 0.5$$

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Frequency response

$$A_{(j\omega)} = \frac{A_o}{1 + jf/f_b}, \quad \text{where } f_u = f_{b\omega} = A_o f_b$$

$$\frac{v_O}{v_i}(j\omega) = -\frac{1/R_1 - R_4/(R_2 + R_4)\,(1/R_1 + 1/R_3 + 1/R_F)}{1/R_F + 1/A_o(j\omega)\,(1/R_1 + 1/R_3 + 1/R_F)}$$

$$= -\frac{1/R_1 - R_4/(R_2 + R_4)\,(1/R_1 + 1/R_3 + 1/R_F)}{1/R_F + (1/R_1 + 1/R_3 + 1/R_F)((1 + jf/f_b)/A_o)}$$

$$= -\frac{\dfrac{1}{R_1} - \dfrac{R_4}{R_2 + R_4}\left(\dfrac{1}{R_1} + \dfrac{1}{R_3} + \dfrac{1}{R_F}\right)}{\dfrac{1}{R_F} + \left(\dfrac{1}{R_1} + \dfrac{1}{R_3} + \dfrac{1}{R_F}\right)\dfrac{1}{A_o} + \left(\dfrac{1}{R_1} + \dfrac{1}{R_3} + \dfrac{1}{R_F}\right)_{A_o}\dfrac{jf}{f_b}}$$

For large A_o, the second term in the denominator tends to zero. Therefore,

$$\frac{v_O}{v_i}(j\omega) = -\frac{1/R_1 - R_4/(R_2 + R_4)\,(1/R_1 + 1/R_3 + 1/R_F)}{1/R_F + (1/R_1 + 1/R_3 + 1/R_F)\cdot(jf/f_{b\omega})}$$

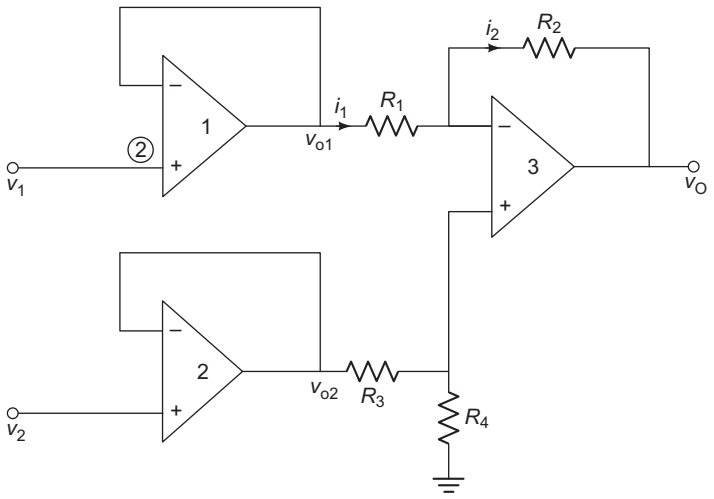
$$= \frac{-R_F/R_1 - R_4/(R_2 + R_4)\,(1/R_1 + 1/R_3 + 1/R_F)}{1 + jf\ R_F\,(1/R_1 + 1/R_3 + 1/R_F)/f_{b\omega}}$$

$$= \frac{500\text{ k}/40\text{ k} - 500\text{ k} \times 100\text{ k}/80\text{ k} \times 100\text{ k}\,(1/40\text{ k} + 1/50\text{ k} + 1/500\text{ k})}{1 + jf\ 500\text{ k}/10^6\,(1/40\text{ k} + 1/50\text{ k} + 1/500\text{ k})}$$

$$\frac{v_O}{v_i}(j\omega) = -\frac{12.5 - 13.05}{1 + jf\ 23.5 \times 10^{-6}} = +\frac{0.55}{1 + jf\ 23.5 \times 10^{-6}}$$

2.33

(a)



$$(v_{(+)1} - v_{(-)1})A_o = v_{o1}, \quad v_{(+)1} = v_1,\ v_{(-)1} = v_{o1}$$

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$$(v_1 - v_{o1}) = \frac{v_{o1}}{A_o} = 0$$

For large A_o, $v_1 = v_{o1}$, and similarly $v_{o2} = v_2$.

Now $i_1 = i_2$; then

$$i_1 = \frac{v_{o1} - v_{(-)3}}{R_1}$$

$$i_2 = \frac{v_{(-)3} - v_o}{R_2}$$

$$\therefore \quad \frac{v_{o1} - v_{(-)3}}{R_1} = \frac{v_{(-)3} - v_O}{R_2}$$

$$\frac{v_{o1}}{R_1} - \frac{v_{(-)3}}{R_1} = \frac{v_{(-)3}}{R_2} - \frac{v_O}{R_2}$$

$$-\frac{v_{(-)3}}{R_2} - \frac{v_{(-)3}}{R_2} = \frac{-v_{o1}}{R_1} - \frac{v_O}{R_2}, \quad v_{(-)3}\left(\frac{1}{R_1} + \frac{1}{R_2}\right) = \frac{v_{o1}}{R_1} + \frac{v_o}{R_2}$$

$$\therefore v_{(-)3}\frac{R_1 + R_2}{R_1 R_2} = \frac{v_{o1}}{R_1} + \frac{v_o}{R_2}$$

$$v_{(-)3} = \frac{R_2}{R_1 + R_2} v_1 + \frac{R_1}{R_1 + R_2} v_O$$

$$v_{(+)3} = v_{o2}\frac{R_4}{R_3 + R_4}, \qquad [v_{(+)3} = -v_{(-)3}]\, A_o = v_O$$

or $$v_{(+)3} - v_{(-)3} = \frac{v_O}{A_o}$$

Substituting for $v_{(-)3}$ and $v_{(+)3}$

$$v_2\frac{R_4}{R_3 + R_4} - \frac{R_2}{R_1 + R_2} v_1 - \frac{R_1}{R_1 + R_2} v_O = \frac{v_O}{A_o}$$

For large A_o

$$v_2 = \frac{R_4}{R_3 + R_4} - \frac{R_2}{R_1 + R_2} v_1 = \frac{R_1}{R_1 + R_2} v_O$$

$$v_O\frac{R_1}{R_1 + R_2} = -v_1\frac{R_2}{R_1 + R_2} + v_2\frac{R_4}{R_3 + R_4}$$

$$v_O = -v_1\frac{R_2}{R_1} + v_2 \cdot \frac{R_4}{R_1} \cdot \frac{R_1 + R_2}{R_3 + R_4}$$

For $R_1 = R_3 = 10\ \text{k}\Omega$ and $R_2 = R_4 = 1\ \text{M}\Omega$,

$$v_O = -v_1 \cdot \frac{10^6}{10^4} + v_2 \cdot \frac{10^6}{10^4} \cdot \frac{10\,\text{k} + 1\,\text{M}}{10\,\text{k} + 1\,\text{M}}$$

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$$= -v_1\,100 + v_2\,100$$

$$= (-100)\,v_1 - (-100)\,v_2$$

$$\therefore \qquad a_1 = -100, \;\; a_2 = -100$$

(b) Assume $v_2 = 0$; then $v_o = a_1 v_1$.

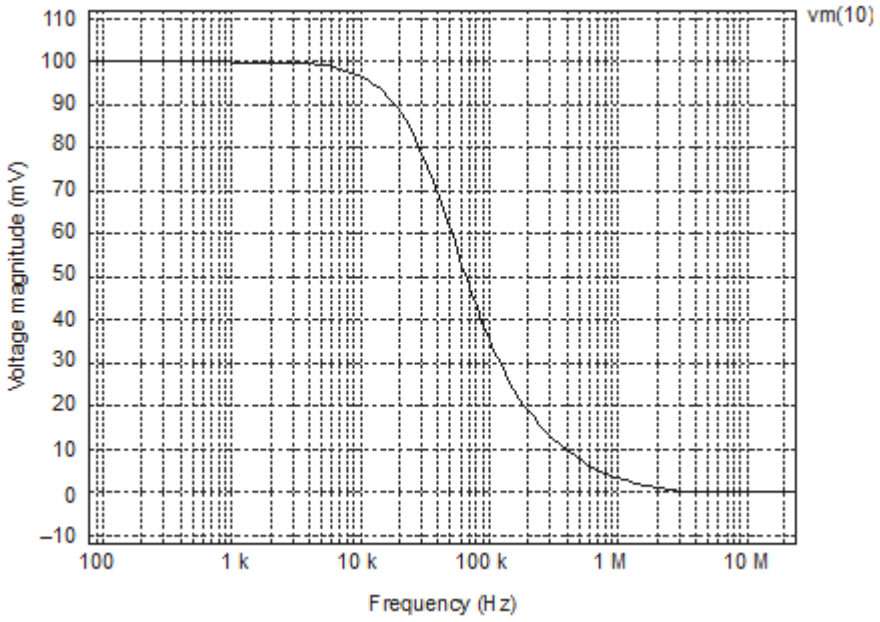
$$f_{max} = \frac{SR}{2\pi\, v_O} = \frac{6\ \text{V}/\mu\text{s}}{2\pi \times 10} = 95.5\ \text{kHz}$$

(c) Problem 2.33

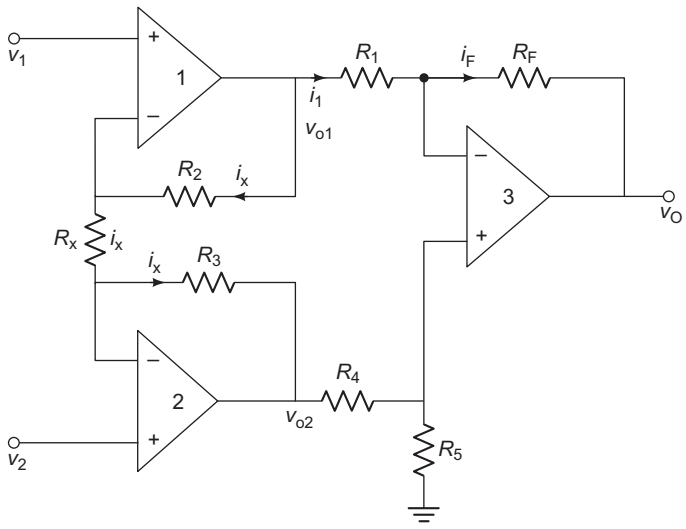
```
VS1    2    0    AC   1MV
VS2    5    0    AC   2MV
R1     4    9    10K
R3     7    8    10K
R2     9    10   1MEG
R4     8    0    1MEG
XA1    2    4    4    0    LF411_AC
XA2    5    7    7    0    LF411_AC
XA3    8    9    10   0    LF411_AC
. SUBCKT  LF411_AC 1    2    3    4
RI     1    2    2E12
RO     6    3    50
GB     4    5    1    2    0.1M
R1     5    4    10K
C1     5    4    0.79UF
EA     4    6    5    4    2E5
D1     3    7    DMOD
D2     4    7    DMOD
. MODEL   DMOD D    (BV = 14 V)
. ENDS    LF411_AC
. AC  DEC 10   100  20MEGHZ
. PRINT   AC   VM(10)
. PROBE
. END
```


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2.34



Assume there is virtual short circuit at the input of op-amps 1 and 2. Then

$$v_{(-)1} = v_1, \quad v_{(-)2} = v_2$$

Current i_x through R_x is given by

$$i_x = \frac{v_1 - v_2}{R_x}$$

$$\therefore \qquad v_{o1} = v_1 + i_x R_2 = v_1 + \frac{v_1 - v_2}{R_x} R_2 \qquad \text{(i)}$$

$$v_{o2} = v_2 - i_x R_3 = v_2 - \frac{v_1 - v_2}{R_x} R_3 \qquad \text{(ii)}$$

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$$i_1 = i_F,\ i_1 = \frac{v_{o1} - v_{(-)3}}{R_1},\quad i_F = \left(\frac{v_{(-)3} - v_O}{R_F}\right)$$

$$i_1 = i_F$$

$$\frac{v_{o1} - v_{(-)3}}{R_1} = \frac{v_{(-)3} - v_O}{R_F}$$

$$\frac{v_{o1}}{R_1} - \frac{v_{(-)3}}{R_1} = \frac{v_{(-)3}}{R_F} - \frac{v_O}{R_F}$$

$$-\frac{v_{(-)3}}{R_1} - \frac{v_{(-)3}}{R_F} = -\frac{v_{o1}}{R_1} - \frac{v_O}{R_F}$$

$$v_{(-)3}\left(\frac{1}{R_1} + \frac{1}{R_F}\right) = \frac{R_1 + R_F}{R_1 R_F}$$

$$v_{(-)3}\frac{R_1 + R_F}{R_1 R_F} = \frac{v_{o1}}{R_1} + \frac{v_O}{R_F}$$

$$v_{(-)3} = \frac{R_1 R_F}{R_1 + R_F}\frac{v_{o1}}{R_1} + \frac{R_1 R_F}{R_1 + R_F}\cdot\frac{v_O}{R_F}$$

$$= \frac{R_F}{R_1 + R_F}v_{o1} + \frac{R_1}{R_1 + R_F}v_O$$

$$v_{(+)3} = \frac{R_5}{R_4 + R_5}v_{o2}, \qquad [v_{(+)3} - v_{(-)3}]A_o = v_O$$

$$\therefore \quad \frac{R_5}{R_4 + R_5}v_{o2} - \frac{R_F}{R_1 + R_F}v_{o1} - \frac{R_1}{R_1 + R_F}\cdot v_O = \frac{v_O}{A_o}$$

Substituting for v_{o1} and v_{o2} from (i) and (ii)

$$\frac{R_5}{R_4 + R_5}\left[v_2 - (v_1 - v_2)\frac{R_3}{R_x}\right] - \frac{R_F}{R_1 + R_F}\left[v_1 + (v_1 - v_2)\frac{R_2}{R_x}\right] - \frac{R_1}{R_1 + R_F}v_O = \frac{v_O}{A}$$

$$\frac{R_1 v_O}{R_1 + R_F} = \frac{R_5}{R_4 + R_5}v_2 - \frac{R_5}{R_4 + R_5}\cdot\frac{R_3}{R_x}v_1 + \frac{R_5}{R_4 + R_5}\cdot\frac{R_3}{R_x}v_2$$

$$- \frac{R_F}{R_1 + R_F}v_1 - \frac{R_F}{R_1 + R_F}\frac{R_2}{R_x}v_1 + \frac{R_F}{R_1 + R_F}\frac{R_2}{R_x}\cdot v_2$$

Given $R_2 = R_3$, $R_1 = R_4$ and $R_F = R_5$,

$$\therefore \quad \frac{R_1 v_O}{R_1 + R_F} = \frac{R_F v_2}{R_1 + R_F} - \frac{R_F}{R_1 + R_F}\cdot\frac{R_2}{R_x}v_1 + \frac{R_F}{R_1 + R_F}\cdot\frac{R_2}{R_x}v_2$$

$$- \frac{R_F}{R_1 + R_F}v_1 - \frac{R_F}{R_1 + R_F}\cdot\frac{R_2}{R_x}v_1 + \frac{R_F}{R_1 + R_F}\cdot\frac{R_2}{R_x}\cdot v_2$$

$$= \frac{R_F}{R_1 + R_F}(v_2 - v_1) - \frac{2R_F}{R_1 + R_F}\frac{R_2}{R_x}v_1 + \frac{2R_F}{R_1 + R_F}\cdot\frac{R_2}{R_x}v_2$$

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$$= \frac{R_F}{R_1 + R_F}(v_2 - v_1) + \frac{2R_F}{R_1 + R_F} \cdot \frac{R_2}{R_x}(v_2 - v_1)$$

$$= (v_2 - v_1)\frac{R_F}{R_1 + R_F}\left[1 + \frac{2R_2}{R_x}\right]$$

$$\therefore \quad \frac{R_1 v_O}{R_1 + R_F} = (v_2 - v_1)\frac{R_F}{R_1 + R_F}\left[1 + \frac{2R_2}{R_x}\right]$$

$$v_O = (v_2 - v_1) \cdot \frac{R_F}{R_1}\left[1 + \frac{2R_2}{R_x}\right]$$

2.35

From Eq. (2.73)

$$\frac{v_O}{v_{s1} - v_{s2}} = -\left(1 + \frac{2R}{R_g}\right)\left(\frac{R_F}{R_1}\right)$$

Take $R_F = 500\ \text{k}\Omega$, $R_1 = 10\ \text{k}\Omega$ and $R = 1\ \text{k}\Omega$. Then

$$\frac{v_O}{v_{s1} - v_{s2}} = 1 + \frac{2 \times 1000}{R_g} \times 50 \simeq \frac{2000}{R_g} \times 50$$

R_g can be varied from 100 to 200 Ω.

2.36

$$A_v = \frac{v_O}{v_{s2} - v_{s1}} = \frac{R_F}{R_1}$$

For $R_1 = 1\ \text{k}\Omega$, $R_F = 750\ \text{k}\Omega$.

Problem 2.36

```
VS1    1      0      DC     1MV
VS2    4      0      DC     2MV
R1     2      5      1K
RA     3      6      1K
RX     6      0      750
RF     5      7      750K
XA1    1      2      2      0      OPAMP
XA2    4      4      3      0      OPAMP
XA3    6      5      7      0      OPAMP
.SUBCKT OPAMP    1      2      3      4
RI     1      2      2E12
RO     5      3      50
EA     4      5      1      2      2E5
.ENDS OPAMP
.OP
.END
```


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2.37

$$v_O = V_{co} - \frac{1}{R_2 C_F}\int_0^t v_S \, dt$$

For $0 \le t \le 1$ ms

$$v_O = 0 - \frac{1}{10^{-5}}\int_0^t (+1)\, dt = -10^5\,(t)$$

For $t = 1$ ms, $v_O = -10^5 \times 10^{-3} = -100$ V. The amplifier goes in saturation at $v_O = -14$ V and $V_{co} = -14$ V.

For $1 \le t \le 2$ ms

$$v_O = -14 - 10^5 \int_0^{t-1} (-1)\, dt = -14 + 10^5\,(t-1)_{\text{terms}}$$

For $t = 2$ ms, $v_O = -14 + 10^5\,(10^{-3})$. The amplifier goes in saturation at $v_O = +14$ V and $V_{co} = 14$ V.

For $2 \le t \le 3$ ms

$$v_O = 14 - 10^5 \int_0^{t-2} (+1)\, dt = 14 - 10^5\,(t-2)_{\text{terms}}$$

At $t = 3$ ms

$$v_O = V_{sat} = -14 \text{ V}$$

$$V_{co} = -14 \text{ V}$$

For $3 \le t \le 4$

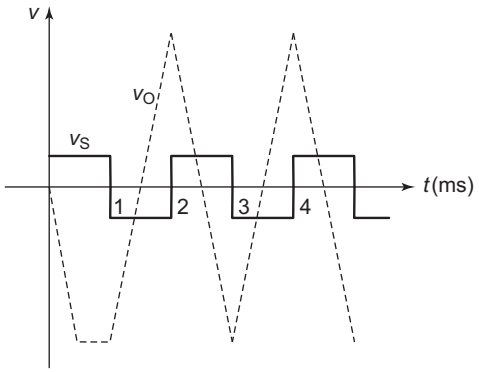
$$v_O = -14 - 10^5 \int_0^{t-3} (-1)\, dt = -14 + 10^5\,(t-3)$$

At $t = 4$ ms

$$v_O = V_{sat} = +14 \text{ V}$$

$$V_{co} = 14 \text{ V}$$

Waveform is shown below.



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2.38

$$v_S = \frac{10}{10^{-3}}\, t \qquad 0 \le t \le 1 \text{ ms}$$

$$v_S = -\frac{10}{10^{-3}}\, t + 20 \qquad 1 \text{ ms} \le t \le 2 \text{ ms}$$

For $0 \le t \le 1$ ms, $V_{co} = 0$.

$$v_O = 0 - \frac{1}{R_1 C_F} \int_0^t \frac{10}{10^{-3}} t\, dt = -\frac{1}{10^{-3}} \frac{10}{10^{-3}} \frac{t^2}{2}$$

At $t = 1$ ms

$$V_o = -5 \text{ V} = -10^7 \frac{t^2}{2}$$

2.39

$$R_1 \parallel R_F = R_1 \text{ for } R_F >> R_1$$

$$C_X = C_F (1 + A_O) = 0.01\ \mu\text{F}\ (1 + 5 \times 10^5) \cong 5000\ \mu\text{F}$$

$$C_Y = C_F \left(1 + \frac{1}{A_o}\right) \simeq C_F = 0.01\ \mu\text{F}$$

From Example 2.11

$$A(s) = \frac{A_o}{1 + R_1 C_x s}$$

3-dB frequency

$$\omega_b = \frac{1}{R_1 C_x} = \frac{1}{10^4 \times 5000 \times 10^{-6}} = \frac{1}{50} \text{ rad/s}$$

$$f_b = 3.18 \times 10^{-3} \text{ Hz}$$

2.40

Since $A = 10$ at $f = \frac{1}{2\pi} = 0.16$ Hz

$$f_b = 10 \times 0.16 = 1.6 \text{ Hz}$$

Let $C_1 = 1\ \mu$F. Then

$$\tau_i = \frac{1}{2\pi \times 1.6} = 99.5 \text{ ms}$$

$$R_1 = \frac{99.5 \times 10^{-3}}{10^{-6}} \cong 100\ \text{k}\Omega$$

$$\tau_F = \frac{10}{1.6} = 6.25 \text{ s}, \quad R_F = \frac{6.25}{1\ \mu\text{F}} = 6.25\ \text{M}\Omega$$

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Problem 2.40

```
VS    1      0      AC     1MV
CF    3      0      1UF
R1    1      3      100K
RF    3      4      6.3MEG
RX    2      0      100K
VCC   5      0      12V
VEE   0      6      12V
XA1   2      3      5      6      4      UA741
. Vi+ Vi-    +VCC   -VEE   Vo
. LIB NOM.LIB
. AC DEC 101 0.01HZ 10HZ
. PROBE
. END
```

2.41

(a)

Given values $A_{BP} := 20$ $R_1 := 1 \cdot 10^3$ $R_L := 20 \cdot 10^3$ $f_H := 1000$

Using Eq. (2.86), dc gain (for an ideal op-amp and neglecting the effect of RL)

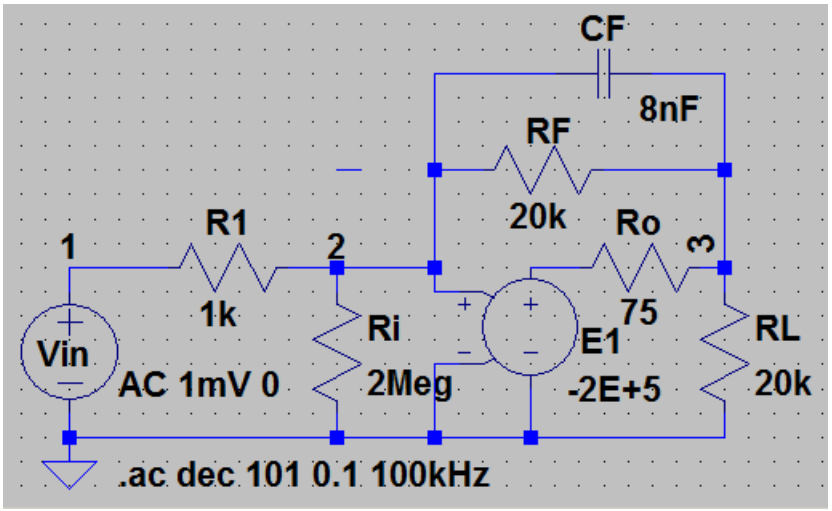
$$R_F := A_{BP} \cdot R_1 \qquad R_F = 2 \times 10^4$$

From Eq. 2.87

$$C_F := \frac{1}{2\pi\ R_F \cdot f_H} \qquad C_F = 7.958 \times 10^{-9}$$

$\therefore \qquad C_F = 8$ nF

(b) For SPICE verification,



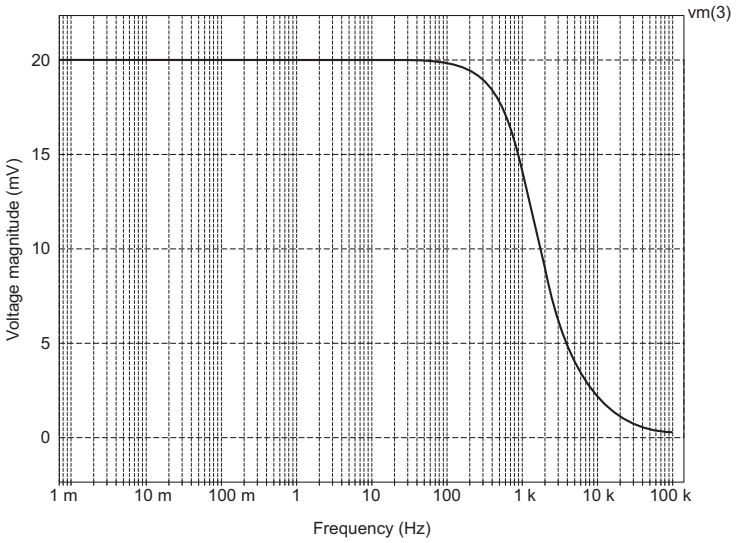
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Problem 2.41

```
VS    1    0    AC   1MV
R1 2 1 1k
RF 3 2 20k
CF 3 2 8nF
Ri 2 0 2Meg
E1 N002 0 2 0 -2E+5
Vin 1 0 AC 1mV 0
RL 3 0 20k
Ro 3 N002 75
.ac dec 101 0.1 100kHz
 . PROBE
 . END
```

Plot



2.42

(a) From Eq. (2.108)

$$f_b = \frac{1}{2\pi R_1 C_1}, \; 10^4 = \frac{1}{2\pi R_1 C_1}$$

For $C_1 = 0.1\ \mu F$, $R_1 = 159\ \Omega$.

From Eq. (2.110),

$$A_{f(max)} = \frac{R_F}{R_1}, \; R_F = 20 \times 159\ \Omega$$

$$R_F = 3180\ \Omega$$

(b) Problem 2.42

```
VS    1      0      AC     0.1V
R1    1      7      159
C1    7      3      0.1UF
RF    3      4      3180
```


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```
RX    2      0      3180
VCC   5      0      15V
VEE   0      6      15V
XA1   2      3      5      6      4      UA741
. LIB NOM.LIB
. AC DEC 10 100Hz 1MEGHZ
. PROBE
. END
```

2.43

(a) $\tau_d = R_1 C_1 = 2 \times 10^3 \times 10^{-8} = 20\ \mu s$

(b) $f_b = \dfrac{1}{2\pi R_1 C_1} = \dfrac{1}{2\pi \times 2 \times 10^3 \times 10^{-8}} \simeq 7958\ \text{Hz}$

(c) $A_{f(max)} = \dfrac{R_F}{R_1} = \dfrac{10\ \text{k}}{2\ \text{k}} = 5$

2.44

Using Eq. (2.110)

$$|A_{PB}| = \frac{R_F}{R_1}$$

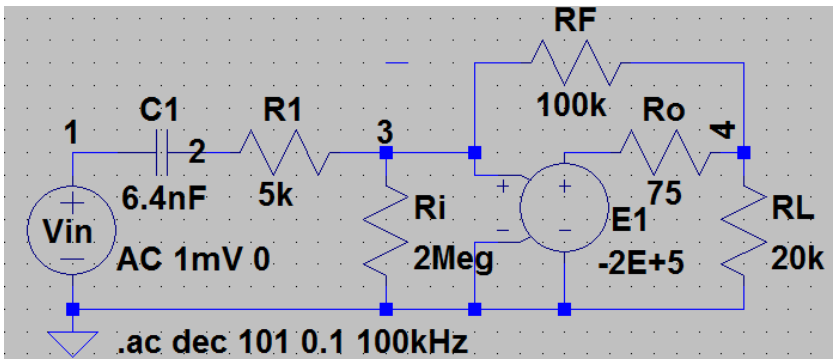
Assume $R_1 = 5\ \text{k}\Omega$ and $A_{PB} = 20$.

$\therefore \quad R_F = 5 \times 20 = 100\ \text{k}\Omega$

$$f_L = \frac{1}{2\pi R_{C1} C_1}, \quad C_1 = \frac{1}{2\pi \times 5\ \text{k} \times 5\ \text{k}} = 6.4\ \text{nF}$$

$$f_H = \frac{1}{2\pi R_F C_1} = \frac{1}{2\pi \times 10 \times 10^3 \times 6.4 \times 10^{-9}} = 250 Hz$$

For SPICE verification: using op-amp model of Fig. 2.3(a) as



Problem 2.44

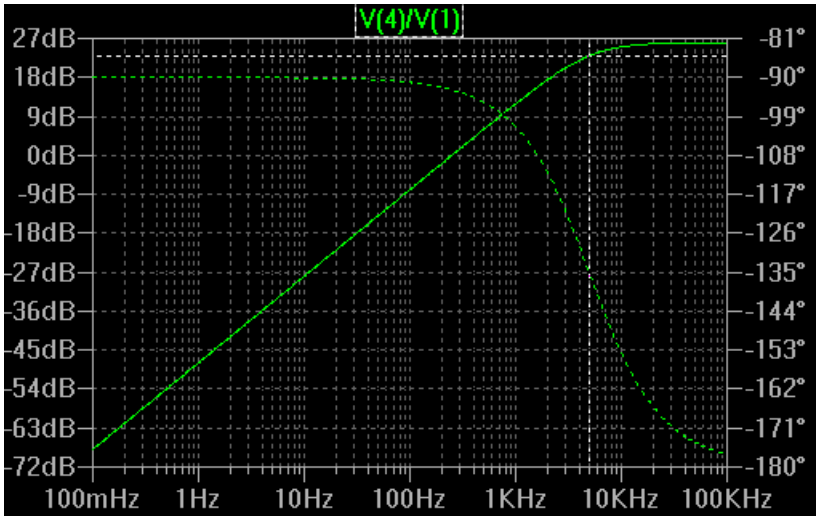
R1 3 2 5k
RF 4 3 100k
C1 2 1 6.4nF
Ri 3 0 2Meg

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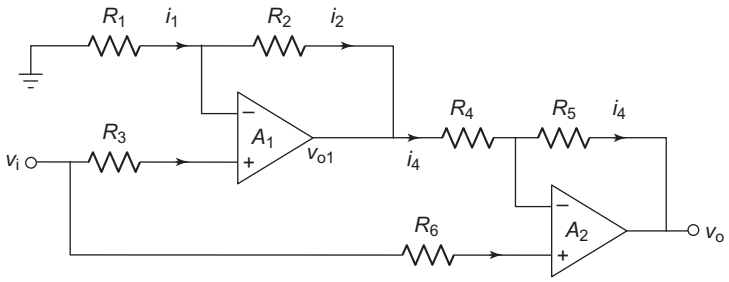
```
E1 N002 0 3 0 -2E+5
Vin 1 0 AC 1mV 0
RL 4 0 20k
Ro 4 N002 75
.ac dec 101 0.1 100kHz
  . PROBE
. END
```

Plot



2.45

(a)



Assume $i_i = 0$

$$i_1 = \frac{0 - v_{-(1)}}{R_1} = i_2 = \frac{v_{-(1)} - v_{o1}}{R_2} \qquad \text{(i)}$$

$$\frac{v_{o1} - v_{-(2)}}{R_4} = \frac{v_{-(2)} - v_o}{R_5} \qquad \text{(ii)}$$

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From (i)

$$-\frac{v_{-(1)}}{R_1} = \frac{v_{-(1)} - v_{o1}}{R_2}$$

$$-\frac{v_{-(1)}}{R_1} = \frac{v_{-(1)}}{R_2} - \frac{v_{o1}}{R_2}$$

$$-\left(\frac{v_{-(1)}}{R_1} + \frac{v_{-(1)}}{R_2}\right) = -\frac{v_{o1}}{R_2}$$

$$v_{-(1)}\left(\frac{1}{R_1} + \frac{1}{R_2}\right) = \frac{v_{o1}}{R_2}$$

$$v_{-(1)}\frac{R_1 + R_2}{R_1 R_2} = \frac{v_{o1}}{R_2}$$

$$v_{-(1)} \times \frac{R_1 + R_2}{R_1} = v_{o1}, \qquad v_{-(1)} = v_{o1} \cdot \frac{R_1}{R_1 + R_2}$$

$$v_{o1} = A_{o1}(V_{+(1)} - v_{-(1)}) = A_o\left(v_i - v_{o1}\frac{R_1}{R_1 + R_2}\right)$$

$$\therefore \quad v_{o1} = A_o(v_i) - A_o v_{o1} \cdot \frac{R_1}{R_1 + R_2}$$

$$v_{o1} + A_o v_{o1}\frac{R_1}{R_1 + R_2} = A_o v_i$$

$$v_{o1} = \frac{A_o}{1 + A_o R_1/(R_1 + R_2)} \cdot v_i$$

Now $v_{+2} = v_i$

$$\therefore \quad \frac{v_{o1} - v_{-(2)}}{R_4} = \frac{v_{-(2)} - v_O}{R_5}$$

$$\frac{v_{o1}}{R_4} - \frac{v_{-(2)}}{R_4} = \frac{v_{-(2)}}{R_5} - \frac{v_O}{R_5}$$

$$v_O = A_o(V_{+(2)} - v_{-(2)}), \qquad \frac{v_O}{A_o} = v_{+(2)} - v_{-(2)}$$

$$\therefore \quad \frac{v_O}{A_o} = v_i - v_{-(2)}, \quad v_{-(2)} = v_i - \frac{v_O}{A_o}$$

$$\frac{v_{o1}}{R_4} + \frac{v_O}{R_5} = v_{-(2)}\left(\frac{R_4 + R_5}{R_4 R_5}\right)$$

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$$\frac{v_{o1}}{R_4}+\frac{v_O}{R_5}=\left(v_i-\frac{v_O}{A_o}\right)\frac{(R_4+R_5)}{R_4R_5}$$

$$\frac{A_o}{1+A_o\,R_1/(R_1+R_2)}\cdot\frac{v_1}{R_4}+\frac{v_O}{R_5}=v_i\frac{R_4+R_5}{R_4R_5}-v_O\frac{R_4+R_5}{R_4R_5}$$

$$\frac{v_O}{R_5}+\frac{v_O}{A_o}\frac{(R_4+R_5)}{R_4R_5}=v_i\frac{R_4+R_5}{R_4R_5}-\frac{A_o}{1+A_o\,R_1/(R_1+R_2)}\cdot\frac{v_i}{R_4}$$

$$v_O\left[\frac{1}{R_5}+\frac{R_4+R_5}{A_o\;R_4R_5}\right]=v_i\left[\frac{R_4+R_5}{R_4R_5}-\frac{A_o}{\left(1+R_1\,A_o/(R_1+R_2)\right)R_4}\right]$$

$$\frac{v_O}{v_i}=\frac{(R_4+R_5)/R_4R_5-\dfrac{A_o}{\left[1+R_1/(R_1+R_2)\,A_o\right]R_4}}{1/R_5+(R_4+R_5)/A_o\;R_4R_5}$$

Now let $A_o=\dfrac{A_o}{1+jf/f_b}$

$$\frac{v_o}{v_i}=\frac{(R_4+R_5)/R_4R_5-\dfrac{A_o}{(1+jf/f_b)\left[1+\left(R_1/(R_1+R_2)\right).(A_o/1+jf/f_b)\right]R_4}}{1/R_5+\left(R_4+R_5/R_4R_5\right).[(1+jf/f_b)/A_o]}$$

$$=\frac{\dfrac{(R_4+R_5)}{R_4R_5}-\dfrac{A_o}{\left[(1+jf/f_b)\,R_4+\dfrac{R_1}{(R_1+R_2)}R_4A_o\right]}}{\dfrac{1}{R_5}+\dfrac{(R_4+R_5)}{R_4R_5\;A_o}+\left[\dfrac{(R_4+R_5)}{R_4R_5\;A_o}\right].\left(\dfrac{jf}{f_b}\right)}$$

$$=\frac{\dfrac{(R_4+R_5)}{R_4R_5}-\dfrac{A_o}{\left[R_4+\dfrac{jf}{f_b}R_4+\dfrac{R_1R_4\;A_o}{(R_1+R_2)}\right]}}{\dfrac{1}{R_5}+\dfrac{(R_4+R_5)}{R_4R_5\;A_o}+\left[\dfrac{(R_4+R_5)}{R_4R_5\;A_o}\right].\dfrac{jf}{f_b}}$$

$$=\frac{\dfrac{(R_4+R_5)}{R_4R_5}-\dfrac{1}{\left[jf\dfrac{R_4}{f_b\;A_o}+\dfrac{R_1R_4}{(R_1+R_2)}\right]}}{\dfrac{1}{R_5}+\dfrac{(R_4+R_5)}{R_4R_5}.\left(\dfrac{jf}{A_o\;f_b}\right)}$$

$$=\frac{\dfrac{(R_4+R_5)}{R_4R_5}-\dfrac{1}{\left[jf\dfrac{R_4}{A_o\;f_b}+\dfrac{R_1R_4}{(R_1+R_2)}\right]}}{1+\dfrac{(R_4+R_5)}{R_4R_5}.\left(\dfrac{jf}{A_o\;f_b}\right)}$$

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$$= \frac{\dfrac{(R_4 + R_5)}{R_4 R_5} - \dfrac{1}{\left[\dfrac{R_1 R_4}{(R_1 + R_2)}\right]\left\{1 + jf\dfrac{R_4}{A_o\, f_b} + \dfrac{(R_1 + R_2)}{R_1 R_4}\right\}}}{1 + \dfrac{(R_4 + R_5)}{R_4}\cdot\left(\dfrac{jf}{A_o\, f_b}\right)}$$

check $\Delta_o \to \alpha$

$$\frac{R_1 R_4 - R_2 R_5}{R_1 R_4}$$

Further

$$f_{c1} = \frac{A_o\, f_b\, R_1}{R_1 + R_2} = 90.9 \times 10^3$$

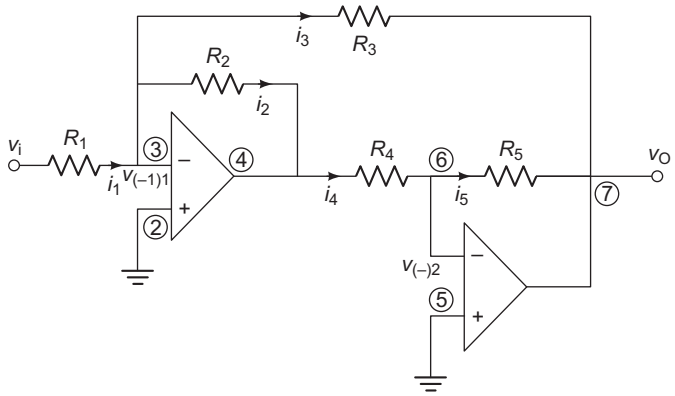
$$f_{c2} = A_o\, f_b \frac{R_4}{R_4 + R_5} = \frac{10^6 \times 50}{50 + 500} = \frac{10^6 \times 50}{550}$$

(b) $f_{max} < \dfrac{SR}{2\pi V_o}$

$$f_{max} = \frac{SR}{2\pi V_o} = \frac{6}{10^{-6} \times 2\pi \times 10}$$

$$= 95.49 \text{ kHz}$$

2.46



(a) $i_1 = \dfrac{v_i - v_{(-)\,1}}{R_1}$, $i_2 = \dfrac{v_{(-)\,1} - v_{o1}}{R_2}$, $\qquad i_3 = \dfrac{v_{(-)\,1} - v_O}{R_3}$

$$i_1 = i_2 + i_3$$

Substituting for i_1, i_2, and i_3

$$\frac{v_i}{R_1} - \frac{v_{(-)1}}{R_1} = \frac{v_{(-)1}}{R_2} - \frac{v_{o1}}{R_2} + \frac{v_{(-)1}}{R_3} - \frac{v_O}{R_3}$$

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$$\frac{v_i}{R_1} = \frac{v_{(-)1}}{R_1} + \frac{v_{(-)1}}{R_2} + \frac{v_{(-)1}}{R_3} - \frac{v_{o1}}{R_2} - \frac{v_O}{R_3} \tag{i}$$

Also $i_4 = i_5$

$$\frac{v_{o1} - v_{(-)2}}{R_4} = \frac{v_{(-)2} - v_O}{R_5}$$

$$\frac{v_{o1}}{R_4} - \frac{v_{(-)2}}{R_4} = \frac{v_{(-)2}}{R_5} - \frac{v_O}{R_5} \tag{ii}$$

Further $(0 - v_{(-)1})A_o = v_{o1}$, $(0 - v_{(-)2})\, A_o = v_O$

or

$$-v_{(-)1} = \frac{v_{o1}}{A_o}, -v_{(-)2} = \frac{v_O}{A_o}$$

or

$$v_{(-)1} = -\frac{v_{o1}}{A_o}, \quad v_{(-)2} = -\frac{v_O}{A_o}$$

$$\frac{v_i}{R_1} = v_{(-)1}\left(\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}\right) - \frac{v_{o1}}{R_1} - \frac{v_O}{R_3}$$

$$= -\frac{v_{o1}}{A_o}\left(\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}\right) - \frac{v_{o1}}{R_2} - \frac{v_O}{R_3}$$

$$= -v_{o1}\left[\frac{1}{R_o}\left(1/R_1 + \frac{1}{R_2} + \frac{1}{R_3}\right) + \frac{1}{R_2}\right] - \frac{v_O}{R_3} \tag{iii}$$

From (ii)

$$\frac{v_{o1}}{R_4} = v_{(-)2}\left(\frac{1}{R_4} + \frac{1}{R_5}\right) - \frac{v_O}{R_5}$$

$$= -\frac{v_O}{A_o}\left(\frac{1}{R_4} + \frac{1}{R_5}\right) - \frac{v_O}{R_5}$$

$$v_{o1} = -\frac{R_4}{A_o}\, v_O\left(\frac{1}{R_4} + \frac{1}{R_5}\right) - \frac{R_4}{R_5}\, v_O$$

Substituting in (iii) we have

$$\frac{v_i}{R_1} = +\left(\frac{R_4}{A_o}\left(\frac{1}{R_4} + \frac{1}{R_5}\right) v_o + \frac{R_4}{R_5}\, v_O\right)\left[\frac{1}{A_o}\left(\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}\right) + \frac{1}{R_2}\right]$$

For large $A_D - \frac{v_O}{R_3}$

$$\frac{v_i}{R_1} = \frac{R_4}{R_5} v_O \cdot \frac{1}{R_2} - \frac{v_o}{R_3} = \left[\frac{R_4}{R_2\, R_5} - \frac{1}{R_3}\right] v_O$$

$$= \frac{R_3\, R_4 - R_2\, R_5}{R_2\, R_3\, R_5} v_O$$

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Substituting the values

$$\frac{v_O}{v_i} = \frac{R_2\, R_3\, R_5}{R_1\left(R_3\, R_4 - R_2\, R_5\right)} = \frac{100\,\text{k} \times 150\,\text{k} \times 160\,\text{k}}{20\,\text{k}\left(150\,\text{k} \times 20\,\text{k} - 100\,\text{k} \times 160\,\text{k}\right)}$$

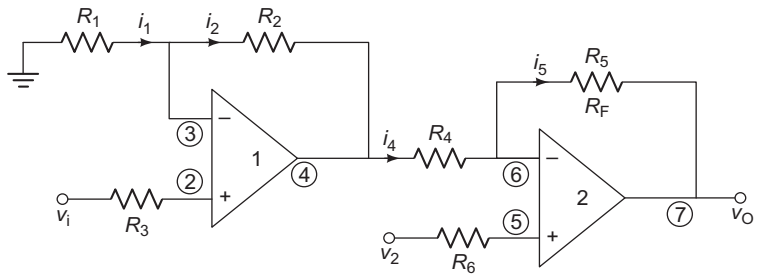
$$= -9.23$$

(b) Problem 2.46

```
VS        1       0     AC   0.1V
R1        1       3     20K
R2        3       4     100K
R3        3       7     150K
R4        4       6     20K
R5        6       7     160K
RX1       2       0     10K
RX2       5       0     10K
XA1       2       3     4     0     UA741-AC
XA2       5       6     7     0     UA741-AC
. SUBCKT UA741_AC 1 2 3 4
RI        1       2     2MEG
RO        6       3     75
GB        4       5     1     2     0.1M
R1        5       4     10K
C1        5       4     1.59UF
EA        4       6     5     4     2E5
D1        3       7     DMOD
D2        4       7     DMOD
. MODEL DMOD  D     (BV = 14V)
. AC     DEC   10   100  20MEG
. PRINT AC     VM/7
. PROBE
. END
```

2.47

(a)



$$i_1 = i_2, \qquad i_1 = \frac{0 - v_{(-)1}}{R_1}, \qquad i_2 = \frac{v_{(-)1} - v_{o1}}{R_2}$$

$$-\frac{v_{(-)1}}{R_1} = \frac{v_{(-)1}}{R_2} - \frac{v_{o1}}{R_2}, \quad -\frac{v_{(-)1}}{R_1} - \frac{v_{(-)1}}{R_2} = -\frac{v_{o1}}{R_2}$$

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$$\therefore \qquad v_{(-)1}\left(\frac{1}{R_1}+\frac{1}{R_2}\right) = \frac{v_{o1}}{R_2} \qquad \text{(i)}$$

$$\text{or} \qquad v_{(-)1}\left(\frac{R_1+R_2}{R_1R_2}\right) = \frac{v_{o1}}{R_2} \qquad \text{or} \qquad v_{(-)1} = \frac{R_1}{R_1+R_2}\,v_{o1}$$

$$i_4 = i_5, \qquad i_4 = \frac{v_{o1}-v_{(-)2}}{R_4}, \qquad i_5 = \frac{v_{(-)2}-v_O}{R_5}$$

$$\frac{-v_{o1}-v_{(-)2}}{R_4} = -\frac{v_{(-)2}-v_O}{R_5}$$

$$\frac{-v_{(-)2}}{R_4}-\frac{v_{(-)2}}{R_5} = \frac{v_{o1}}{R_4}-\frac{v_O}{R_5}$$

$$-v_{(-)2}\left[\frac{1}{R_4}+\frac{1}{R_5}\right] = -\frac{v_{o1}}{R_4}-\frac{v_O}{R_5}$$

$$v_{(-)2}\,\frac{R_4+R_5}{R_4R_5} = \frac{v_{o1}}{R_4}+\frac{v_O}{R_5} \qquad \text{(ii)}$$

Also $\qquad (v_1 - v_{(-)1})\,A_o = v_{o1} \qquad \text{(iii)}$

And $\qquad (v_2 - v_{(-)2})\,A_o = v_O \qquad \text{(iv)}$

From (iii)

$$\left(v_1 - v_{o1}\,\frac{R_1}{R_1+R_2}\right)A_o = v_{o1}$$

$$v_1 A_o - \frac{v_{o1}A_oR_1}{R_1+R_2} = v_{o1}$$

$$v_{o1}\left(1+\frac{A_oR_1}{R_1+R_2}\right) = v_1 A_o$$

$$v_{o1} = v_1\,\frac{A_o}{1+A_o\,R_1/(R_1+R_2)}$$

From (ii)

$$v_{(-)2}\,\frac{R_4+R_5}{R_4R_5} = v_1\,\frac{A_o}{1+A_o\,R_1/(R_1+R_2)}\times\frac{1}{R_4}+\frac{v_O}{R_5}$$

$$v_{(-)2} = \frac{R_4+R_5}{R_4R_5}\cdot\frac{A_o\,v_1}{1+A_o\,R_1/(R_1+R_2)}\times\frac{1}{R_4}+\frac{R_4R_5}{R_4+R_5}\cdot\frac{v_O}{R_5}$$

$$= \frac{R_5}{R_4+R_5}\cdot\frac{v_O}{1+A_o\,R_1/(R_1+R_2)}\,v_1+\frac{R_4}{R_4+R_5}\,v_O$$

From (iv) $v_2 - \dfrac{R_5}{R_4+R_5}\cdot\dfrac{A_o\,v_1}{1+A_o\,R_1/(R_1+R_2)}-\dfrac{R_4}{R_4+R_5}\,v_O = \dfrac{v_O}{A_o}$

$$v_2 - \frac{R_5}{R_4+R_5}\cdot\frac{A_o\,v_1}{1+A_o\,R_1/(R_1+R_2)} = \frac{v_O}{A_o}+\frac{R_4}{R_4+R_5}\,v_O$$

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$$v_O\left(\frac{1}{A_o}+\frac{R_4}{R_4+R_5}\right)=v_2-\frac{R_5}{R_4+R_5}\cdot\frac{A_o}{1+A_o\,R_1/(R_1+R_2)}\,v_1$$

$$v_O=\frac{v_2}{1/A_o+R_4/(R_4+R_5)}-\frac{v_1\times 1}{1/A_o+R_1/(R_1+R_2)}\cdot\frac{R_5/(R_4+R_5)}{1/A_o+R_4/(R_4+R_5)}$$

For large A_o

$$v_O=\frac{v_2}{R_4/(A_o+R_5)}-\frac{v_1}{R_1+R_2}\cdot\frac{R_5}{R_4}$$

Given $R_1 = R_5 = 10$ kΩ and $R_2 = R_4 = 500$ k kΩ; then

$$v_O=\frac{R_4+R_5}{R_4}v_2-\frac{R_1+R_2}{R_1}v_1\times\frac{R_5}{R_4}$$

$$=\left(-\frac{R_1+R_2}{R_1}\cdot\frac{R_5}{R_4}\right)v_1-\left(-\frac{R_4+R_5}{R_4}\right)v_2$$

$$=a_1\,v_1-b_1\,v_2$$

where

$$a_1=-\frac{R_1+R_2}{R_1}\cdot\frac{R_5}{R_4},\qquad b_1=-\frac{R_4+R_5}{R_4}$$

$$a_1=-\frac{10\text{ k}+500\text{ k}}{10\text{ k}}\times\frac{10\text{ k}}{500\text{ k}}=-1.02$$

$$b_1=-\frac{R_4+R_5}{R_4}=\frac{500\text{ k}+10\text{ k}}{500\text{ k}}=-1.02$$

$$\therefore\qquad v_O=(-1.02)\,v_1-(-1.02)\,v_2$$

Note b_1 is same as a_2.

(b) $$f_{max}=\frac{SR}{2\pi\,.\,V_{out}}=\frac{SR}{2\pi\times 10\text{ V}}=\frac{6\text{ V}/\mu\text{s}}{2\,\pi\times 10\text{ V}}=95.5\text{ kHz}$$

2.48

Same as Problem 2.47.

2.49

$$A_1=5,\,A_2=7,\,A_3=3,\,B_1=2,\,B_2=1,\,B_3=6$$

$$A=5+7+3=15,\,B=2+1+6=9,\,C=A-B-1=15-9-1=5$$

$$C>0,\,R_x=\infty,\,R_y=\frac{R_F}{C}=\frac{R_F}{C}=\frac{R_F}{5}$$

For $R_A = 20$ kΩ, $R_F = MR_A = 15 \times 20$ k $= 300$ kΩ.

$$R_y=\frac{300\text{ k}}{5}=60\text{ k}\Omega,\,R_a=\frac{R_F}{A_1}=\frac{300\text{ k}}{5}=60\text{ k}\Omega$$

$$R_b=\frac{R_F}{A_2}=\frac{1300}{7}\text{k}=42.86\text{ k}\Omega$$

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$$R_c = \frac{300}{3}\text{ k} = 100\text{ k}\Omega$$

$$R_1 = \frac{R_F}{B_1} = \frac{300}{2}\text{ k} = 150\text{ k}\Omega$$

$$R_2 = \frac{R_F}{B_2} = \frac{300}{1}\text{ k} = 300\text{ k}\Omega,\ R_3 = \frac{R_F}{B_3} = \frac{300\text{ k}}{6} = 50\text{ k}\Omega$$

From Eq. (2.117)

$$R_B = R_1 \parallel R_2 \parallel R_3 \parallel R_y = (150 \parallel 300 \parallel 50 \parallel 60)\ \text{k}\Omega = 33.33\ \text{k}\Omega$$

$$R_B \parallel R_F = 33.33 \parallel 300 = 30\ \text{k}\Omega$$

2.50

$$A_1 = 5, A_2 = 9, A_3 = 3, B_1 = 8, B_2 = 2, B_3 = 6$$

$$A = 5 + 9 + 3 = 17, B = 8 + 2 + 6 = 16, C = A - B - 1 = 17 - 16 - 1 = 0$$

$$R_x = \infty, R_y = \infty; M = 17$$

Assume $R_A = 20\ \text{k}\Omega$; then $R_F = MR_A = 340\ \text{k}\Omega$.

$$R_a = \frac{R_F}{A_1} = \frac{340}{5}\text{ k} = 68\text{ k}\Omega,\ R_b = \frac{R_F}{A_2} = \frac{340}{9} = 37.77\text{ k}\Omega$$

$$R_c = \frac{R_F}{A_3} = \frac{340}{3} = 113.33\text{ k}\Omega,\ R_1 = \frac{R_F}{B_1} = \frac{340}{8} = 42.5\text{ k}\Omega$$

$$R_2 = \frac{R_F}{B_2} = 340/2 = 170\text{ k}\Omega,\ R_3 = \frac{R_F}{B_3} = \frac{340}{6} = 56.66\text{ k}\Omega$$

From Eq. (2.117)

$$R_B = (R_1 \parallel R_2 \parallel R_3 \parallel R_y) = R_1 \parallel R_2 \parallel R_3$$

$$= \left(\frac{340}{8} \parallel 170 \parallel \frac{340}{6}\right)\text{ k}\Omega = 21.25\text{ k}\Omega$$

$$R_B \parallel R_F = (21.25 \parallel 340)\text{ k} = 20\ \text{k}\Omega$$

2.51

Referring to Fig. (2.34) and Eq. (2.119)

$$v_o = (5v_a + 7v_b + 3v_c) - (2v_1 + v_2 + 6v_3)$$

$$v_o = A_1 v_a + A_2 v_b + A_3 v_c - B_1 v_1 - B_2 v_2 - B_3 v_3$$

where

$$A = A_1 + A_2 + A_3 = 5 + 7 + 3 = 15$$

$$B = B_1 + B_2 + A_3 = 2 + 1 + 6 = 9$$

$$C = A - B - 1 = 15 - 9 - 1 = 5$$

Since $C > 0,\ R_x = \infty, R_y = \frac{R_F}{C} = \frac{R_F}{5}$

For $R_A = 20K$

$R_F = MR_A$, where M is the largest value of A. Thus in this problem, $M = 15$

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$$R_F = MR_A = 15\,x\,20K\Omega = 300\,K\Omega$$

$$R_y = \frac{R_F}{C} = \frac{300K\Omega}{5} = 60\,K\Omega$$

$$R_a = \frac{R_F}{A_1} = \frac{300\,K\Omega}{5} = 60\,K\Omega$$

$$R_b = \frac{R_F}{A_2} = \frac{300\,K\Omega}{7} = 42.86\,K\Omega$$

$$R_c = \frac{R_F}{A_3} = \frac{300\,K\Omega}{3} = 100\,K\Omega$$

$$R_1 = \frac{R_F}{B_1} = \frac{300\,K\Omega}{2} = 150\,K\Omega$$

$$R_2 = \frac{R_F}{B_2} = \frac{300\,K\,\Omega}{1} = 300\,K\Omega$$

$$R_3 = \frac{R_F}{B_3} = \frac{300\,K\Omega}{6} = 50\,K\Omega$$

$$R_x = \infty$$

Check:

From Eq. (2.116)

$$R_A = R_a \| R_b \| R_c = 60\,K\Omega \| 42.86\,K\Omega \| 100\,K\Omega = 20\,K\Omega$$

From Eq. (2.117)

$$R_B = R_1 \| R_2 \| R_3 \| R_y = 150\,K\Omega \| 300\,K\Omega \| 50\,K\Omega \| 60\,K\Omega = \frac{150}{7}\,K\Omega$$

From Eq. (2.118)

$$R_B \| R_F = \frac{150\,K\Omega}{7} \| 300\,K\Omega = 20\,K\Omega$$

Therefore, $R_A = (R_B \| R_F)$ is satisfied.

2.52

Given

$$vo = (5v_a + 9v_b + 3v_c) - (8v_1 - 2v_2 - 6v_3)$$

$$R_{\min} = 20\,K\Omega$$

$$v_o = A_1 v_a + A_2 v_b + A_3 v_c - B_1 v_1 - B_2 v_2 - B_3 v_3$$

where

$$A = A_1 + A_2 + A_3 = 5 + 9 + 3 = 17$$

$$B = B_1 + B_2 + B_3 = 8 + 2 + 6 = 16$$

$$C = A - B - a = 17 - 16 - 1 = 0$$

Since $C = 0$, $R_x = 0$, $R_y = 0$

$$R_F = NR_{\min} \quad \text{and} \quad N = 9$$

$$R_F = 9\,x\,20\,K\Omega = 180K\Omega$$

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$$R_a = \frac{R_F}{A_1} = \frac{180\,K\Omega}{5} = 36\,K\Omega$$

$$R_b = \frac{R_F}{A_2} = \frac{180\,K\Omega}{9} = 20\,K\Omega$$

$$R_c = \frac{R_F}{A_3} = \frac{180\,K\Omega}{3} = 60\,K\Omega$$

$$R_1 = \frac{R_F}{B_1} = \frac{180\,K\Omega}{8} = 22.5\,K\Omega$$

$$R_2 = \frac{R_F}{B_2} = \frac{180\,K\Omega}{2} = 90\,K\Omega$$

$$R_3 = \frac{R_F}{B_3} = \frac{180\,K\Omega}{6} = 30\,K\Omega$$

From Eq. (2.116)

$R_A = R_a \| R_b \| R_c = 36\,K\Omega \| 20K\Omega \| 60\,K\Omega = 10.58\,K\Omega$

From Eq. (2.117)

$R_B = R_1 \| R_2 \| R_3 = 22.5\,K\Omega \| 90\,K\Omega \| 30\,K\Omega = 11.25\,K\Omega$

From Eq. (2.118)

$R_B \| R_F = 11.25\,K\Omega \| 80\,K\Omega = 10.58\,K\Omega$

Therefore,

$R_A = (R_B \| R_F)$ is satisfied

2.53

Closed loop gain $A_f = \frac{R_F}{R_1} = \frac{1x10^6}{1x10^4} = 100$

From Eq. (2.120)

$$\frac{v_o(\min)}{A_f} \le v_s \le \frac{v_o(\max)}{A_f}$$

$$-\frac{13}{100} \le v_s \le \frac{13}{100}$$

Maximum input signal = $\pm 130\,mV$

2.54

(a) Closed loop gain $A_f = \frac{1x10^6\,\Omega}{10K\,\Omega} = 100$

Peak input signal = $\pm\frac{13}{100} = \pm 130\,mV$

(b) Undistorted output voltage = $\pm 12\,V$

Limiting Op-amp current = $\pm 18\,mA$

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Allowable load current $i_L = 18 - \frac{v_o}{R_F} = 18 - \frac{12}{1K\Omega} = 18 - 12 = 6\,mA$

Minimum load resistance $R_L > \frac{v_o}{R_L} = \frac{12}{6\,mA} = 2\,K\Omega$

2.55

$$SR = 10\frac{V}{\mu s}$$

(a) From Eq. (2.126)

$$SR = 6.286 v_s f$$

$$f = \frac{SR}{6.286 v_s} = \frac{10}{1x10^{-6}\ x\ 6.286x10x10^{-3}} = 1.59\,x10^{8}\ Hz$$

(b) From Eq. (2.128)

$$f_{s(\max)} = \frac{SR}{2\ \pi\, x V_m} = \frac{10}{10^{-6}\,x2\ \pi\, x10} = 159.2KHz$$

2.56

From Eq. (2.123)

$$t_r = 0.3\,\mu s$$

$$t_r = 2.2\,\tau$$

$$\tau = \frac{t_r}{2.2} = 136.36\,x10^{-9}\ s$$

From Eq. (2.125)

$$f_{\max} = \frac{1}{2\pi\tau} = \frac{1}{2\pi\, x136.36\,x10^{-9}} = 1.16\,MHz$$

2.57

$$SR = 10\frac{V}{\mu s},\ V_S = 10V$$

(a) From Eq. (2.128)

$$\tau = \frac{V_S}{SR} = \frac{10\,x1\,x10^{-6}}{10} = 10^{-6}\ s$$

$$f_{\max} = \frac{1}{2\pi\tau} = \frac{1}{2\pi\, x10^{-6}} = 1.59\,x10^{5}\ KHz$$

(b)

From Eq. (2.128)

$$f_{s(\max)} = \frac{SR}{2\pi V_m} = \frac{10}{2\pi\, x10\,\mu s} = \frac{10^{6}}{2\pi} = 159\,KHz$$

2.58

$$SR = 10\frac{V}{\mu s},\quad f_s = 250\,KHz$$

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(a) From Eq. (2.127)

$$V_m = \frac{SR}{2\pi f_s} = \frac{10}{1x10^{-6}\ x2\pi\ x250\,x10^3} = 6.37V$$

(b) From Eq. (2.127)

$$f_{s(\max)} = \frac{SR}{2\,\pi V_m} = \frac{10\,x10^6}{2\pi\,x10} = 159.1\,KHz$$

2.59

(a) From Eq. (2.130)

$$v_{oo} = \pm(1+\frac{R_F}{R_1})v_{io}$$

$$v_{io} = \pm 6\,mV$$

$$v_{oo} = \pm(1+\frac{50\,K\Omega}{15\,K\Omega})6\,mV$$

$$v_{oo} = \pm 26\,mV$$

(b)

$$v_{oo} = v_{io} = \pm 6\,mV$$

2.60

$$v_{io} = \pm 6\,mV$$

$$v_{oo} = \pm 12\,V$$

Referring to Fig. (2.40) and using the expression given below

$$v_{oo} = v_{io} + \frac{v_{io}}{CR}t = v_{io}(1+\frac{t}{CR})$$

$$\pm 12 = \pm 6\,mV(1+\frac{t}{CR})$$

$$\frac{t}{CR} \simeq 2\,x10^3$$

$$t = 2\,x10^3\ x0.1x10^{-6}\ x10x10^3 = 2\,s$$

2.61

(a) If I_B is the biasing current

$V_{ob} = R_F I_B = 50 \times 10^3 \times 500 \times 10^{-9}$

$= 25$ mV

(b) Offset minimizing resistance

$$R_x = R_1 \parallel R_F\ (15 \parallel 50)\ \text{k} = 11.538\ \text{k}\Omega$$

2.62

Using Eq. (2.138)

$$V_{oi} = \left(1+\frac{R_F}{R_1}\right) R_x\, I_{io} = \left(1+\frac{R_F}{R_1}\right) R_x\, I_{io}$$

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$$= \left(1+\frac{R_F}{R_1}\right)(R_1 \parallel R_F)\, I_{io} = \left(1+\frac{50}{15}\right)(15 \parallel 50)\text{k}\, I_{io}$$

$$= \pm \frac{65}{15} \times \frac{15 \times 50}{65} \times 10^3 \times 200 \times 10^{-9} = \pm 10^{-2}\ \text{V}$$

2.63

(a) $V_{oi} = R_F\, I_{io} = \pm 150 \times 10^3 \times 300 \times 10^{-9} = \pm 45$ mV

(b) $V_{ob} = 150 \times 10^3 \times 500 \times 10^{-9} = 75$ mV

2.64

(a) $R_1 \parallel R_F = (15 \parallel 50)\ \text{k} = 11.54\ \text{k}\Omega = R_x$

$$V_{ob} = 0$$

$$V_{oi} = R_F\, I_{io} = \pm 50 \times 10^3 \times 300 \times 10^{-9}$$

$$= \pm 15\ \text{mV}$$

(b) For $R_x = 0$, Eq. (2.2.134) gives

$$V_{ob} = R_F\, I_B = 50 \times 10^3 \times 500 \times 10^{-9} = 25\ \text{mV}$$

2.65

(a) From Eq. (2.142) for $v_C(t = 0)$

$$+v_{of} = \frac{V_{io}}{C_F R_1}\, t - \frac{I_{io}}{C_F}\, t + V_{io} - R_x\, I_{B1}$$

$$12 = \frac{6 \times 10^{-3}}{10^{-7} \times 15 \times 10^3}\, t - \frac{300 \times 10^{-9}}{10^{-7}}\, t + 6 \times 10^{-3} - 10 \times 10^3 \times 500 \times 10^{-9}$$

$$= \frac{6}{1.5}\, t - 3t + 6 \times 10^{-3} - 5 \times 10^{-3}$$

$$= 4t - 3t, \quad t \simeq 12\ \text{s}$$

(b) $R_x = 0$, hardly makes any difference. The value remains the same.

2.66

From Fig.P2.66

$i_s \simeq i_f$

$i_f = i_1 + i_o$

$i_o = i_f - i_1$

Since $v_o = i_1 R_2$

$$i_o = i_f - i_1 = i_f - \frac{v_o}{R_2}$$

Since $v_s = i_s\, R_1 \simeq i_f R_1$

$$i_o = \frac{v_s}{R_1} - \frac{v_o}{R_2}$$

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$$v_o = -i_f R_F$$

$$i_o = \frac{v_s}{R_1} + i_f \frac{R_F}{R_2} = \frac{v_s}{R_1} + \frac{v_s}{R_1}\frac{R_F}{R_2} = \frac{v_s}{R_1}(1 + \frac{R_F}{R_2})$$

$$i_o = \frac{v_s}{R_1}(1 + \frac{R_F}{R_2}) \qquad (1)$$

Given $R_F = 1M\Omega, \quad R_2 = 1K\Omega, \; i_o = 500\,mA, \; v_s = 10\ mV$

From Eq. (1) above

$$500\,mA = \frac{10\,mV}{R_1}(1 + \frac{10^3\ K\Omega}{1K\Omega})$$

$$R_1 \simeq 20\,\Omega$$

2.67

Power produced by the photodiode

$$P = D_p\, a = 10^{-6} \times 40 \times 10^{-2} = 400 \text{ nW}$$

$$i_S = PD_i = 400 \times 10^{-9} \times 1 = 400 \text{ nA}$$

$$R_F = |-v_O/i_S| = \frac{1}{400 \text{ nA}} = \frac{10^7}{4} = 2.5 \text{ M}\Omega$$

2.68

For $R_F >> R_2$,

$$V_S = \frac{R_1 R_2}{R_F} I_M$$

Let $R_F = 100$ kΩ; then $R_2 = 100$ Ω.

$$R_1 = \frac{V_S R_F}{I_M R_2} = \frac{200 \times 10^{-3} \times 100 \times 10^3}{100 \times 10^{-6} \times 10^2} = 2 \text{ M}\Omega$$

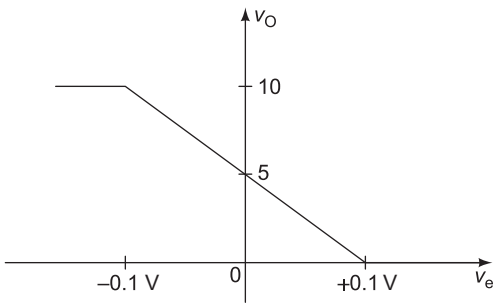
2.69

$$z_{in} = -R\,(R_1/R_F)$$

Assume $R_1 = R_F = 10$ kΩ and $R = 15$ kΩ. Then

$$z_{in} = -15 \text{ k}\Omega$$

2.70



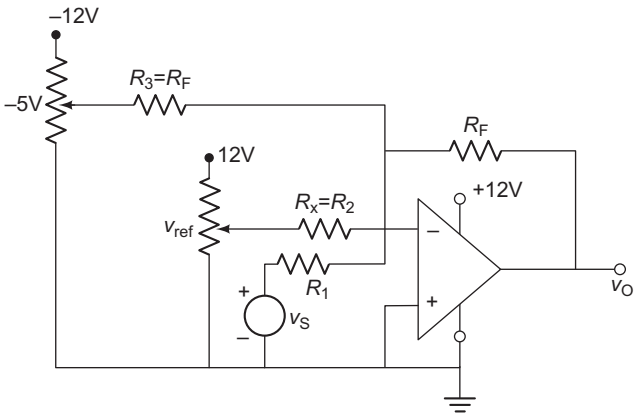
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$$v_O = -50\, v_e + 5$$

$$= -50\,(v_{ref} - v_S) + 5 = 50\, v_S - 50\, v_{ref} + 5$$

Let $R_1 = 10\ \text{k}\Omega$ and $R_2 = 10\ \text{k}\Omega$. $R_F = 50 \times 10 = 500\ \text{k}\Omega = R_3$.



2.71

There is no unique solution. Hint: Use an op-amp comparator to compare the dc voltage with the sifted sine wave to produce a square-wave output and then pass the signal to a R-C circuit, this is to differentiate.

2.72

Same as Problem 2.70.

2.73

$$A_o = 1 + R_F/R_1 = 100$$

From Eq. (2.31)

$$A_f(j\omega) = \frac{1 + R_F/R_1}{1 + jf\,(1 + R_F/R_1)/f_{bw}}$$

From Eq. (2.32)

$$f_c = f_{bw} \times \frac{1}{1 + R_F/R_1}, \quad f_{bw} = 4 \times 10^6\ \text{Hz}$$

$$f_{bw} = 4 \times 10^6\ \text{Hz}$$

$$f_c = 4 \times 10^6 \times \frac{1}{100} = 40\ \text{kHz}$$

Let $R_1 = 2.5\ \text{k}\Omega$. Then

$$\frac{R_F}{R_1} = 99,\ R_F = 2.5 \times 99\ \text{k}\Omega$$

$$= 247.5\ \text{k}\Omega$$

$$= 250\ \text{k}\Omega$$

Voltage swing:

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We know

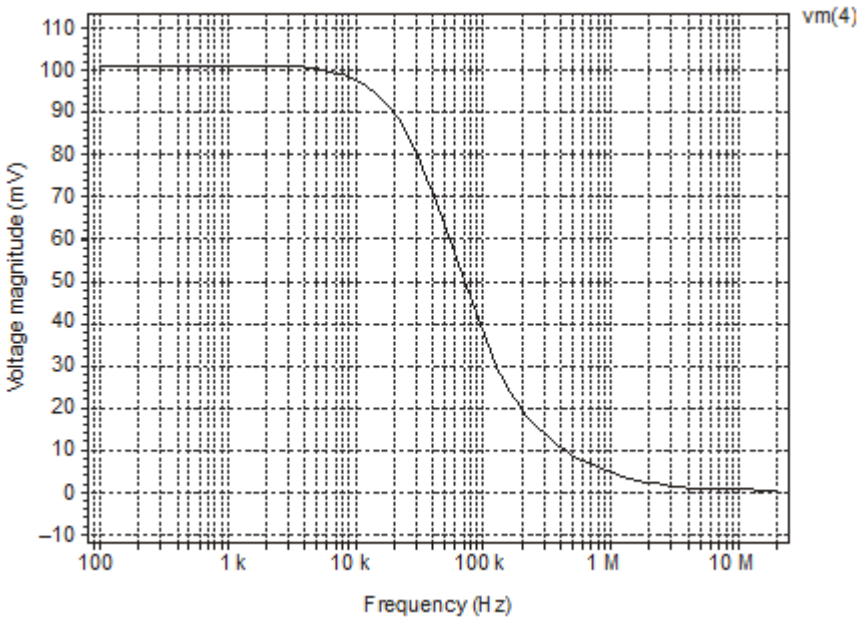
$$f_s = \frac{SR}{2\pi v_O} = \frac{SR}{2\pi \times 11} = 25 \times 10^3 \text{ Hz}$$

$$SR = 25 \times 10^3 \times 2\pi \times 11 = 1.73 \text{ V/}\mu\text{s}$$

Problem 2.73

```
VS     1    0    AC   1MV
RX     1    2    10K
R2     3    0    2.5K
R3     3    4    250K
XA1    2    3    40    LF411_AC
. SUBCKT  LF411_AC 1    2    3    4
RI     1    2    2E12
RO     6    3    50
GB     4    5    1    2    0 .1M

R1     5    4    10K
C1     5    4    0.79UF
EA     4    6    5    4    2E5
D1     3    7    DMOD
D2     4    7    DMOD
. MODEL   DMOD D (BV = 14V)
. ENDS    LF411_AC
. AC  DEC 10   100  20MEGHZ
. PRINT   AC   VM(4)
. PROBE
. END
```

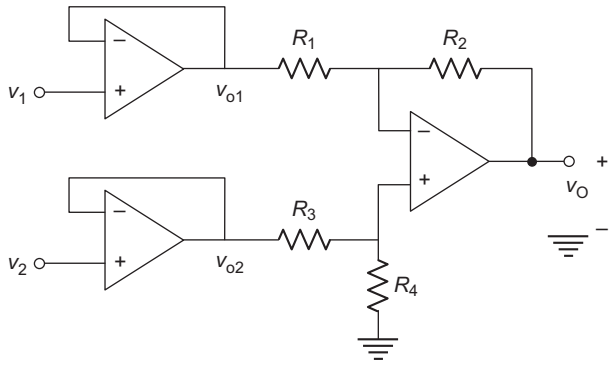


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2.74

Use the circuit of Problem 2.33 to design the desired differential amplifier circuit with $A_f = 5$ kV/V and $R_i \geq 500$ kΩ.



From Problem 2.33

$$R_1 = R_3 = 10 \text{ k}\Omega, \quad R_2 = R_4 = 1 \text{ M}\Omega$$

$$A_{v1} = -100\, v_1 + 100\, v_2 = -100\,(v_1 - v_2)$$

Now add one stage of noninverting op-amp of gain 50.

$$A_f = A_{v1} \times A_{v2} = 100 \times 50 = 5000 = 5 \text{ kV/V}$$

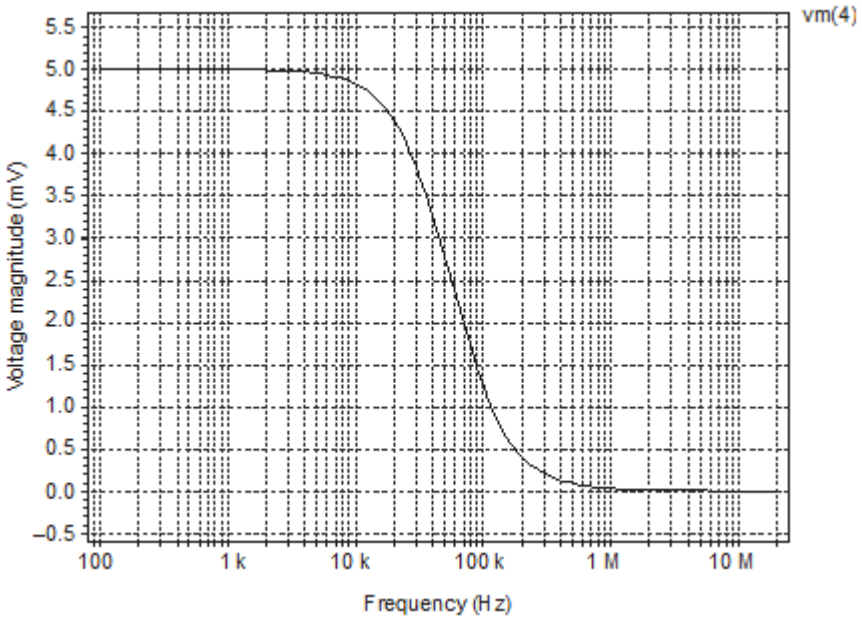
Problem 2.74

```
VS1    2    0    AC   1MV
VS2    5    0    AC   2MV
R1     4    9    10K
R3     7    8    10K
R2     9    10   1MEG
R4     8    0    1MEG
R6     12   0    1K
R7     12   13   49K
R8     10   11   1K
XA1    2    4    4    0    LF411_AC
XA2    5    7    7    0    LF411_AC
XA3    8    9    10   0    LF411_AC
XA4    11   12   13   0    LF411_AC
. SUBCKT  LF411_AC 1    2    3    4
RI     1    2    2E12
RO     6    3    50
GB     4    5    1    2    0.1M
R1     5    4    10K
C1     5    4    0.79UF
EA     4    6    5    4    2E5
D1     3    7    DMOD
D2     4    7    DMOD
. MODEL   DMOD D    (BV = 14V)
. ENDS    LF411_AC
```


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```
. PRINT    AC   VM(13)
. AC  DEC  10   100  20MEGH2
. PROBE
. END
```



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