

Microelectronic Circuits Analysis and Design 3rd Edition

Solution Manual for Microelectronic
Circuits Analysis and Design 3rd
Edition Rashid 1305635166-9781305635166

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Chapter 2

2.1

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

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

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 $\pm 14 \text{ V}$.

2.5

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

2.6

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

(b) $v_c = \frac{v_+ + v_-}{2} = \frac{200}{2} = 100 \text{ } \mu\text{V}$

(c) $20 \log \text{CMMR} = 90$

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

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

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

(b) $v_c = \frac{v_+ + v_-}{2} = \frac{60 + 100}{2} \text{ } \mu\text{V} = 80 \text{ } \mu\text{V}$

(c) $20 \log \text{CMRR} = 90 \text{ dB}$

$$\log \text{CMRR} = 4.5$$

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

$$A_c = \frac{A_d}{3.1622 \times 10^4} = \frac{2 \times 10^5}{29}$$

$$= 3.1622 \times 10^4$$

$$= 6.3247$$

(d) $v_O = A_d v_d + A_c v_c$
 $= 2 \times 10^5 (-40 \times 10^{-6}) + 6.3247 \times 80 \times 10^{-6}$
 $= -8 \pm 5.05976 \times 10^{-4} = -7.9994 \text{ V or } -8.00050 \text{ V}$

2.8

Choose $1 \text{ k}\Omega < R_1 < 10 \text{ M}\Omega$; let $R_1 = 10 \text{ k}\Omega$.

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

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

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

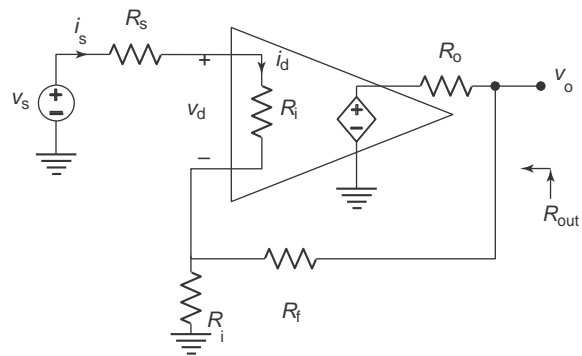
$$i_S = i_d = \frac{v_O}{A_d R_i}, R_i \gg R_s$$

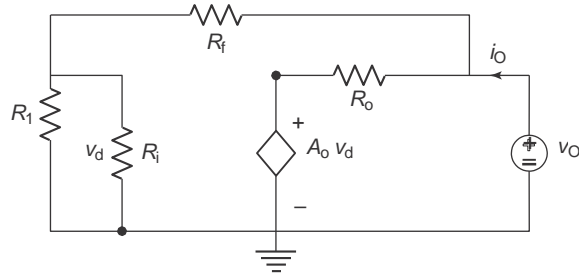
Substituting for $v_O = \left(1 + \frac{R_F}{R_1}\right) v_S$

$$i_S = \frac{(1 + R_F/R_1) v_S}{A_d R_i}, R_{in} = \frac{v_S}{i_S} = \frac{A_d R_i}{1 + R_F/R_1} \tag{i}$$

i_O from the circuit

$$i_O = \frac{v_O - A v_d}{R_o} + \frac{v_O}{R_i + R_f} \tag{ii}$$





Also $-v_d = \frac{R_1}{R_1 + R_f} v_o$ Assuming $R_1 \gg R_f$ (iii)

From (ii) and (iii),

$$\frac{1}{R_{out}} = \frac{i_o}{V_o} = \frac{1 + A_o \frac{R_1}{R_1 + R_f}}{R_o} + \frac{1}{R_1 + R_f}$$

Assuming $(R_1 + R_f) \gg \frac{R}{1 + A_o R_1 / (R_1 + R_f)}$ (iv)

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

(a) From (i)

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

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

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

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

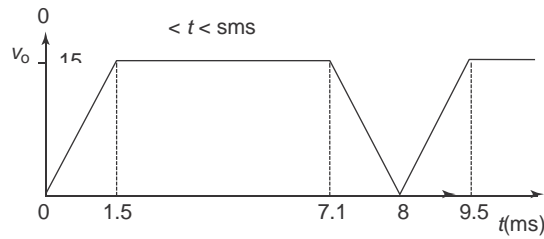
2.10

Let $R_1 = 10 \text{ k}\Omega$. Then

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

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

2.11



v_S needed for $v_O = \pm 15 \text{ V}$

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

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

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

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

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)

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

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

(a) $A_f = \frac{5 \times 10^5 \times 40 \times 10^3}{40 \times 10^3 + 5 \times 10^5 \times 10^4} = 3.999968$

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

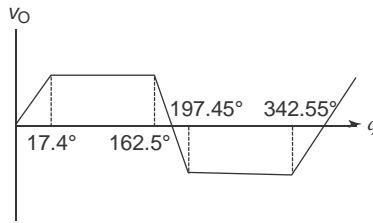
(c) For $A_o \rightarrow \infty, A_f = \left\{ 1 + \frac{R_F}{R_1} \right\} = 1 + \frac{30 \text{ k}}{10 \text{ k}} = 4, v_O = 4 v_S$ Error insignificant

2.13 $\left\{ \pm 15 \text{ V} \right.$

$$v_O = v_S \left(1 + \frac{v_O}{\dots} \right)$$

$$\left. \frac{R_2}{R_1} \right) = 5 v_s$$

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



2.14

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

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

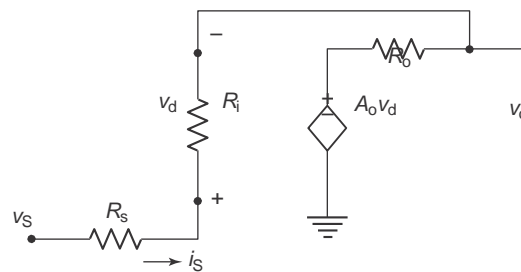
$$i_S = i_i = v_d/R_i \text{ and}$$

$$v_d = v_O/A_o$$

$$i_S = i_i = \frac{v_O}{A_o R_i} \approx \frac{v_S}{A_o R_i}, \frac{v_S}{i_S} = R_S + A_o R_i$$

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

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



Also

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

(i) and (ii) give

$$i_O = \frac{v_O + A_o \frac{v_O R_i}{R_i + R_S}}{R_o} + \frac{v_O}{R_i + R_S}$$

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

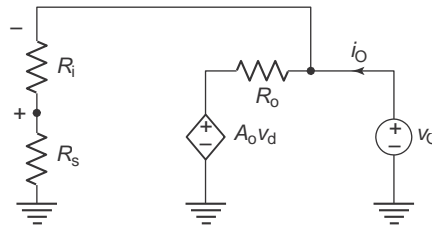
$$\frac{R_o}{1 + A_o R_i / (R_i + R_S)} \ll (R_i + R_S)$$

Hence

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

$$= \frac{75}{1 + 5 \times 10^5 \times 2 \times 10^6} \approx 7.5 \times 10^{-6} \Omega$$

$$(2 \times 10^6 + 10^4) \approx 15 \times 10 \ \Omega$$



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

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

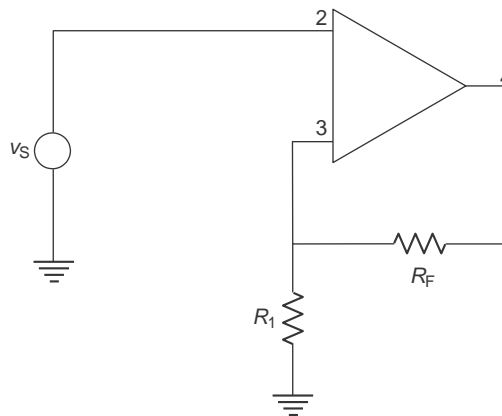
$$R_F = 50 \text{ k}\Omega, R_1 = 15 \text{ k}\Omega$$

$$\begin{aligned} \therefore A_f(j\omega) &= \frac{1 + 50 \text{ k}/15 \text{ k}}{1 + j\omega(1 + 50 \text{ k}/15 \text{ k})/2 \times 10^6} \\ &= \frac{4.333}{1 + j 100 \times 10^3 (4.333)/2 \times 10^6} \\ &= \frac{4.333}{1 + j 0.2167} = 4.235 \angle -12.23^\circ \end{aligned}$$

From Eq. (2.32)

$$\begin{aligned} f_c &= \beta A_o f_b = \frac{R}{R_1 + R_F} A_o f_b \\ &= \frac{15 \text{ k}}{15 \text{ k} + 50 \text{ k}} \times 2 \times 10^5 \times 10 \text{ Hz} \\ &= 461.54 \text{ kHz} \end{aligned}$$

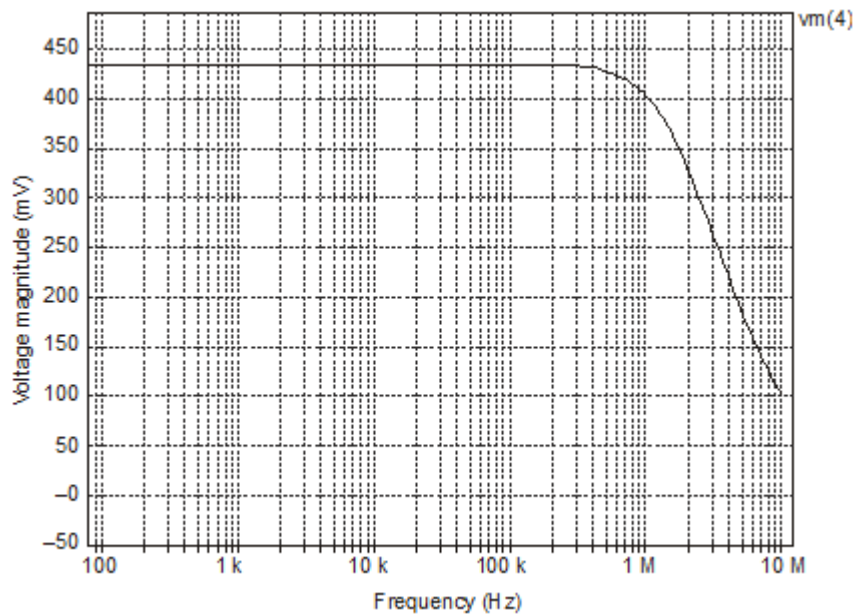
(b)



```

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

```



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)

$$\begin{aligned} A_f(j\omega) &= \frac{1+R_F \frac{R_1}{R_1}}{1+jf \left(1+\frac{R_F}{R_1}\right) / f_{bw}} \\ &= \frac{1+1}{1+jf(1+1)/2 \times 10^6} = \frac{2}{1+j100 \times 10^3 \times 10^{-6}} \\ &= \frac{2}{1+j0.1} = 1.998 \angle -5.71^\circ \end{aligned}$$

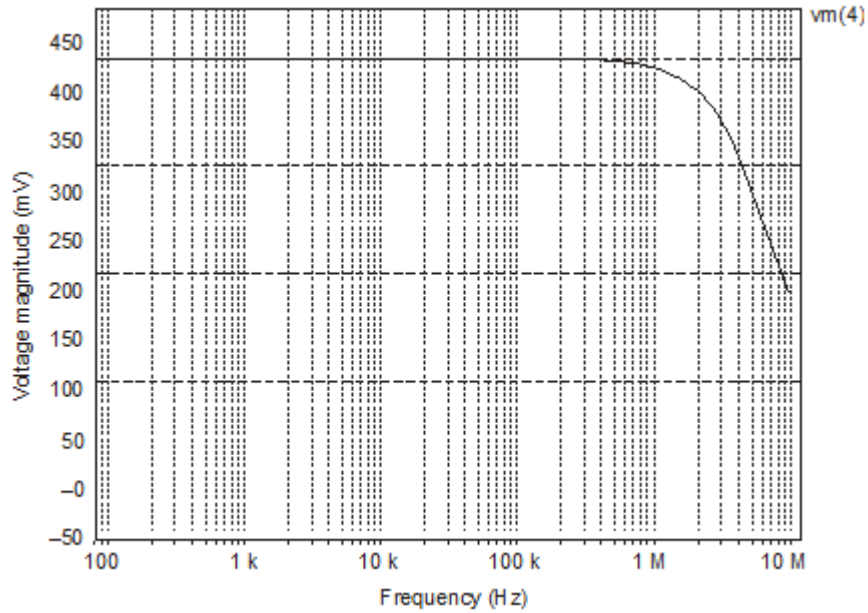
(b) From Eq. (2.32)

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

```

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

```



2.17

From Eq. (2.35)

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

20

$$R_A = R_a \parallel R_b \parallel R_c = \frac{1}{\frac{1}{30} + \frac{1}{30} + \frac{1}{30}} \text{ k}\Omega$$

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

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

2.18

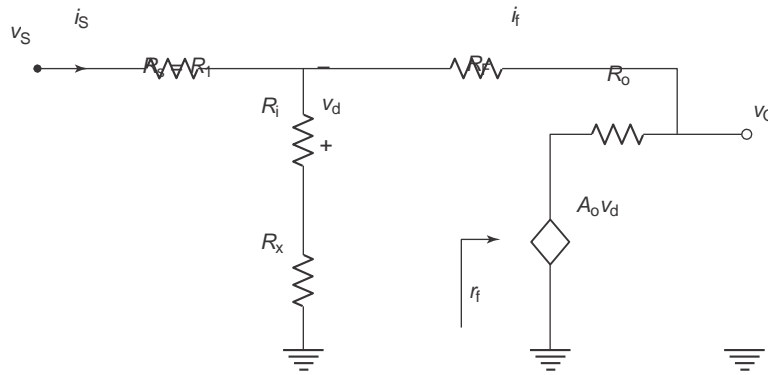
$$i_S = \frac{v_S}{R_S} = \frac{50 \text{ mV}}{5 \text{ k}\Omega} = 10 \mu\text{A} \quad (R_1 = R_S)$$

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

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

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

2.19



Assume $R_i \gg R_x$

$$R_{in} = \frac{v_s}{i_s} = R_1 + R_i \parallel r_f \quad (i)$$

where

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

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

or

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

$$r_f = \frac{R_F + R_o}{1 + A_o} \quad (ii)$$

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

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

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

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

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

From Eq. (2.45)

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

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

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

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

$$= 5 \text{ k} + 10^{12} \parallel 1 \approx 5001 \Omega$$

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

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

(c) From Eq. (2.45)

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

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

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)

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

(b) $v_o = A_f v_s = -4.9998 \times 100 \times 10^{-3} = -0.4998 \text{ V}$

(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)

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

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

$$= \frac{-3.333}{1 + j 0.216} = -3.258 \angle -12.19^\circ$$

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

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

(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

```

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)

$$A_f = - \frac{R_F/R_1}{1 + jf(1 + R_F/R_1)/f_{bw}} = \frac{-1}{1 + j100 \times 10^3 (1+1)/2 \times 10^6}$$

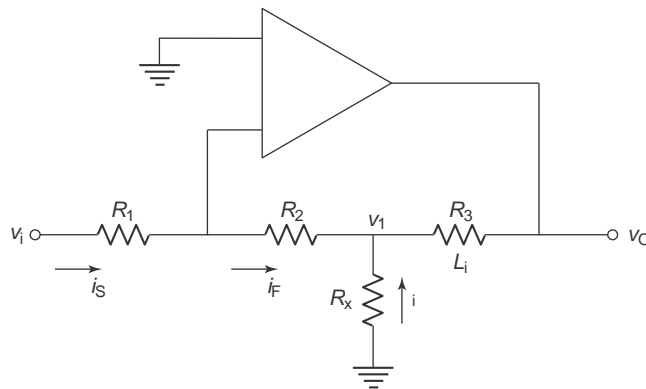
$$= - \frac{1}{1 + j0.1} = -0.99 \angle -5.71^\circ$$

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

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

2.24

(a)



Ignoring v_d (virtual ground)

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

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

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

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

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

$$v_i \left(\frac{R_2}{R_1} + \frac{R_3}{R_1} + \frac{R_3 R_2}{R_1 R_x} \right)$$

$$-10 = - \frac{1 + \frac{20k}{20k} + \frac{20k}{R_x}}{50k}$$

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

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

(b) $SR = 6 \text{ V}/\mu\text{s}, f_{s(\text{max})} = \frac{SR}{2\pi V_m}$

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

(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

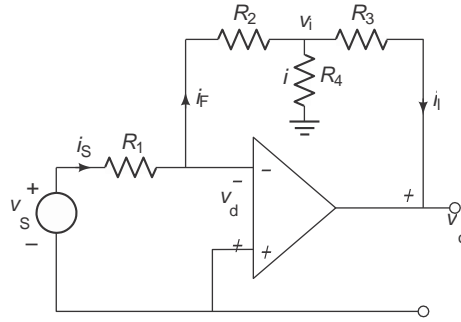
From Eq. (2.60)

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

$$= - \left(\frac{40\text{k}}{1} \times 2 + \frac{40\text{k}}{43} (-3) + \frac{40\text{k}}{(-2)} (-2) \right)$$

$$\left(20 \text{ k} \quad 20 \text{ k} \quad 20 \text{ k} \right)$$
$$= -(4 - 6 - 4) = + 6 \text{ V}$$

2.26



$$i_s = i_F = \frac{v_s}{R_1}, \quad v_1 = -i_F R_2 = -\frac{v_s}{R_1} R_2$$

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

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

Also
$$v_o = v_1 - i R_3 = -\frac{v_s}{R_1} R_2 - v_s \frac{R_2}{R_1 R_4} R_3 + \frac{v_s}{R_1} R_3$$

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

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

$$= -\frac{R_2}{R_1} \left(1 + \frac{R_3}{R_2} + \frac{R_3}{R_4} \right), \quad \text{Given } \frac{v_o}{v_s} = \frac{-12}{0.05} = -240$$

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

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

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

Let $R_2 = 10 \text{ k}\Omega$ and $R_3 = 300 \text{ k}\Omega$. Then

$$R_4 = \frac{300\text{k}}{9} = \frac{100}{45}$$

3

$$k = 33.33 \text{ k}\Omega$$

$$R_1 = \frac{10}{6} \text{ k}\Omega$$

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

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

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

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

2.29

(a) $A_o \rightarrow \infty$, 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 $R_F = 0.5 \text{ M}\Omega$.

(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

$$v_o = -\frac{A_o R_x}{R_a + R_x} + \frac{A_o R_F v}{R_1 + R_F} + \frac{A_o R_b v}{R_1 + R_F}$$

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

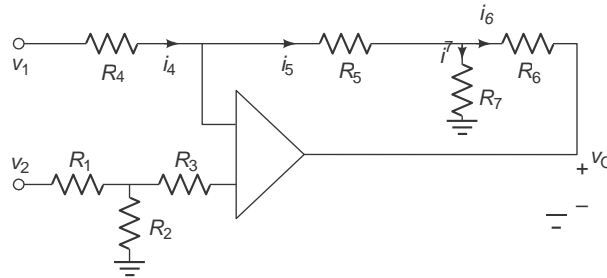
$$+ \frac{5 \times 10^5 \times 5 \times 10^3 v}{5 \times 10^3 + 50 \times 10^3}$$

$$= 6.818 \times 10^3 + 2.777 \times 10^3 + 4545 \times 10^3 v_o$$

$$v_o \approx -0.2 \text{ V}$$

2.31

(a)



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

$$i_7 = \frac{v}{R_7}, \quad i_6 = \frac{v - v}{R_6}$$

$$i_4 = i_5$$

$$\frac{v_1 - v}{R_4} = \frac{v - v_3}{R_5} \quad (i)$$

$$i_5 = i_6 + i_7, \quad \frac{-3}{R_5} = \frac{3 - 0}{R_6} + \frac{-3}{R_7}$$

$$\therefore \quad -\frac{v_3}{R_5} - \frac{v_3}{R_6} - \frac{v_3}{R_7} = -\frac{v_-}{R_5} - \frac{v_0}{R_6}$$

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

From (i)

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

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

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

From (ii)

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

From (iii) using (iv)

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

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

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

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

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

(1)

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

$$v_- = \frac{5}{\left(\frac{1}{R_4} + \frac{1}{R_5} X \right)}$$

$$(R_4 + R_5)/R_4 R_5 - R \int X(1 R_5)$$

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

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

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

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

$$\frac{R_2}{R_1 + R_2} v_2 - \frac{v_1}{R \left[\frac{R_4 + R_5}{R_4 R_5} - \left(\frac{1}{R_5} \right) X \left(\frac{1}{R_5} \right) \right]} = \frac{1}{R_5} \cdot \frac{X}{\left[\frac{R_4 + R_5}{R_4 R_5} - \left(\frac{X}{R_5} \right) \left(\frac{1}{R_5} \right) \right]} v_0 / R_6 + \frac{v_0}{A_0}$$

$$\left[\begin{array}{c|c} R & R \\ \hline 4 & 5 \end{array} \right] \left[\begin{array}{c|c} R & \\ \hline 5 & 5 \end{array} \right] \left[\begin{array}{c|c} R & \\ \hline 5 & 5 \end{array} \right] \left[\begin{array}{c|c} R & R \\ \hline 4 & 5 \end{array} \right] \left[\begin{array}{c|c} R & \\ \hline 5 & 5 \end{array} \right] \left[\begin{array}{c|c} R & \\ \hline 5 & 5 \end{array} \right]$$

$$\left[\frac{R_2}{R_1 + R_2} \right] v_2 - \frac{v_1}{\left[\frac{R_4 + R_5}{R_4 R_5} - \left(\frac{1}{R_5} \right) X \left(\frac{1}{R_5} \right) \right]} = \frac{1}{R_5} \cdot \frac{X}{\left[\frac{R_4 + R_5}{R_4 R_5} - \left(\frac{X}{R_5} \right) \left(\frac{1}{R_5} \right) \right]} v_0 / R_6 + \frac{v_0}{A_0}$$

$$v_0 = \frac{\left[\frac{R_2}{R_1 + R_2} \right] v_2 - \frac{v_1}{\left[\frac{R_4 + R_5}{R_4 R_5} - \left(\frac{1}{R_5} \right) X \left(\frac{1}{R_5} \right) \right]}}{\left(\frac{1}{R_5} \right) \frac{X}{\left[\frac{R_4 + R_5}{R_4 R_5} - \left(\frac{X}{R_5} \right) \left(\frac{1}{R_5} \right) \right]} + \frac{1}{R_6}} + \frac{1}{A_0}$$

Assume A_0 is large

$$\left[\frac{R_2}{R_1 + R_2} \right] v_2 - \frac{v_1}{\left[\frac{R_4 + R_5}{R_4 R_5} - \left(\frac{1}{R_5} \right) X \left(\frac{1}{R_5} \right) \right]} = \frac{1}{R_5} \cdot \frac{X}{\left[\frac{R_4 + R_5}{R_4 R_5} - \left(\frac{X}{R_5} \right) \left(\frac{1}{R_5} \right) \right]} v_0 / R_6 + \frac{v_0}{A_0}$$

$$V_0 = \frac{\left[\frac{R_2}{R_1 + R_2} \right] v_2 - \frac{v_1}{\left[\frac{R_4 + R_5}{R_4 R_5} - \left(\frac{1}{R_5} \right) X \left(\frac{1}{R_5} \right) \right]}}{\left(\frac{1}{R_5} \right) \frac{X}{\left[\frac{R_4 + R_5}{R_4 R_5} - \left(\frac{X}{R_5} \right) \left(\frac{1}{R_5} \right) \right]} + \frac{1}{R_6}}$$

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

$$\left[\frac{R_2}{R_1 + R_2} \right] v_2 - \frac{v_1}{\left[\frac{R_4 + R_5}{R_4 R_5} - \left(\frac{1}{R_5} \right) X \left(\frac{1}{R_5} \right) \right]} = \frac{1}{R_5} \cdot \frac{X}{\left[\frac{R_4 + R_5}{R_4 R_5} - \left(\frac{X}{R_5} \right) \left(\frac{1}{R_5} \right) \right]} v_0 / R_6 + \frac{v_0}{A_0}$$

$$V_0 = \frac{\left[\frac{R_2}{R_1 + R_2} \right] v_2 - \frac{v_1}{\left[\frac{R_4 + R_5}{R_4 R_5} - \left(\frac{1}{R_5} \right) X \left(\frac{1}{R_5} \right) \right]}}{\left(\frac{1}{R_5} \right) \frac{X}{\left[\frac{R_4 + R_5}{R_4 R_5} - \left(\frac{X}{R_5} \right) \left(\frac{1}{R_5} \right) \right]} + \frac{1}{R_6}}$$

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

$$\therefore v_0 = \frac{(150\text{k} / 250\text{k}) v_2 - \frac{v_1}{(100\text{k} / 50\text{k} - 50\text{k} / 3 \times 50\text{k})}}{50\text{k} / 3 (100\text{k} - 50\text{k} / 3)}$$

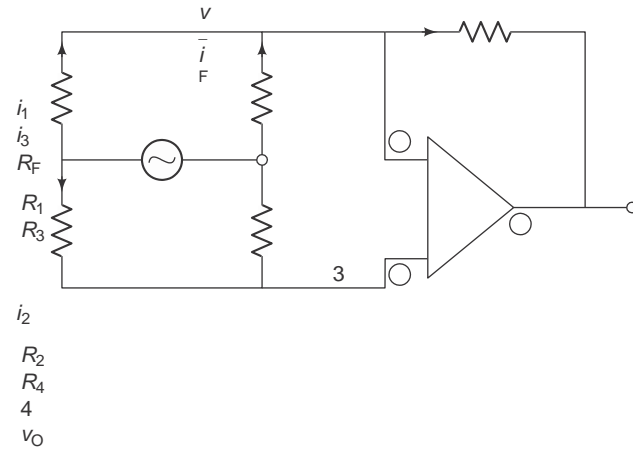
$$= \frac{0.6 v_2 - 0.6 v_1}{50\text{k} / 250\text{k}} \approx 3(v_2 - v_1)$$

2.32

(a)

1 v_i

○



2

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

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

Also

$$i_F = \frac{-v_O}{R_F} = \frac{i}{R_1} - \frac{v}{R_1} - \frac{v}{R_3}$$

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

$$i_2 = \frac{i - v_-}{R_2} = \frac{v}{R_4}, \quad \frac{i - v_-}{R_2} = \frac{v}{R_2} + \frac{v}{R_4}$$

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

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

Also

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

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

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

Substituting in (i)

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

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

For large A_o

$$\frac{v_O}{v_i}$$

$$\frac{v_O}{v_i}$$

$$\begin{aligned}
v_i &= - \frac{1/R_1 - R_1/(R_2 + R_4)}{1/R_F + 1/A_o (1/R_1 + 1/R_3 + 1/R_F)} (1/R_1 + 1/R_3 + 1/R_F) \\
&= - \frac{1/R_1 - R_1/R_2 + R_4}{1/R_F} (1/R_1 + 1/R_3 + 1/R_F) \\
&= - \frac{R_F}{R_1} + \frac{R_F R_4}{R_2 + R_4} \left(\frac{1}{R_1} + \frac{1}{R_3} + \frac{1}{R_F} \right)
\end{aligned}$$

$$\begin{aligned}
\frac{v_o}{v_i} &= \frac{-500k}{40k} + \frac{500k \times 100k}{80k + 100k} \left(\frac{1}{40k} + \frac{1}{50k} + \frac{1}{500k} \right) \\
&= -12.5 + 277k (20 \times 10^{-6} + 20 \times 10^{-6} + 2 \times 10^{-6}) \\
&= -12.5 + 13.0 = 0.5
\end{aligned}$$

Frequency response

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

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

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

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

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

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

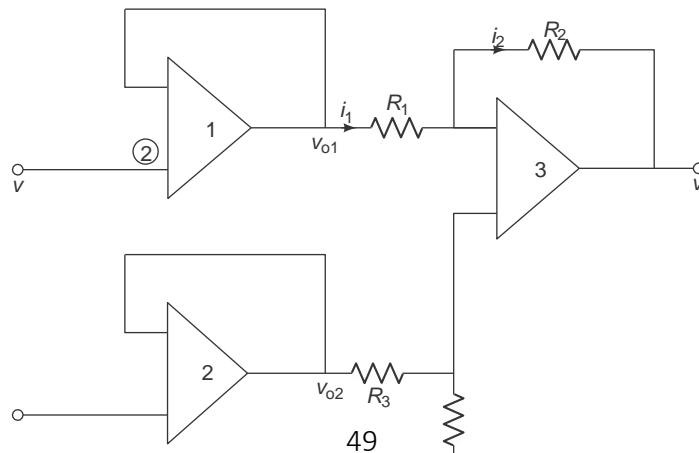
$$= \frac{-R_F/R_1 - R_4/(R_2 + R_4)(1/R_1 + 1/R_3 + 1/R_F)}{1 + jf R_F (1/R_1 + 1/R_3 + 1/R_F)/f_{b\omega}}$$

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

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

2.33

(a)



v R_4

$$(v_{(+)}1 - v_{(-)}1)A_0 = v_01, \quad v_{(+)}1 = v_1, \quad v_{(-)}1 = v_01$$

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

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

Now $i_1 = i_2$; then

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

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

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

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

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

$$\therefore v_{(-)3} \frac{1}{R_1 + R_2} = \frac{v_{o1}}{R_1} - \frac{v_o}{R_2}$$

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

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

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

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

$$v_2 = \frac{R_4}{R_3 + R_4} - \frac{R_2}{R_1 + R_2} v_1 = \frac{1}{R_1 + R_2} v_o$$

$$v_o \frac{1}{R_1 + R_2} = -v_1 \frac{R_2}{R_1 + R_2} + v_2 \frac{R_4}{R_3 + R_4}$$

$$R_3 + R_4$$

$$v_O = -v_1 \frac{R_2}{R_1} + v_2 \cdot \frac{R_4}{R_1} \cdot \frac{1}{R_3 + R_4}$$

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

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

$$= -v_1 100 + v_2 100$$

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

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

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

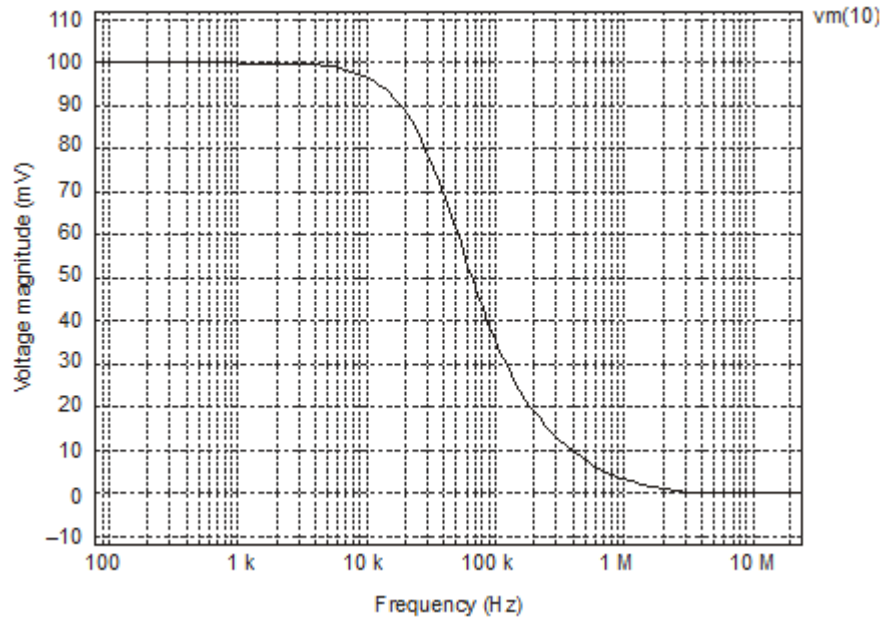
$$f_{\max} = \frac{SR}{2\pi v_o} = \frac{6 \text{ V}/\mu\text{s}}{2\pi \times 10} = 95.5 \text{ kHz}$$

(c) Problem 2.33

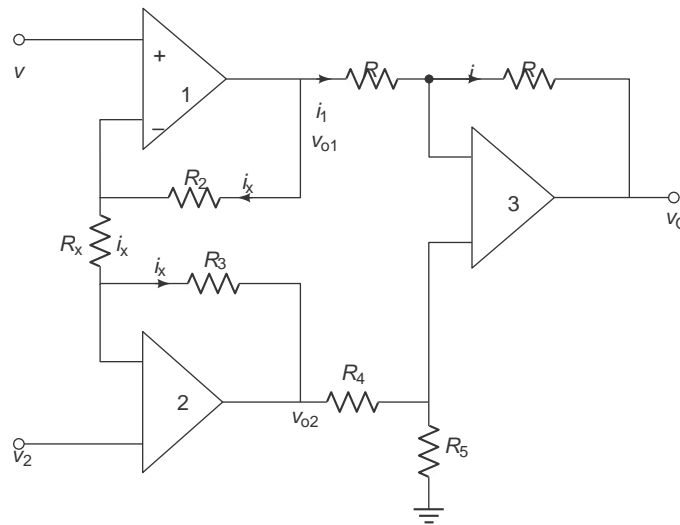
```

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

```



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

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

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

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

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

$$i_1 = i_F$$

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

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

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

$$v_{(-)3} \left(\frac{1}{R_1} + \frac{1}{R_F} \right) = \frac{R_1 + R_F}{R_1 R_F} v_{o1} + \frac{v_O}{R_F}$$

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

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

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

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

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

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

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

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

G e R =
iv n 2 R

3, $R_1 = R_4$ and $R_F = R_5$,

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

$$\begin{aligned} \therefore \frac{R_1 v_O}{R_1 + R_F} &= \frac{R_F v_2}{R_1 + R_F} - \frac{R_F}{R_1 + R_F} \cdot \frac{R_2}{R_x} v_1 + \frac{R_F}{R_1 + R_F} \cdot \frac{R_2}{R_x} v_2 \\ &\quad - \frac{R_F}{R_1 + R_F} v_1 - \frac{R_F}{R_1 + R_F} \cdot \frac{R_2}{R_x} v_1 + \frac{R_F}{R_1 + R_F} \cdot \frac{R_2}{R_x} \cdot v_2 \\ &= \frac{R_F}{R_1 + R_F} (v_2 - v_1) - \frac{2R_F}{R_1 + R_F} \frac{R_2}{R_x} v_1 + \frac{2R_F}{R_1 + R_F} \cdot \frac{R_2}{R_x} v_2 \end{aligned}$$

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

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

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

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      5E5
. ENDS OPAMP

```

- . OP
- . END

2.37

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

For $0 \leq t \leq 1$ 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 $1 \leq t \leq 2$ 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 $2 \leq t \leq 3$ ms

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

At $t = 3$ ms

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

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

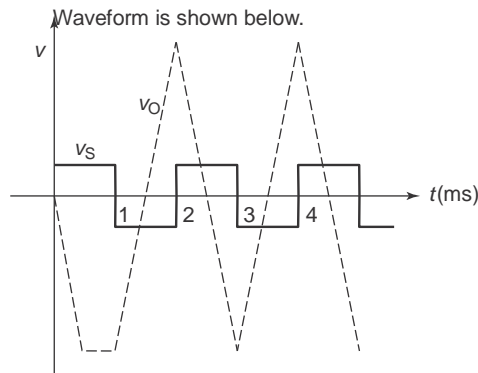
For $3 \leq t \leq 4$

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

At $t = 4$ ms

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

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



2.38

$$v_S = \frac{10}{10^{-3}} t \quad 0 \leq t \leq 1 \text{ ms}$$

$$v_S = -\frac{10}{10^{-3}} t + 20 \quad 1 \text{ ms} \leq t \leq 2 \text{ ms}$$

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

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

At $t = 1 \text{ ms}$

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

2.39

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

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

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

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 $f = \frac{1}{2\pi} = 0.16 \text{ Hz}$

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

Let $C_1 = 1 \mu\text{F}$. Then

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

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

$$\frac{10}{\quad} \qquad \frac{6.25}{\quad}$$

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

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 R_L)

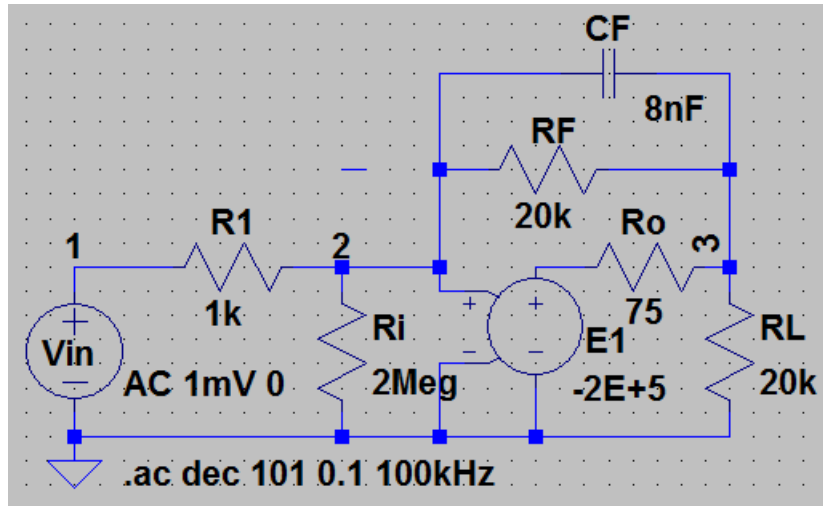
$$R_F := A_{BP} \cdot R_1 \quad R_F = 2 \times 10^4$$

From Eq. 2.87

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

$$\therefore C_F = 8 \text{ nF}$$

(b) For SPICE verification,

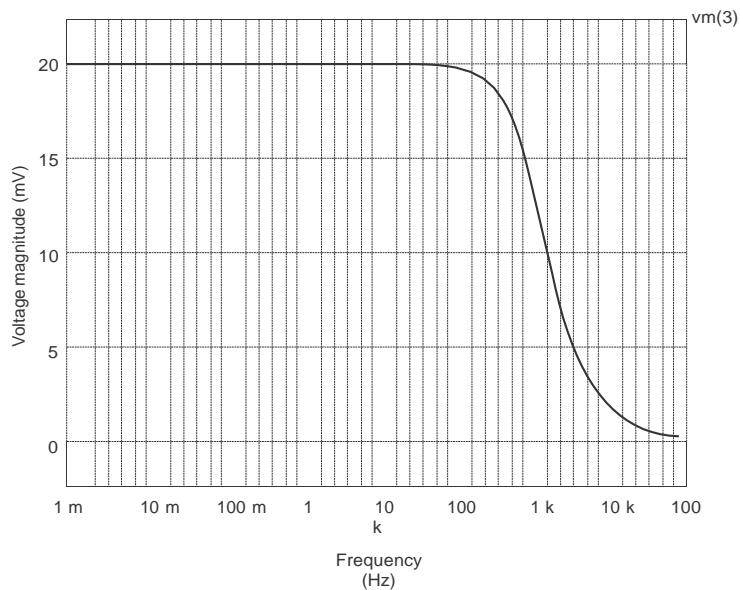


Problem 2.41

```

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 $C_1 = 0.1 \mu\text{F}$, $R_1 = 159 \Omega$.

From Eq. (2.110),

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

$$R_F = 3180 \Omega$$

(b) Problem 2.42

```

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

```

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

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

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

2.44

Using Eq. (2.110)

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

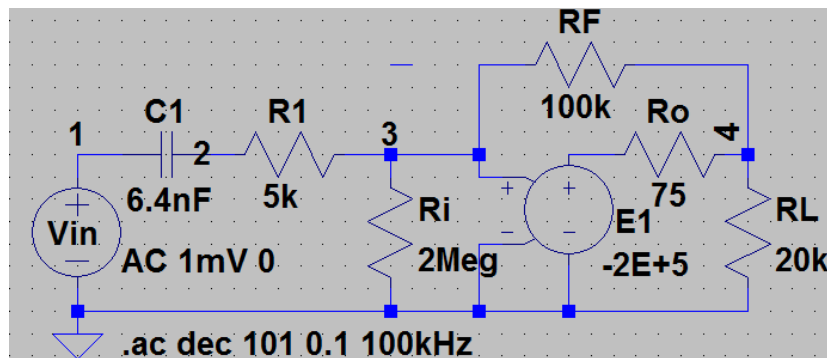
Assume $R_1 = 5 \text{ k}\Omega$ and $A_{\text{PB}} = 20$.

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

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

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

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

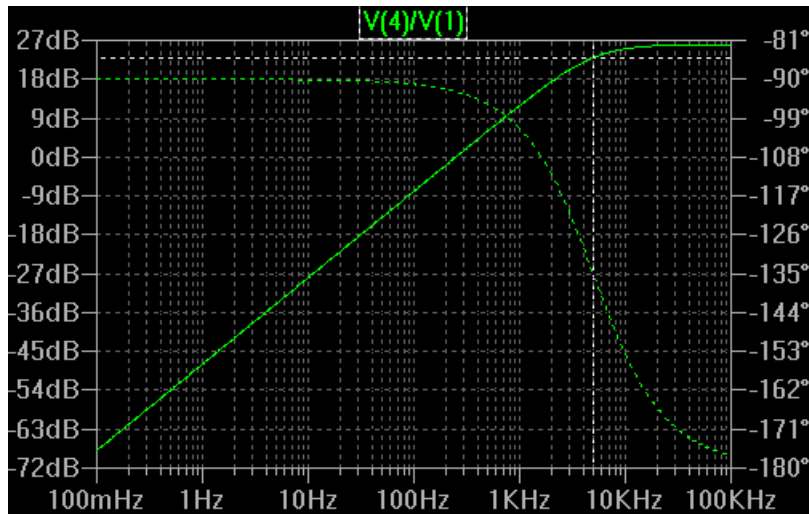
2 1 6.4nF Ri
3 0 2Meg

```

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

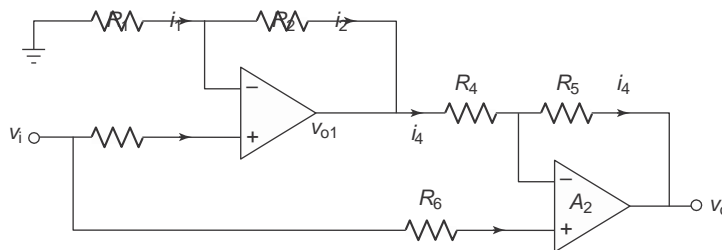
```

Plot



2.45

(a)



Assume $i_i = 0$

$$i_1 = \frac{0 - v}{R_1} = i_2 = \frac{v - v}{R_2} \quad (i)$$

$$\frac{v_{01} - v_{-(2)}}{R_4} = \frac{v_{-(2)} - v_o}{R_5} \quad (ii)$$

From (i)

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

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

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

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

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

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

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

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

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

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

Now $v_{+2} = v_i$

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

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

$$\underline{v}_O = A_o (V_{+(2)} - v_{-(2)}), \quad v_{-(2)} = v_{+(2)} - \frac{v_O}{A_o}$$

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

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

$$\frac{v_{o1} + v_{o2}}{R_4 R_5} = \left(v_i - \frac{v_o}{A_o} \right) \frac{(R_4 + R_5)}{R_4 R_5}$$

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

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

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

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

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

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

$$= \frac{\frac{(R_4 + R_5)}{R_4 R_5} \frac{A_o}{\left[\frac{1}{R_5} + \frac{R_4 + R_5}{A_o R_4 R_5} \right]}}{\frac{1}{R_5} + \frac{(R_4 + R_5)}{R_4 R_5 A_o} + \left[\frac{(R_4 + R_5)}{R_4 R_5 A_o} \right] \left(\frac{1}{f_b} \right)}$$

$$\frac{(R_4 + R_5)}{R_4 R_5} \frac{A_o}{\left[\frac{1}{R_5} + \frac{jf}{R_4 R_5 A_o} \right]}$$

+

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

$$= \frac{\frac{(R_4 + R_5)}{R_4 R_5} - \frac{1}{j\omega \left[\frac{R_4}{R_1 R_4} + \frac{R_1 R_4}{R_1 R_4} \right]}}{R_5 + \frac{(R_4 + R_5)}{R_4 R_5} \left(\frac{j\omega}{A_o f_b} \right)}$$

$$= \frac{\frac{(R_4 + R_5)}{R_4 R_5} - \frac{1}{j\omega \left[\frac{R_4}{R_1 R_4} + \frac{R_1 R_4}{R_1 R_4} \right]}}{1 + \frac{(R_4 + R_5)}{R_4 R_5} \left(\frac{j\omega}{A_o f_b} \right)}$$

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

check $\Delta_o \rightarrow \alpha$

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

Further

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

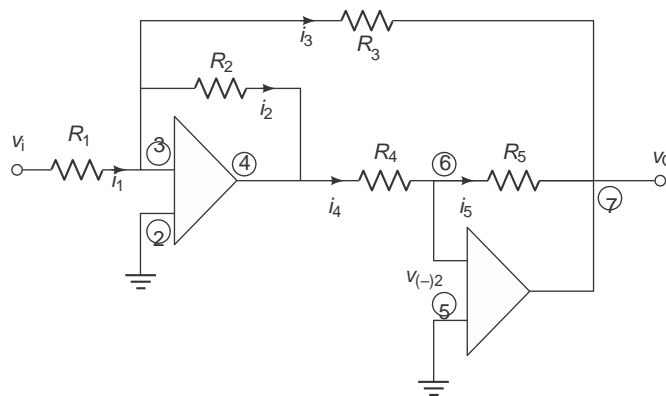
$$f_{c2} = A_o f_b \frac{R_4}{R_4 + R_5} = \frac{10^6 \times 50}{50 + 500} = \frac{10^6 \times 50}{550}$$

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

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

$$= 95.49 \text{ kHz}$$

2.46



(a) $i_1 = \frac{v_i - v_1}{R_1}$, $i_2 = \frac{v_1 - v_2}{R_2}$, $i_3 = \frac{v_1 - v_2}{R_3}$

$$i_1 = i_2 + i_3$$

Substituting for i_1 , i_2 , and i_3

$$\frac{V_i}{R_1} - \frac{V_{(-1)}}{R_1} = \frac{V_{(-1)}}{R_2} - \frac{V_{o1}}{R_2} + \frac{V_{(-1)}}{R_3} - \frac{V_O}{R_3}$$

$$v_i = \frac{v_{(-)1}}{R_1} + \frac{v_{(-)1}}{R_2} + \frac{v_{(-)1}}{R_3} - \frac{v_1}{R_2} - \frac{v_0}{R_3} \quad (i)$$

Also $i_4 = i_5$

$$\frac{v_{o1} - v_{(-)2}}{R_4} = \frac{v_{(-)2} - v_0}{R_5}$$

$$\frac{v_{o1}}{R_4} - \frac{v_{(-)2}}{R_4} = \frac{v_{(-)2}}{R_5} - \frac{v_0}{R_5} \quad (ii)$$

Further $(0 - v_{(-)1})A_o = v_{o1}$, $(0 - v_{(-)2})A_o = v_0$

or

$$-v_{(-)1} = \frac{v_{o1}}{A_o}, \quad -v_{(-)2} = \frac{v_0}{A_o}$$

or

$$v_{(-)1} = -\frac{v_1}{A_o}, \quad v_{(-)2} = -\frac{v_0}{A_o}$$

$$v_i = v_{(-)1} \left(\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} \right) - \frac{v_{o1}}{R_1} - \frac{v_0}{R_3}$$

$$= -\frac{v_1}{A_o} \left(\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} \right) - \frac{v_{o1}}{R_1} - \frac{v_0}{R_3}$$

$$= -v_{o1} \left[\frac{1}{R_1} \left(\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} \right) + \frac{1}{R_1} \right] - \frac{v_0}{R_3} \quad (iii)$$

From (ii)

$$\frac{v_{o1}}{R_4} = v_{(-)2} \left(\frac{1}{R_4} + \frac{1}{R_5} \right) - \frac{v_0}{R_5}$$

$$= -\frac{v_0}{A_o} \left(\frac{1}{R_4} + \frac{1}{R_5} \right) - \frac{v_0}{R_5}$$

$$v_{o1} = -\frac{R_4}{A_o} v_0 \left(\frac{1}{R_4} + \frac{1}{R_5} \right) - \frac{R_4}{A_o} v_0$$

Substituting in (iii) we have

$(R_4$

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

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

$$\begin{aligned} \frac{v_i}{R_1} &= \frac{R_4}{R_5} v_O \cdot \frac{1}{R_2} - \frac{v_O}{R_3} = \left[\frac{R_4}{R_2 R_5} - \frac{1}{R_3} \right] v_O \\ &= \frac{R_3 R_4 - R_2 R_5}{R_2 R_3 R_5} v_O \end{aligned}$$

Substituting the values

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

$$= -9.23$$

(b) Problem 2.46

```

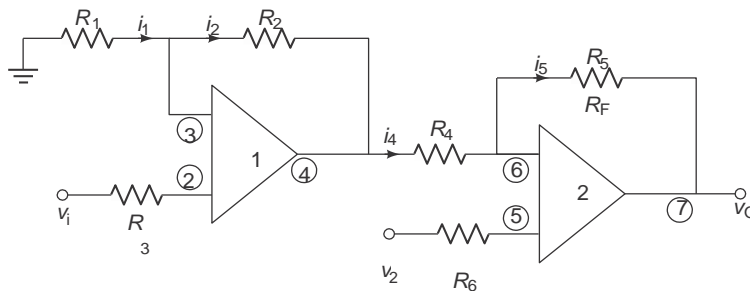
VS      1      0      AC      0.1V
R1      1      3      20K
R2      3      4      100K
R3      3      7      150K
R4      4      6      20K
R5      6      7      160K
RX1     2      0      10K
RX2     5      0      10K
XA1     2      3      4      0      UA741-AC
XA2     5      6      7      0      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)



$$i_1 = i_2, \quad i_1 = \frac{0 - v_i}{R_1}, \quad i_2 = \frac{v_i - v_o}{R_2}$$

$$-\frac{v_i}{R_1} = \frac{v_i}{R_2} - \frac{v_o}{R_2}, \quad -\frac{v_i}{R_1} - \frac{v_i}{R_2} = -\frac{v_o}{R_2}$$

R_1 R_2 R_2 R_1 R_2 R_2

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

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

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

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

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

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

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

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

$$\text{And } (v_2 - v_{(-)2}) A_o = v_o \quad (iv)$$

From (iii)

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

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

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

$$v_{o1} = v_1 \frac{A_o}{1 + \frac{A_o R_1}{R_1 + R_2}}$$

From (ii)

$$v_{(-)2} \frac{R_4 + R_5}{R_4 R_5} = v_1 \frac{A_o}{R_4} \times \frac{1}{1 + \frac{v_o}{v_1}}$$

$$\begin{aligned}
v_{(-)2} &= \frac{R_4 R_5}{R_4 + R_5} \cdot \frac{1 + A_o R_1 (R_1 + R_2)}{1 + A_o R_1 / (R_1 + R_2)} \times \frac{R_4}{R_4 + R_5} \cdot \frac{v_O}{R_5} \\
&= \frac{e R_5}{R_4 + R_5} \cdot \frac{e v_O}{1 + A_o R_1 / (R_1 + R_2)} v_1 + \frac{e R_4}{R_4 + R_5} v_O
\end{aligned}$$

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

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

$$v_o \left(\frac{1}{A_o} + \frac{R}{R_4 + R_5} \right) = v_2 - \frac{R_5}{R_4 + R_5} \cdot \frac{A}{1 + A_o R_1 (R_1 + R_2)} v_1$$

$$v_o = \frac{v_2}{\frac{1}{A_o} + \frac{R}{R_4 + R_5}} - \frac{v_1 \times 1}{\frac{1}{A_o} + \frac{R}{R_4 + R_5}} \cdot \frac{R_5 (R_4 + R_5)}{\frac{1}{A_o} + \frac{R}{R_4 + R_5}}$$

For large A_o

$$v_o = \frac{v_2}{\frac{R}{R_4} + \frac{R}{R_5}} - \frac{v_1}{\frac{R}{R_1} + \frac{R}{R_2}} \cdot \frac{R_5}{R_4}$$

Given $R_1 = R_5 = 10 \text{ k}\Omega$ and $R_2 = R_4 = 500 \text{ k}\Omega$; then

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

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

$$= a_1 v_1 - b_1 v_2$$

where

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

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

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

$$\therefore v_o = (-1.02) v_1 - (-1.02) v_2$$

Note b_1 is same as a_2 .

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

2.48

Same as Problem 2.47.

2.49

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

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

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

For $R_A = 20 \text{ k}\Omega$, $R_F = MR_A = 15 \times 20 \text{ k} = 300 \text{ k}\Omega$.

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

$$R = \frac{1300}{7}$$

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

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

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

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

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)

$$\begin{aligned} R_B &= (R_1 \parallel R_2 \parallel R_3 \parallel R_y) = R_1 \parallel R_2 \parallel R_3 \\ &= \left(\frac{340}{8} \parallel 170 \parallel \frac{340}{6} \right) \text{ k}\Omega = 21.25 \text{ k}\Omega \end{aligned}$$

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

2.51

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

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

$$v_o = A_1v_a + A_2v_b + A_3v_c - B_1v_1 - B_2v_2 - B_3v_3$$

where

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

$$B = B_1 + B_2 + B_3 = 2 + 1 + 6 = 9$$

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

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

$$x \quad y \quad C \quad 5$$

For $R_A = 20K$

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

$$R_F = MR_A = 15 \times 20 K\Omega = 300 K\Omega$$

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

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

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

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

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

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

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

$$R_x = \infty$$

Check:

From Eq. (2.116)

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

From Eq. (2.117)

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

From Eq. (2.118)

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

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

2.52

Given

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

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

$$v_o = A_1v_a + A_2v_b + A_3v_c - B_1v_1 - B_2v_2 - B_3v_3$$

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

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

$$R_F = 9 \times 20 \text{ K}\Omega = 180 \text{ K}\Omega$$

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

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

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

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

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

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

From Eq. (2.116)

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

From Eq. (2.117)

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

From Eq. (2.118)

$$R_B \parallel R_F = 11.25 K\Omega \parallel 80 K\Omega = 10.58 K\Omega$$

Therefore,

$$R_A = (R_B \parallel R_F) \text{ is satisfied}$$

2.53

$$\text{Closed loop gain } A_f = \frac{R_F}{R_1} = \frac{1 \times 10^6}{1 \times 10^4} = 100$$

From Eq. (2.120)

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

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

$$\text{Maximum input signal} = \pm 130 mV$$

2.54

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

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

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

$$\text{Limiting Op-amp current} = \pm 18 mA$$

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

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

2.55

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

(a) From Eq. (2.126)

$$SR = 6.286 v_s f$$

$$f = \frac{SR}{6.286 v_s} = \frac{10}{1 \times 10^{-6} \times 6.286 \times 10 \times 10^{-3}} = 1.59 \times 10^8 \text{ Hz}$$

(b) From Eq. (2.128)

$$f_{s(\max)} = \frac{SR}{2 \pi \times V_m} = \frac{10}{10^{-6} \times 2 \pi \times 10} = 159.2 \text{ KHz}$$

2.56

From Eq. (2.123)

$$t_r = 0.3 \mu s$$

$$t_r = 2.2 \tau$$

$$\tau = \frac{t_r}{2.2} = 136.36 \times 10^{-9} \text{ s}$$

From Eq. (2.125)

$$f_{\max} = \frac{1}{2 \pi \tau} = \frac{1}{2 \pi \times 136.36 \times 10^{-9}} = 1.16 \text{ MHz}$$

2.57

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

(a) From Eq. (2.128)

$$\tau = \frac{V_s}{SR} = \frac{10 \times 1 \times 10^{-6}}{10} = 10^{-6} \text{ s}$$

$$f_{\max} = \frac{1}{2 \pi \tau} = \frac{1}{2 \pi \times 10^{-6}} = 1.59 \times 10^5 \text{ KHz}$$

(b)

From Eq. (2.128)

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

2.58

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

(a) From Eq. (2.127)

$$V_m = \frac{SR}{2\pi f_s} = \frac{10}{1 \times 10^{-6} \times 2\pi \times 250 \times 10^3} = 6.37V$$

(b) From Eq. (2.127)

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

2.59

(a) From Eq. (2.130)

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

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

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

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

(b)

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

2.60

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

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

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

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

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

$$\frac{t}{CR} \approx 2 \times 10^3$$

$$t = 2 \times 10^3 \times 0.1 \times 10^{-6} \times 10 \times 10^3 = 2 \text{ s}$$

2.61

(a) If I_B is the biasing current

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

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

$$R_x I_{io} = \frac{R_1 I_1}{1 + \dots}$$

$$\frac{R_x}{I_{io}}$$

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

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

2.63

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

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

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 $v_C(t=0)$

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

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

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

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

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

2.66

From Fig.P2.66

$$i_s \approx i_f$$

$$i_f = i_1 + i_o$$

$$i_o = i_f - i_1$$

Since $v_o = i_1 R_2$

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

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

Since $v_s = i_s R_1 \approx i_f R_1$

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

$$v_o = -i_f R_F$$

$$i = \frac{v_s}{R_1} + i_f \frac{R_F}{R_1} = \frac{v_s}{R_1} + \frac{v_s}{R_1} \frac{R_F}{R_2} = \frac{v_s}{R_1} \left(1 + \frac{R_F}{R_2}\right)$$

$$i_o = \frac{v_s}{R_1} \left(1 + \frac{R_F}{R_2}\right) \quad (1)$$

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

From Eq. (1) above

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

$$R_1 \approx 20\Omega$$

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 $R_F \gg R_2$,

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

Let $R_F = 100 \text{ k}\Omega$; then $R_2 = 100 \Omega$.

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

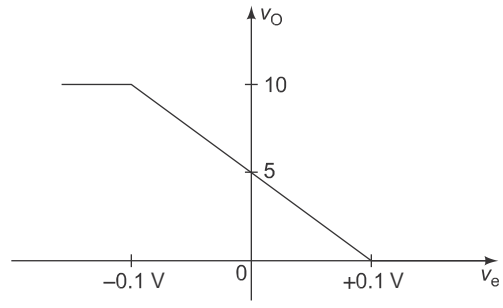
2.69

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

Assume $R_1 = R_F = 10 \text{ k}\Omega$ and $R = 15 \text{ k}\Omega$. Then

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

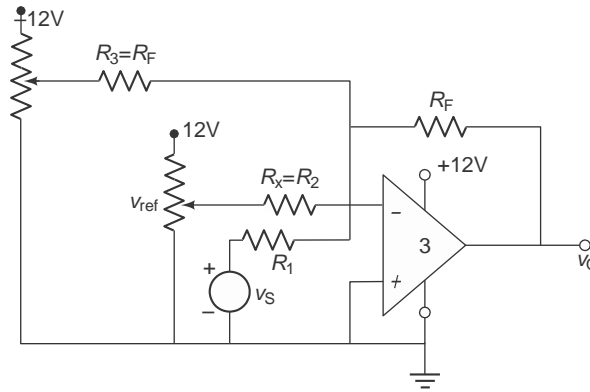
2.70



$$v_O = -50 v_e + 5$$

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

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)

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

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

$$\begin{aligned} \frac{R_F}{R_1} &= 99, R_F = 2.5 \times 99 \text{ k}\Omega \\ &= 247.5 \text{ k}\Omega \\ &= 250 \text{ k}\Omega \end{aligned}$$

Voltage swing:

We know

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

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

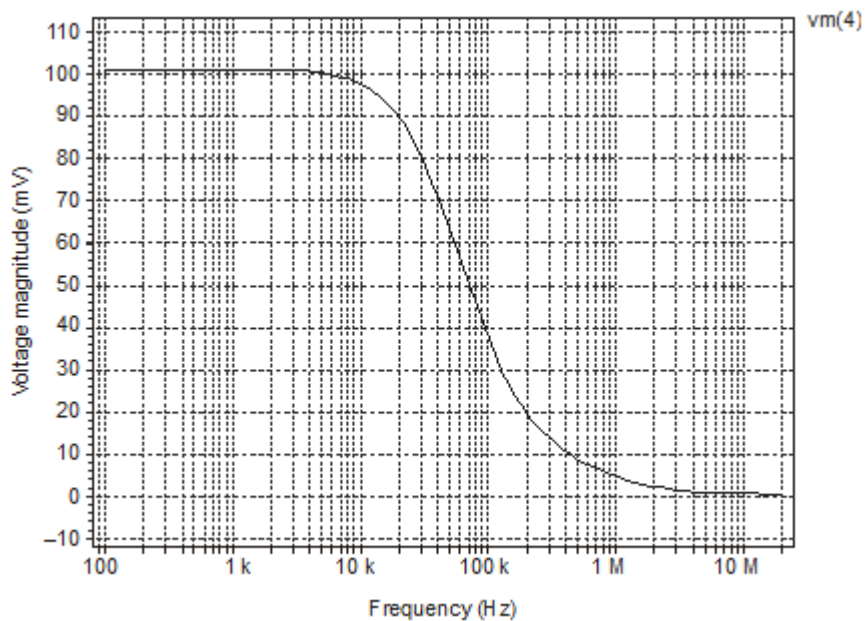
Problem 2.73

```

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

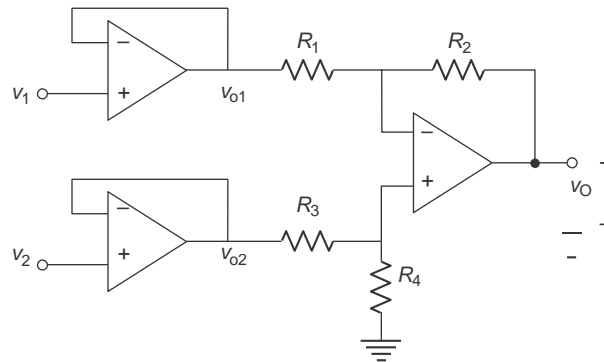
R1      5      4      10K
C1      5      4      0.79UF
EA      4      6      5      4      2E5
D1      3      7      DMOD
D2      4      7      DMOD
. MODEL  DMODD (BV = 14V)
. ENDS    LF411_AC
. AC DEC 10 100 20MEGHZ
. PRINT  AC  VM(4)
. PROBE
. END

```



2.74

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



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  (BV = 14V)
. ENDS  LF411_AC

```

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

