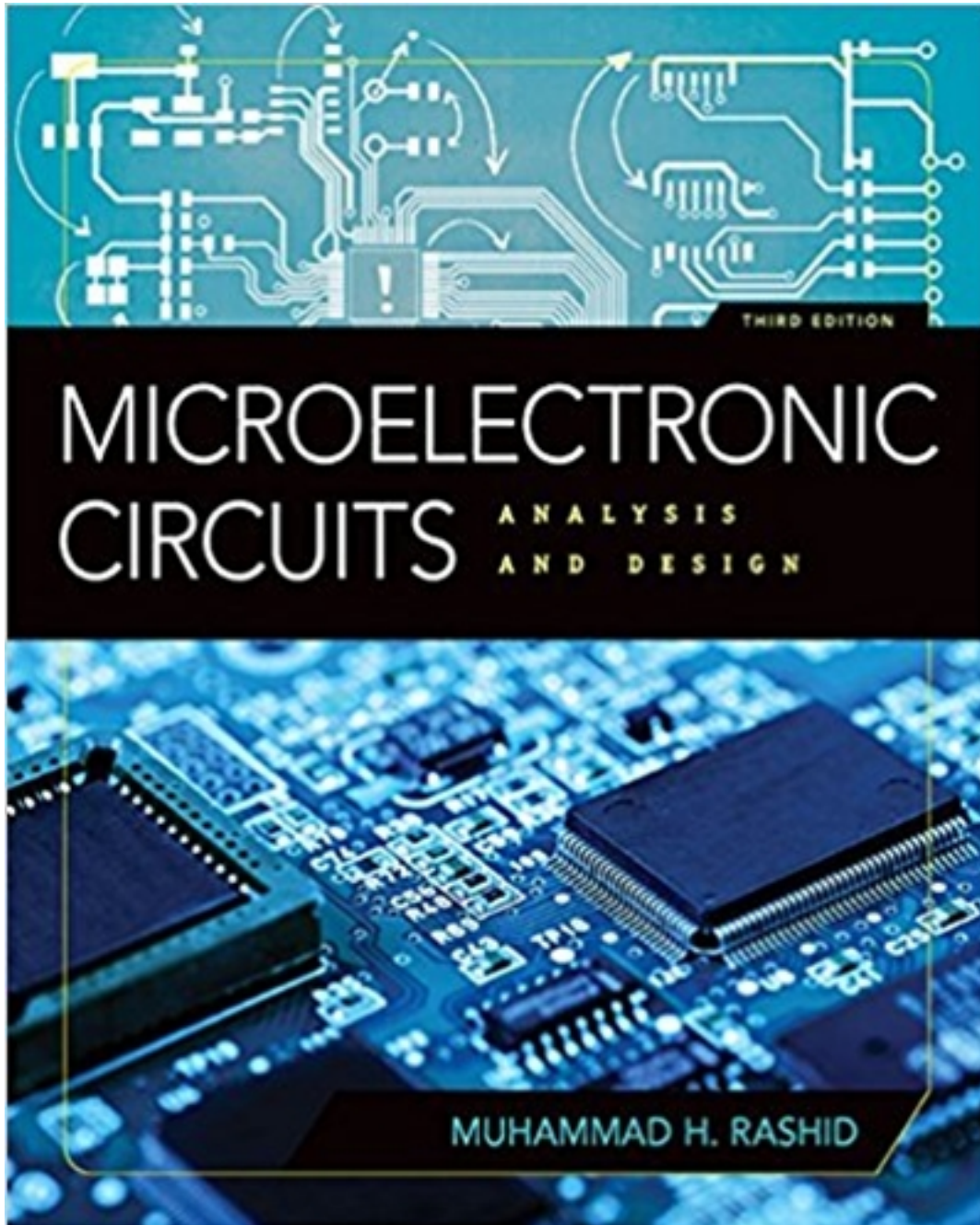


# Solutions for Microelectronic Circuits Analysis and Design 3rd Edition by Rashid

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# Solutions

## 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)  $v_c = \frac{v_1 + v_2}{2} = \frac{200}{2} = 100 \text{ } \mu\text{V}$

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

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

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

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

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

(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

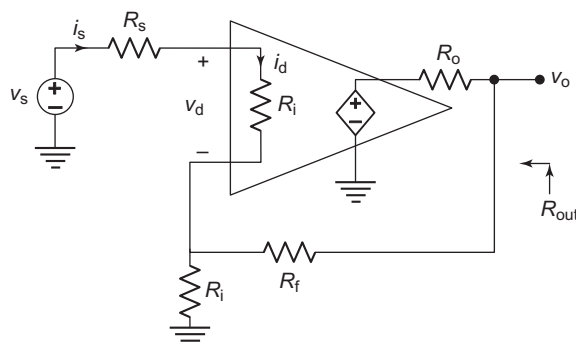
$$i_S = i_d = \frac{v_O}{A_o R_i}, R_i \gg R_s$$

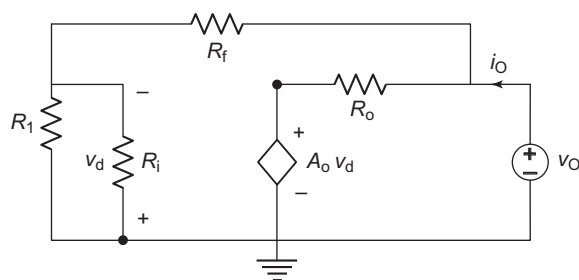
$$\text{Substituting for } v_O = \left(1 + \frac{R_f}{R_1}\right) v_S$$

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

$i_O$  from the circuit

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





$$\text{Also } -v_d = \frac{R_i}{R_i + R_f} v_O \quad \text{Assuming } R_i \gg R_f \quad (\text{iii})$$

From (ii) and (iii),

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

$$\text{Assuming } (R_i + R_f) \gg \frac{R_o}{1 + A_o R_i / (R_i + R_f)} \quad (\text{iv})$$

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

(a) From (i)

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

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

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

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

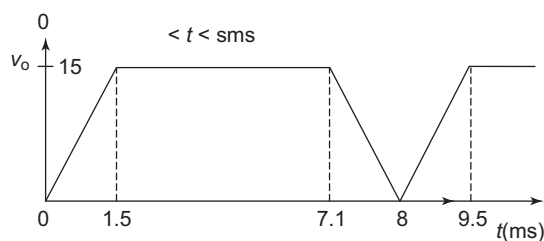
## 2.10

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  $v_O = \pm 15$  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

$$v_- = \frac{v_O R_1}{R_1 + R_F} \quad (\text{i})$$

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

$$v_- = v_S - \frac{v_O}{A_d} \quad (\text{ii})$$

From (i) and (ii)

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

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

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

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

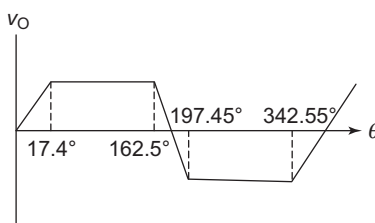
$$(c) \quad \text{For } A_o \rightarrow \infty, A_f = \left( 1 + \frac{R_F}{R_1} \right) = 1 + \frac{30 \text{ k}}{10 \text{ k}} = 4, v_O = 4 v_S \quad \text{Error insignificant}$$

## 2.13

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

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

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



## 2.14

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

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

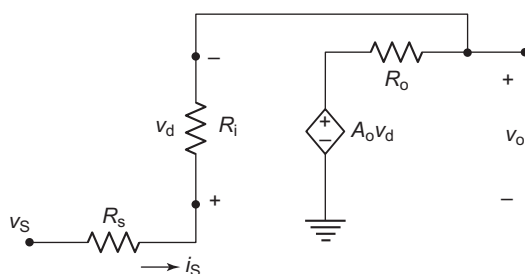
$$i_S = i_i = v_d/R_i \text{ and}$$

$$v_d = v_O/A_o$$

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

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

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



Also

$$v_d = -\frac{v_O R_i}{R_i + R_s} \quad (ii)$$

(i) and (ii) give

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

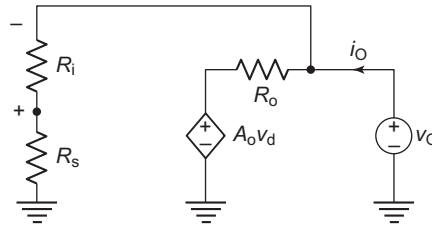
$$\frac{1}{R_{out}} = \frac{i_O}{v_O} = \frac{1 + A_o R_i/(R_i + R_s)}{R_o} + \frac{1}{R_i + R_s}$$

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

Hence

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

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



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

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

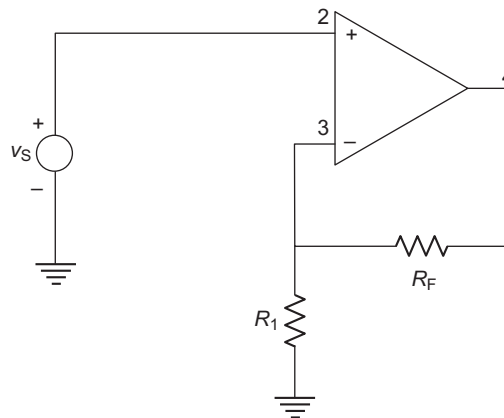
$$R_F = 50 \text{ k}\Omega, R_1 = 15 \text{ k}\Omega$$

$$\begin{aligned} \therefore A_f(j\omega) &= \frac{1 + 50 \text{ k}/15 \text{ k}}{1 + jf(1 + 50 \text{ k}/15 \text{ k})/2 \times 10^6} \\ &= \frac{4.333}{1 + j100 \times 10^3 (4.333)/2 \times 10^6} \\ &= \frac{4.333}{1 + j0.2167} = 4.235 \angle -12.23^\circ \end{aligned}$$

From Eq. (2.32)

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

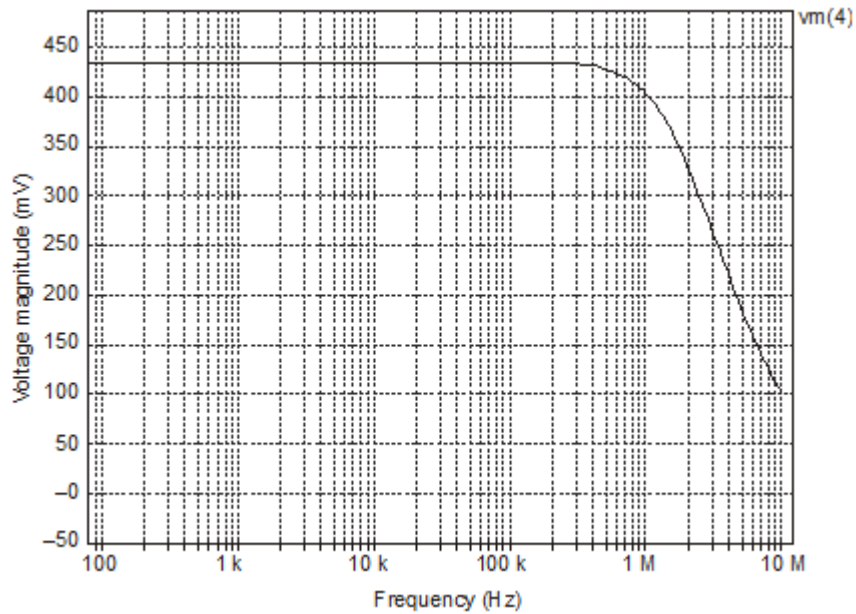
(b)



```

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)

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

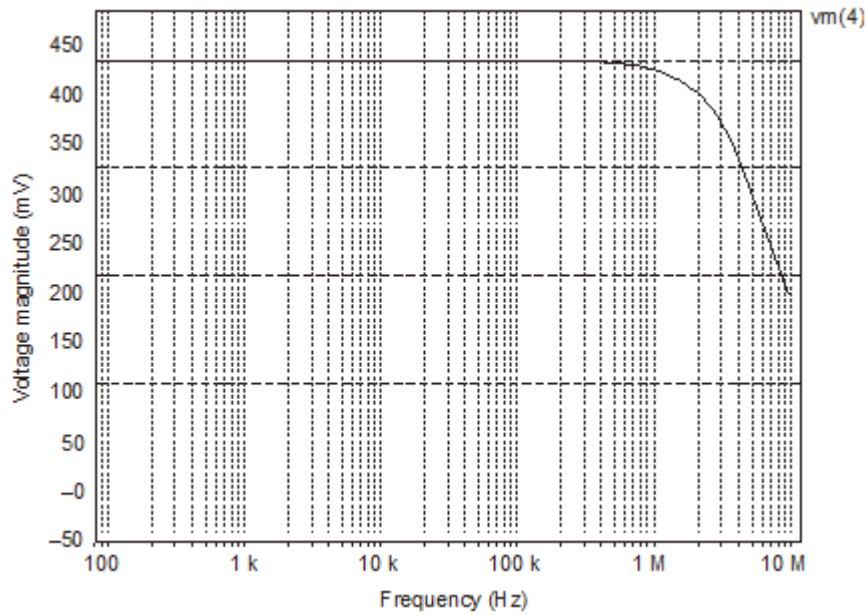
(b) From Eq. (2.32)

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

```

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)

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

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

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

### 2.18

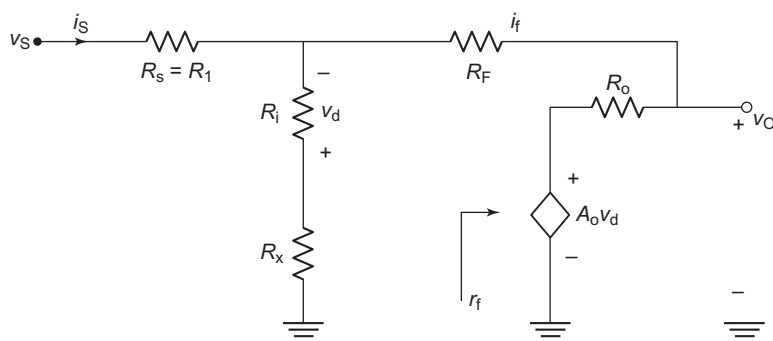
$$i_S = \frac{v_S}{R_s} = \frac{50 \text{ mV}}{5 \text{ k}\Omega} = 10 \text{ }\mu\text{A} \quad (R_1 = R_s)$$

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

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

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

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.

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

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

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

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

From Eq. (2.45)

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

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

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

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

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

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

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

(c) From Eq. (2.45)

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

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

### 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)

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

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

(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)

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

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

$$= \frac{-3.333}{1 + j0.216} = -3.258 \angle -12.19^\circ$$

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

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

(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)

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

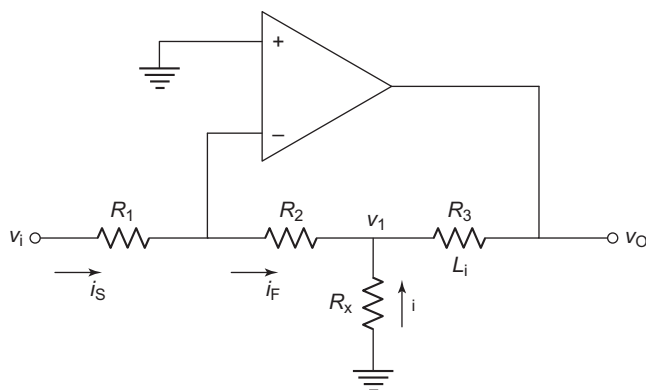
$$= -\frac{1}{1 + j0.1} = -0.99 \angle -5.71^\circ$$

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

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

## 2.24

(a)



Ignoring  $v_d$  (virtual ground)

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

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

$$i_1 = i_F + i = \frac{v_i}{R_1} + v_1 \frac{R_2}{R_1 R_x}$$

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

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

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

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

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

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

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

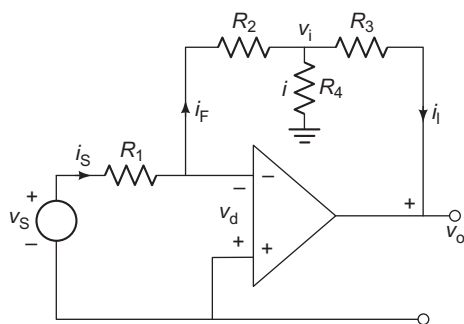
(c) VS 5 0 AC 10MV  
R1 5 3 50K  
R2 2 0 1K  
R3 3 6 20K  
RX 6 0 869.5  
R4 4 6 20K  
XA1 2 3 4 0 UA741-AC  
.SUBCKT UA741-AC1 2 3 4  
RI 1 2 2MEG  
RO 6 3 75  
GB 4 5 1 2 0.5 M  
R1 5 4 10K  
C1 5 4 1.5619UF  
EA 4 6 5 4 1E5  
D1 3 7 DMOD  
D2 4 7 DMOD  
.MODEL DMOD D (BV = 14V)  
.ENDS UA741-AC  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

## 2.25

From Eq. (2.60)

$$\begin{aligned} v_O &= - \left( \frac{R_F}{R_1} v_1 + \frac{R_F}{R_2} v_2 + \frac{R_F}{R_3} v_3 \right) \\ &= - \left( \frac{40 \text{ k}}{20 \text{ k}} \times 2 + \frac{40 \text{ k}}{20 \text{ k}} (-3) + \frac{40 \text{ k}}{20 \text{ k}} (-2) \right) \\ &= -(4 - 6 - 4) = +6 \text{ V} \end{aligned}$$

2.26



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

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

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

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

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

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

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

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

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

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

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

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

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

### 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

$$\begin{aligned} v_O &= -A_o (v_+ - v_-) \\ R_i &= 10^{12} \end{aligned} \quad (\text{i})$$

Ignoring current through  $R_i$

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

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  $R_F = R_x$

$$\begin{aligned} v_O &= -\frac{A_o v_a R_F}{R_1 + R_F} + A_o \frac{R_F v_b}{R_1 + R_F} + \frac{A_o R_1 v_O}{R_1 + R_F} \\ &= -A_o \frac{R_F}{R_1 + R_F} (v_a - v_b) + A_o \frac{R_1 v_O}{R_1 + R_F} \end{aligned} \quad (\text{ii})$$

$$\begin{aligned} \text{or} \quad v_O &= \frac{A_o R_F / (R_1 + R_F)}{1 - A_o R_1 / (R_1 + R_F)} (v_b - v_a) \\ &= \frac{A_o R_F (v_b - v_a)}{R_1 (1 - A_o) + R_F} \end{aligned}$$

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

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

### 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

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

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

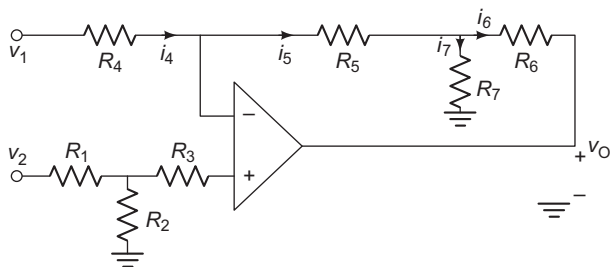
$$+ \frac{5 \times 10^5 \times 5 \times 10^3 v_O}{5 \times 10^3 + 50 \times 10^3}$$

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

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

### 2.31

(a)



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

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

$$i_4 = i_5$$

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

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

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

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

From (i)

$$\begin{aligned} \frac{v_1}{R_4} - \frac{v_-}{R_4} &= \frac{v_-}{R_5} - \frac{v_3}{R_5} \\ \frac{v_1}{R_4} - v_- \left( \frac{1}{R_4} + \frac{1}{R_5} \right) &= -\frac{v_3}{R_5} \\ \frac{v_1}{R_4} - v_- \left( \frac{R_4 + R_5}{R_4 R_5} \right) &= -\frac{v_3}{R_5} \end{aligned} \quad (\text{iii})$$

From (ii)

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

From (iii) using (iv)

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

$$\begin{aligned} \text{Let } X &= \frac{R_5 R_6 R_7}{R_5 R_6 + R_6 R_7 + R_5 R_7} \\ \frac{v_1}{R_4} - v_- \frac{R_4 + R_5}{R_4 R_5} &= -\frac{1}{R_5} X \frac{v_-}{R_5} - \frac{1}{R_5} X \frac{v_O}{R_6} \\ \therefore -v_- \frac{R_4 + R_5}{R_4 R_5} + \frac{1}{R_5} X \frac{v_-}{R_5} &= -\frac{v_1}{R_4} - \frac{1}{R_5} X \frac{v_O}{R_6} \\ -v_- \left[ \frac{R_4 + R_5}{R_4 R_5} + \frac{1}{R_5} X \frac{1}{R_5} \right] &= -\frac{v_1}{R_4} - \frac{1}{R_5} X \frac{v_O}{R_6} \\ v_- &= \frac{v_1/R_4 + \left( \frac{1}{R_5} \right) X (v_O/R_6)}{(R_4 + R_5)/R_4 R_5 - \left( \frac{1}{R_5} \right) X (1/R_5)} \end{aligned}$$

Also  $(v_+ - v_-)A_0 = v_O$ . Substituting for  $v_+$  and  $v_-$

$$\begin{aligned} \frac{R_2}{R_1 + R_2} v_2 - \frac{\frac{v_1}{R_4} + \left( \frac{1}{R_5} \right) X \left( \frac{v_O}{R_6} \right)}{\frac{(R_4 + R_5)}{R_4 R_5} - \left( \frac{1}{R_5} \right) X \left( \frac{1}{R_5} \right)} &= \frac{v_O}{A_0} \\ \frac{R_2}{R_1 + R_2} v_2 - \frac{\frac{v_1}{R_4}}{\frac{(R_4 + R_5)}{R_4 R_5} - \left( \frac{1}{R_5} \right) X \left( \frac{1}{R_5} \right)} - \frac{\left( \frac{1}{R_5} \right) X \left( \frac{v_O}{R_6} \right)}{\frac{(R_4 + R_5)}{R_4 R_5} - \left( \frac{X}{R_5} \right) \cdot \left( \frac{1}{R_5} \right)} &= \frac{v_O}{A_0} \end{aligned}$$

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

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

Assume  $A_o$  is large

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

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

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

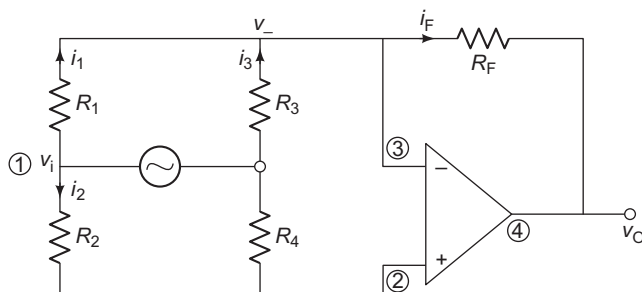
$$X = \frac{50 \text{ k} \times 50 \text{ k} \times 50 \text{ k}}{3(50 \text{ k} \times 50 \text{ k})} = \frac{50 \text{ k}}{3}$$

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

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

2.32

(a)



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

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

Also

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

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

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

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

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

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)

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

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

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

For large  $A_o$

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

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

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

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

$$= -12.5 + 13.0 = 0.5$$

Frequency response

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

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

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

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

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

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

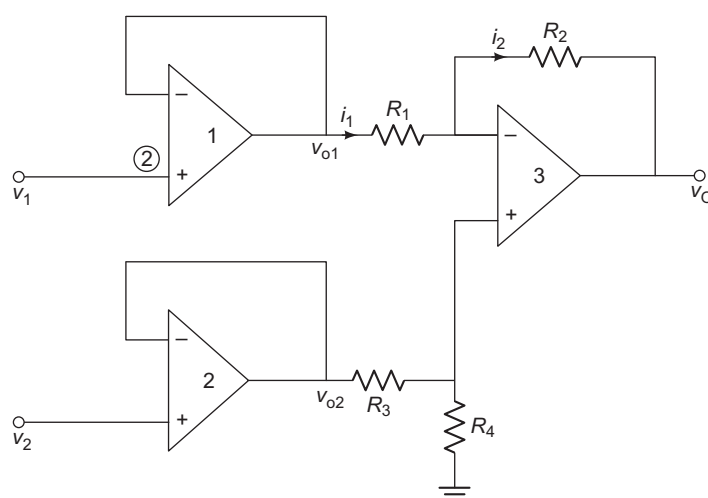
$$= -\frac{R_F/R_1 - R_4/(R_2 + R_4)(1/R_1 + 1/R_3 + 1/R_F)}{1 + jf R_F (1/R_1 + 1/R_3 + 1/R_F)/f_{bw}}$$

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

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

2.33

(a)



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

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

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

Now  $i_1 = i_2$ ; then

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

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

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

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

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

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

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

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

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

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  $R_2 = R_4 = 1 \text{ M}\Omega$ ,

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

$$= -v_1 100 + v_2 100$$

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

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

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

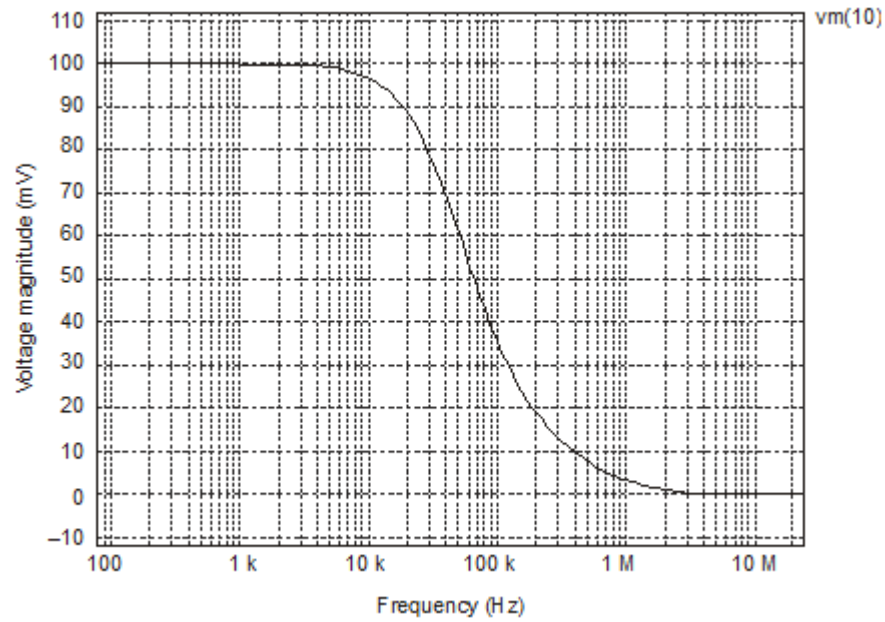
$$f_{\max} = \frac{SR}{2\pi v_o} = \frac{6 \text{ V}/\mu\text{s}}{2\pi \times 10} = 95.5 \text{ kHz}$$

(c) Problem 2.33

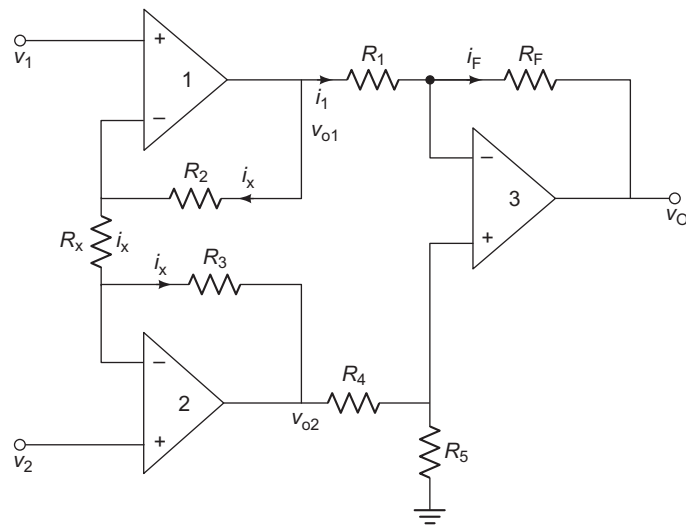
```

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  DMODD    (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

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

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

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

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

$$i_1 = i_F$$

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

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

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

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

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

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

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

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

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

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

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

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

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

### 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  $\Omega$ .

### 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
    
```

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  $3 \leq t \leq 4$

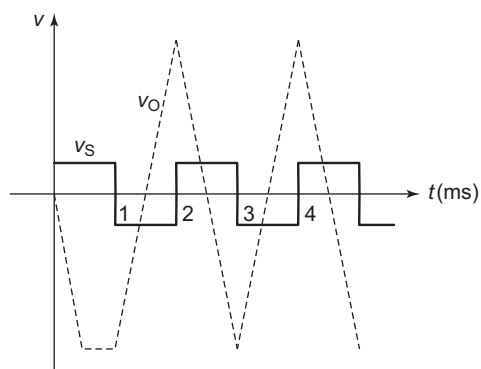
$$v_O = -14 - 10^5 \int_0^{t-3} (-1) dt = -14 + 10^5 (t-3)$$

At  $t = 4$  ms

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

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

Waveform is shown below.



**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**

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

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

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

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**

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

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

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

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

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

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

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  $R_L$ )

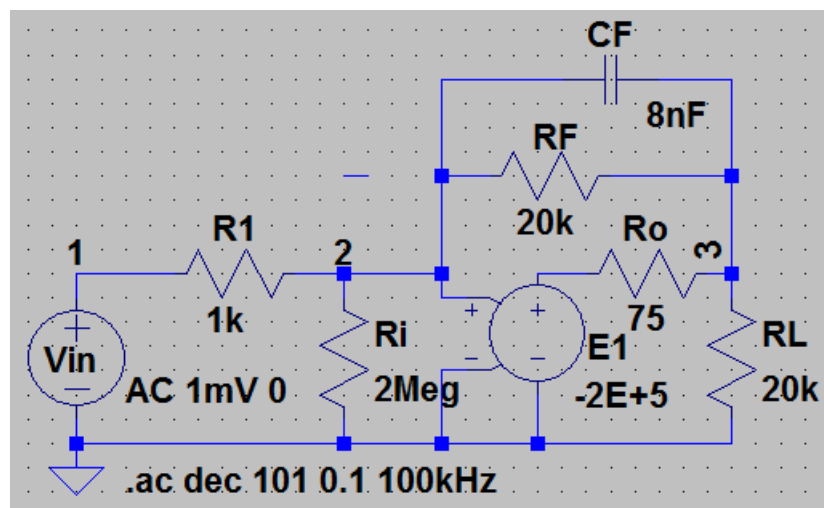
$$R_F := A_{BP} \cdot R_1 \quad R_F = 2 \times 10^4$$

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,

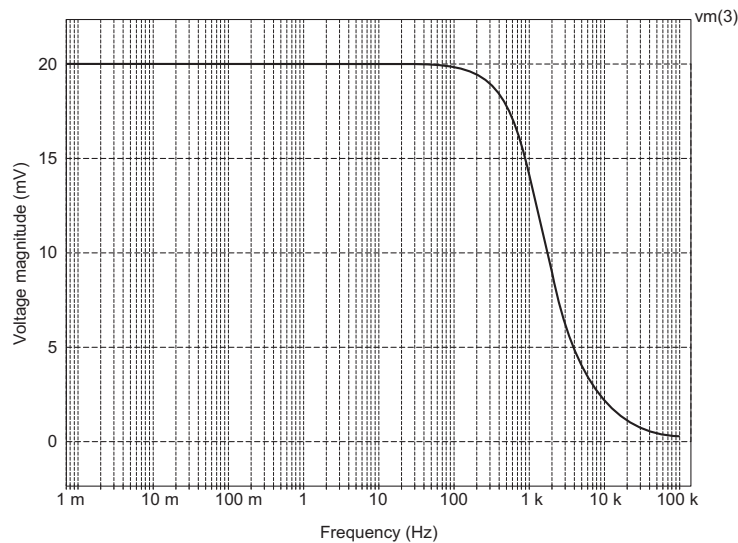


### Problem 2.41

```

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),

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

$$R_F = 3180 \Omega$$

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

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

## 2.44

Using Eq. (2.110)

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

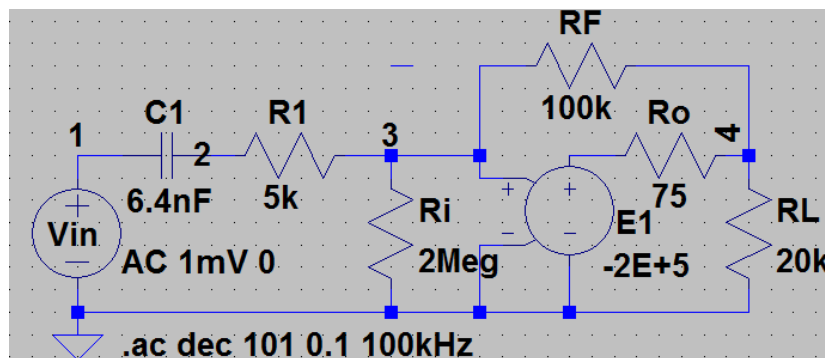
Assume  $R_1 = 5 \text{ k}\Omega$  and  $A_{PB} = 20$ .

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

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

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

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



Problem 2.44

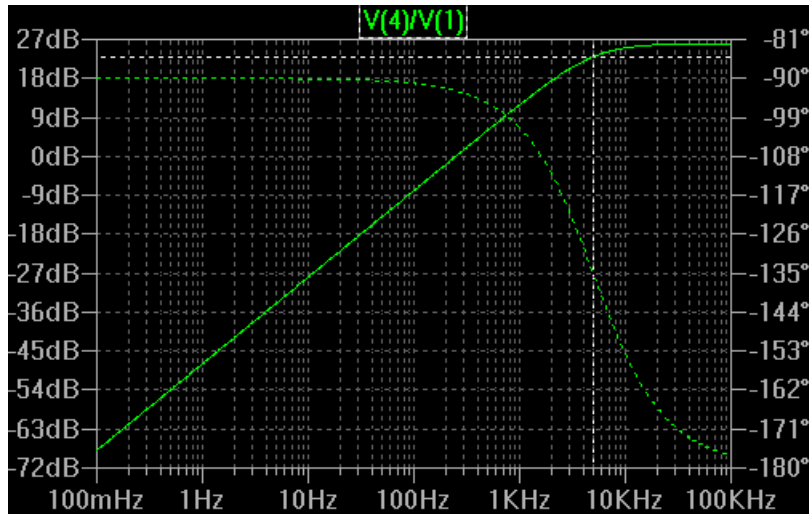
```

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

```

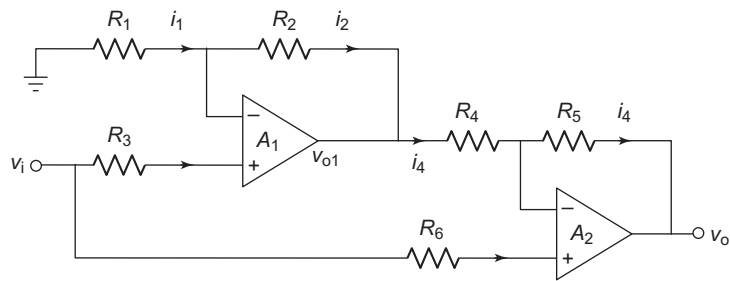
```
E1 N002 0 3 0 -2E+5
Vin 1 0 AC 1mV 0
RL 4 0 20k
Ro 4 N002 75
.ac dec 101 0.1 100kHz
.PROBE
.END
```

Plot



2.45

(a)



Assume  $i_i = 0$

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

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

From (i)

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

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

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

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

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

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

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

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

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

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

Now  $v_{+2} = v_i$

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

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

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

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

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

$$\begin{aligned}\frac{v_{o1}}{R_4} + \frac{v_O}{R_5} &= \left( v_i - \frac{v_O}{A_o} \right) \frac{(R_4 + R_5)}{R_4 R_5} \\ \frac{A_o}{1 + A_o R_1 / (R_1 + R_2)} \cdot \frac{v_i}{R_4} + \frac{v_O}{R_5} &= v_i \frac{R_4 + R_5}{R_4 R_5} - v_O \frac{R_4 + R_5}{R_4 R_5} \\ \frac{v_O}{R_5} + \frac{v_O}{A_o} \frac{(R_4 + R_5)}{R_4 R_5} &= v_i \frac{R_4 + R_5}{R_4 R_5} - \frac{A_o}{1 + A_o R_1 / (R_1 + R_2)} \cdot \frac{v_i}{R_4} \\ v_O \left[ \frac{1}{R_5} + \frac{R_4 + R_5}{A_o R_4 R_5} \right] &= v_i \left[ \frac{R_4 + R_5}{R_4 R_5} - \frac{A_o}{(1 + R_1 A_o / (R_1 + R_2)) R_4} \right] \\ \frac{v_O}{v_i} &= \frac{(R_4 + R_5) / R_4 R_5 - \frac{A_o}{[1 + R_1 / (R_1 + R_2) A_o] R_4}}{1 / R_5 + (R_4 + R_5) / A_o R_4 R_5}\end{aligned}$$

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

$$\begin{aligned}\frac{v_o}{v_i} &= \frac{(R_4 + R_5) / R_4 R_5 - \frac{A_o}{(1 + jf/f_b) [1 + (R_1 / (R_1 + R_2)) \cdot (A_o / (1 + jf/f_b))] R_4}}{1 / R_5 + (R_4 + R_5 / R_4 R_5) \cdot [(1 + jf/f_b) / A_o]} \\ &= \frac{\frac{(R_4 + R_5)}{R_4 R_5} - \frac{A_o}{\left[ (1 + jf/f_b) R_4 + \frac{R_1}{(R_1 + R_2)} R_4 A_o \right]}}{\frac{1}{R_5} + \frac{(R_4 + R_5)}{R_4 R_5 A_o} + \left[ \frac{(R_4 + R_5)}{R_4 R_5 A_o} \right] \cdot \left( \frac{jf}{f_b} \right)} \\ &= \frac{\frac{(R_4 + R_5)}{R_4 R_5} - \frac{A_o}{\left[ R_4 + \frac{jf}{f_b} R_4 + \frac{R_1 R_4 A_o}{(R_1 + R_2)} \right]}}{\frac{1}{R_5} + \frac{(R_4 + R_5)}{R_4 R_5 A_o} + \left[ \frac{(R_4 + R_5)}{R_4 R_5 A_o} \right] \cdot \frac{jf}{f_b}} \\ &= \frac{\frac{(R_4 + R_5)}{R_4 R_5} - \frac{1}{\left[ jf \frac{R_4}{f_b A_o} + \frac{R_1 R_4}{(R_1 + R_2)} \right]}}{\frac{1}{R_5} + \frac{(R_4 + R_5)}{R_4 R_5} \cdot \left( \frac{jf}{A_o f_b} \right)} \\ &= \frac{\frac{(R_4 + R_5)}{R_4 R_5} - \frac{1}{\left[ jf \frac{R_4}{A_o f_b} + \frac{R_1 R_4}{(R_1 + R_2)} \right]}}{1 + \frac{(R_4 + R_5)}{R_4 R_5} \cdot \left( \frac{jf}{A_o f_b} \right)}\end{aligned}$$

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

check  $\Delta_o \rightarrow \alpha$

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

Further

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

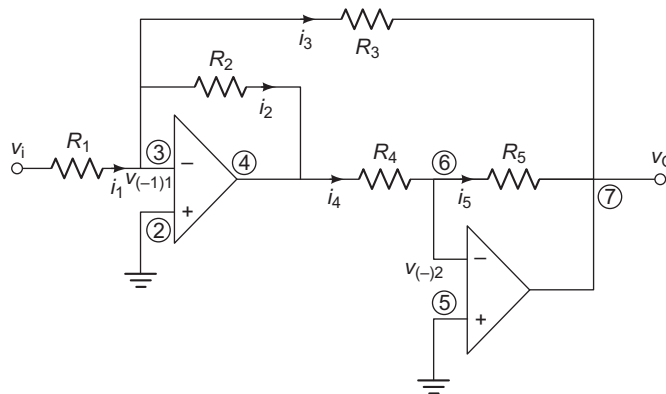
$$f_{c2} = A_o f_b \frac{R_4}{R_4 + R_5} = \frac{10^6 \times 50}{50 + 500} = \frac{10^6 \times 50}{550}$$

(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)  $i_1 = \frac{v_i - v_{(-)1}}{R_1}$ ,  $i_2 = \frac{v_{(-)1} - v_{o1}}{R_2}$ ,  $i_3 = \frac{v_{(-)1} - v_o}{R_3}$

$$i_1 = i_2 + i_3$$

Substituting for  $i_1$ ,  $i_2$ , and  $i_3$

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

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

Also  $i_4 = i_5$

$$\begin{aligned} \frac{v_{o1} - v_{(-)2}}{R_4} &= \frac{v_{(-)2} - v_O}{R_5} \\ \frac{v_{o1}}{R_4} - \frac{v_{(-)2}}{R_4} &= \frac{v_{(-)2}}{R_5} - \frac{v_O}{R_5} \end{aligned} \quad (\text{ii})$$

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

or

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

or

$$\begin{aligned} v_{(-)1} &= -\frac{v_{o1}}{A_o}, \quad v_{(-)2} = -\frac{v_O}{A_o} \\ \frac{v_i}{R_1} &= v_{(-)1} \left( \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} \right) - \frac{v_{o1}}{R_1} - \frac{v_O}{R_3} \\ &= -\frac{v_{o1}}{A_o} \left( \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} \right) - \frac{v_{o1}}{R_1} - \frac{v_O}{R_3} \\ &= -v_{o1} \left[ \frac{1}{A_o} \left( \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} \right) + \frac{1}{R_1} \right] - \frac{v_O}{R_3} \end{aligned} \quad (\text{iii})$$

From (ii)

$$\begin{aligned} \frac{v_{o1}}{R_4} &= v_{(-)2} \left( \frac{1}{R_4} + \frac{1}{R_5} \right) - \frac{v_O}{R_5} \\ &= -\frac{v_O}{A_o} \left( \frac{1}{R_4} + \frac{1}{R_5} \right) - \frac{v_O}{R_5} \\ v_{o1} &= -\frac{R_4}{A_o} v_O \left( \frac{1}{R_4} + \frac{1}{R_5} \right) - \frac{R_4}{R_5} v_O \end{aligned}$$

Substituting in (iii) we have

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

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

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

$$= -9.23$$

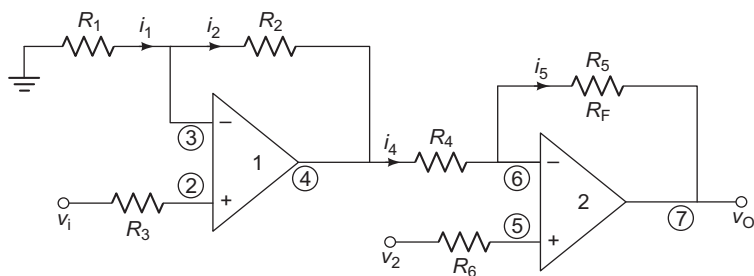
**(b) Problem 2.46**

```

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)**



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

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

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

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

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

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

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

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

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

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

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

From (iii)

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

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

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

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

From (ii)

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

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

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

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

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

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

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

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

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

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

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

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

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**

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

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

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

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

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

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

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

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

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

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)

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

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

## 2.51

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

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

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

where

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

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

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

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

For  $R_A = 20 \text{ k}$

$R_F = MR_A$ , 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)

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

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

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

$$R_F = 9 \times 20 K\Omega = 180 K\Omega$$

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

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

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

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

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

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

From Eq. (2.116)

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

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)

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

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

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

### 2.54

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

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

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

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

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

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

**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**

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

(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)

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

(b) From Eq. (2.127)

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

## 2.59

(a) From Eq. (2.130)

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

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

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

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

(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

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

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

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

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

## 2.61

(a) If  $I_B$  is the biasing current

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

(b) Offset minimizing resistance

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

## 2.62

Using Eq. (2.138)

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

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

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

### 2.63

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

(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  $v_C(t=0)$

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

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

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

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

(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  $v_o = i_1 R_2$

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

Since  $v_s = i_s R_1 \approx i_f R_1$

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

$$v_o = -i_f R_F$$

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

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

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

From Eq. (1) above

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

$$R_1 \approx 20\text{ }\Omega$$

**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  $R_2 = 100\text{ }\Omega$ .

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

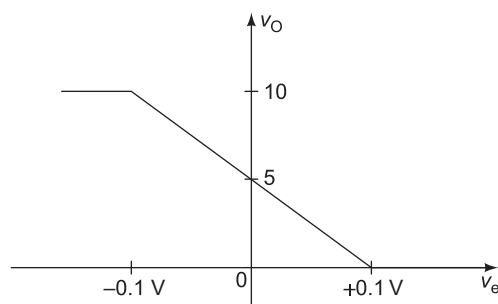
**2.69**

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

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

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

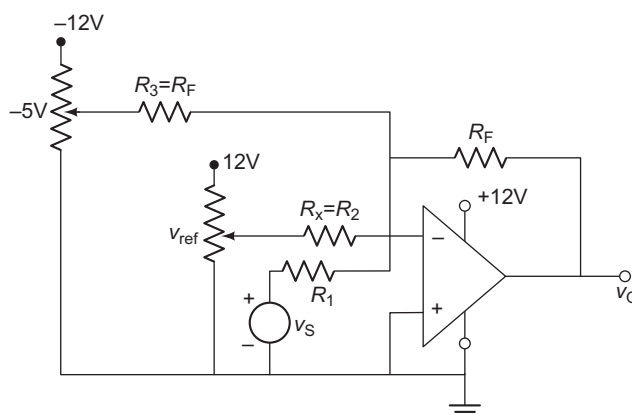
**2.70**



$$v_O = -50 v_e + 5$$

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

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)

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

From Eq. (2.32)

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

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

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

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

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

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

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

Voltage swing:

We know

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

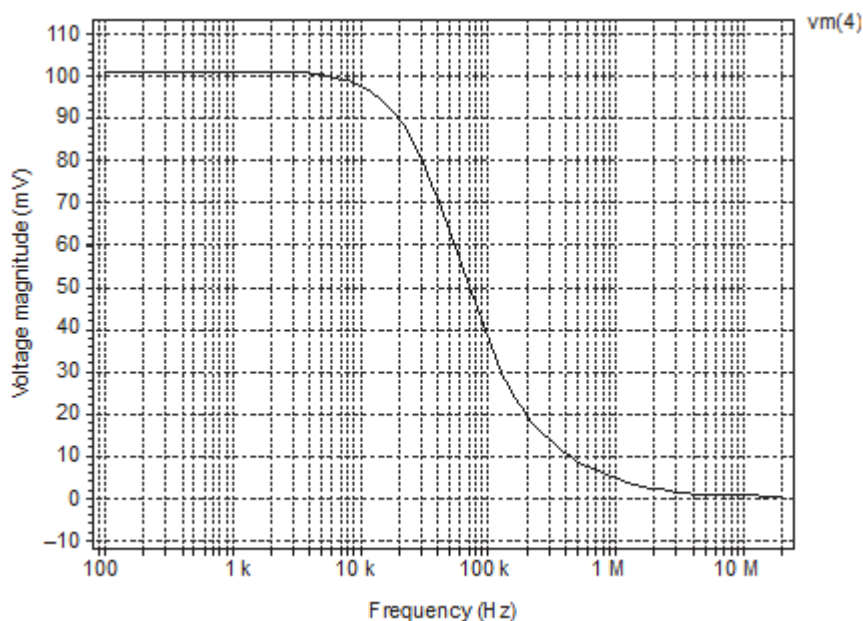
$$SR = 25 \times 10^3 \times 2\pi \times 11 = 1.73 \text{ V}/\mu\text{s}$$

Problem 2.73

```

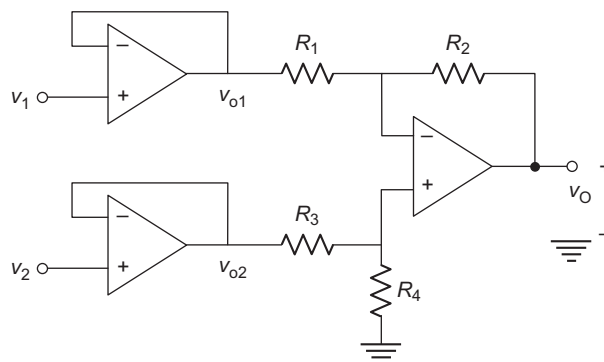
VS      1      0      AC      1MV
RX      1      2      10K
R2      3      0      2.5K
R3      3      4      250K
XA1     2      3      40      LF411_AC
. SUBCKT LF411_AC 1      2      3      4
RI      1      2      2E12
RO      6      3      50
GB      4      5      1      2      0.1M

R1      5      4      10K
C1      5      4      0.79UF
EA      4      6      5      4      2E5
D1      3      7      DMOD
D2      4      7      DMOD
. MODEL  DMOD D (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 $\Omega$ .



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
```

