EEC 233 : Electronics II [1]
Part 2

1 General Consideration of Negative Feedback Amplifiers

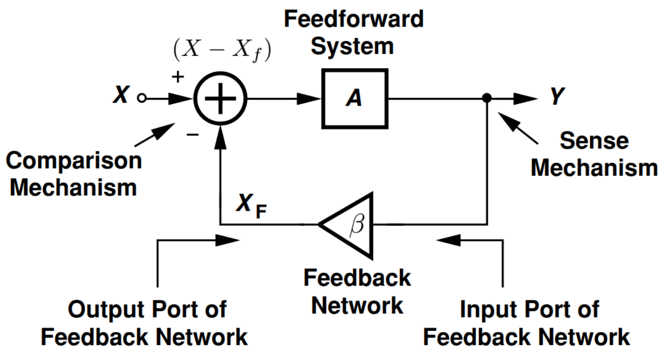

Figure 1

$$A_f = \frac{Y}{X} = \frac{A}{1+\beta A} \tag{1}$$

A_f : Closed loop gain.
A : Open loop gain.
β : Feedback factor.
βA : Loop gain.

2 Characteristics of Feedback Amplifier

2.1 Gain Desensitivity

(A) Special case : if $A\beta >> 1$

$$A_f = \frac{A}{1+\beta A} \approx \frac{1}{\beta} \tag{2}$$

A_f in this case doesn't depend on A
(B) General case:

$$\begin{aligned} A_f &= \frac{1}{1+\beta A} \\ \frac{\mathrm{d}A_f}{\mathrm{d}A} &= \frac{1}{(1+\beta A)^2} < 1 \\ \frac{\mathrm{d}A_f}{A_f} &= \frac{1}{1+\beta A}\frac{\mathrm{d}A}{A} \\ \therefore \frac{\mathrm{d}A_f}{A_f} &< \frac{\mathrm{d}A}{A} \end{aligned} \tag{3}$$

2.2 Bandwidth Extension

$$\text{Closed Loop Gain} = \frac{A_0}{1+\beta A} \tag{4}$$

$$\text{Closed Loop Bandwidth} = (1+\beta A)\omega_0 \tag{5}$$

In other words, the gain and bandwidth are scaled by the same factor but in opposite directions, displaying a *constant* product.

	DC-gain	3 dB BW
Feedforward Amp. $A(s)$	A_0	ω_0
Feedback Amp. $A_f(s)$	$\frac{A_0}{1+\beta A}$	$(1+\beta A)\omega_0$

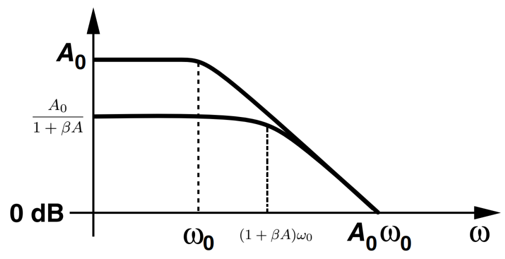

Figure 2

2.3 Linearity Improvement

A system placed in a negative feedback loop provides a more uniform gain for different signal levels.

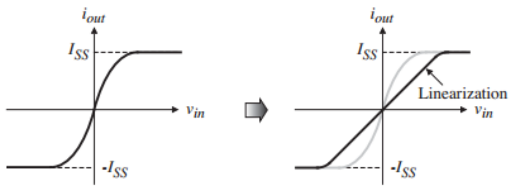

Figure 3

2.4 Effect on Noise

If noise N is added to the signal X

$$Y = \frac{A}{1+\beta A}X + \frac{A}{1+\beta A}N$$

$$\mathrm{SNR}_i = \mathrm{SNR}_o = \frac{X}{N} \tag{6}$$

Negative feedback amplifier reduces the gain inside the loop. However, it doesn't change the SNR.

3 Types of Amplifiers

Input	Output	Type	Gain
V	V	Voltage amplifier	A_v $\frac{V}{V}$
I	V	Transresistance amplifier	R_m $\frac{V}{A}$
V	I	Transconductance amplifier	G_m $\frac{A}{V}$
I	I	Current amplifier	A_i $\frac{A}{A}$

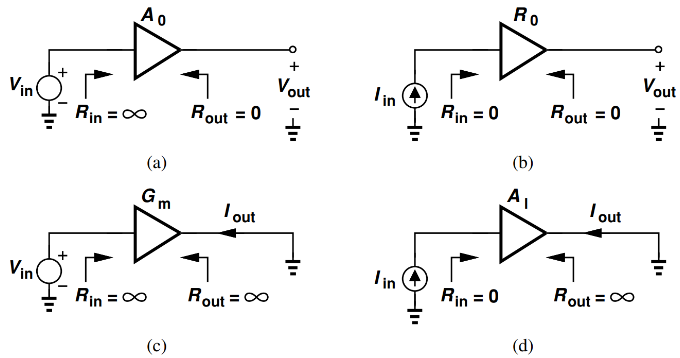

Figure 4: (a) Voltage, (b) transresistance, (c) transconductance, and (d) current amplifiers.

3.1 Voltage Amplifier

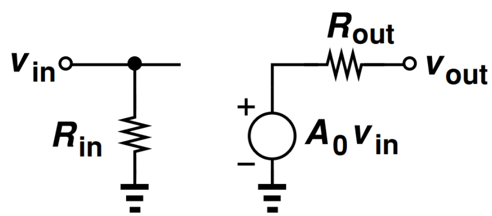

Figure 5

Voltage gain :

[1]Taha Ahmed

$$A_v = \left.\frac{V_0}{V_i}\right|_{R_L=\infty} \tag{7}$$

Input resistance:

$$R_i = \frac{V_i}{I_i} \to \infty \text{ (ideal)} \tag{8}$$

Output resistance:

$$R_o = \left.\frac{V_o}{I_o}\right|_{V_i=0} \to 0 \text{ (ideal)} \tag{9}$$

3.2 Transresistance Amplifier

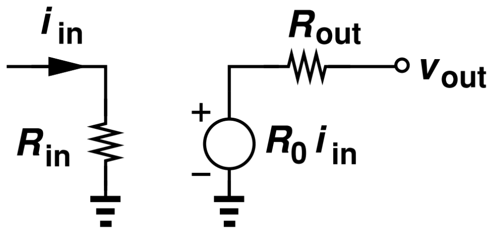

Figure 6

Voltage gain :

$$R_m = \left.\frac{V_0}{I_i}\right|_{R_L=\infty} \tag{10}$$

Input resistance:

$$R_i = \frac{V_i}{I_i} \to 0 \text{ (ideal)} \tag{11}$$

Output resistance:

$$R_o = \left.\frac{V_o}{I_o}\right|_{I_i=0} \to 0 \text{ (ideal)} \tag{12}$$

3.3 Transconductance Amplifier

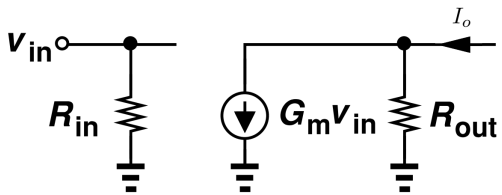

Figure 7

Voltage gain :

$$G_m = \left.\frac{I_o}{V_i}\right|_{R_l=0} \tag{13}$$

Input resistance:

$$R_i = \frac{V_i}{I_i} \to \infty \text{ (ideal)} \tag{14}$$

Output resistance:

$$R_o = \left.\frac{V_o}{I_o}\right|_{V_i=0} \to \infty \text{ (ideal)} \tag{15}$$

3.4 Current Amplifier

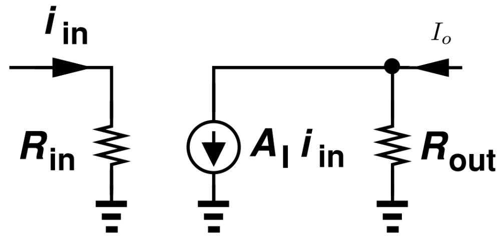

Figure 8

Voltage gain :

$$A_i = \left.\frac{I_o}{I_i}\right|_{R_l=0} \tag{16}$$

Input resistance:

$$R_i = \frac{V_i}{I_i} \to 0 \text{ (ideal)} \tag{17}$$

Output resistance:

$$R_o = \left.\frac{V_o}{I_o}\right|_{I_i=0} \to \infty \text{ (ideal)} \tag{18}$$

4 Sensing and Returning Techniques

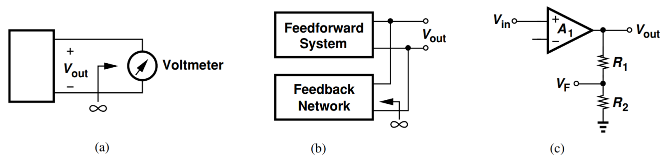

Figure 9: (a) Sensing a voltage by a voltmeter, (b) sensing the output voltage by the feedback network, (d) example of implementation.

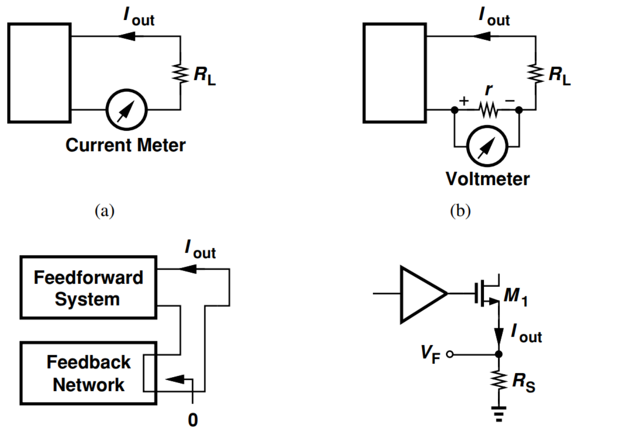

Figure 10: (a) Sensing a current by a current meter, (b) actual realization of current meter, (c) sensing the output current by the feedback network, (d) example of implementation.

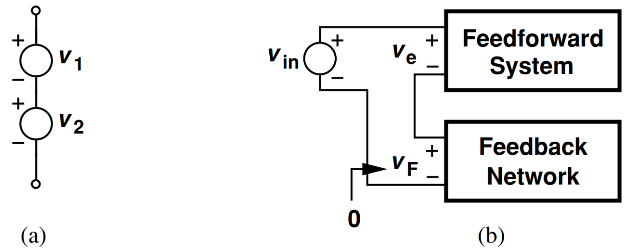

Figure 11: (a) Addition of two voltages, (b) addition of feedback and input voltages.

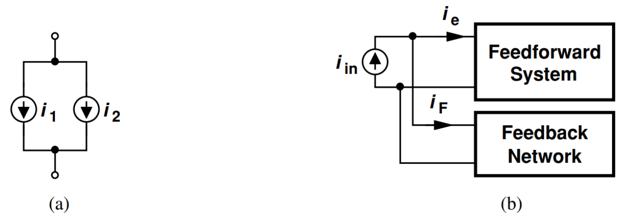

Figure 12: (a) Addition of two currents, (b) addition of feedback current and input current.

5 Feedback Topology

5.1 Voltage Voltage Feedback

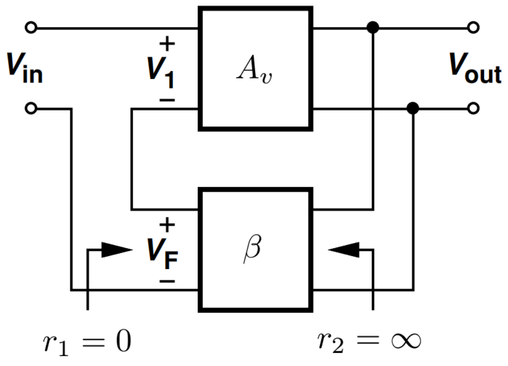

Figure 13

Closed loop gain:

$$A_{vf} = \frac{A_v}{1 + \beta A_v} \tag{19}$$

Input impedance:

$$R_{if} = R_i(1 + \beta A_v) \tag{20}$$

Input impedance is enhanced (closer to the ideal case (∞))

Output impedance:

$$R_{of} = \frac{R_o}{1 + \beta A_v} \tag{21}$$

Output impedance is enhanced (closer to the ideal case (0))

5.2 Voltage Current Feedback

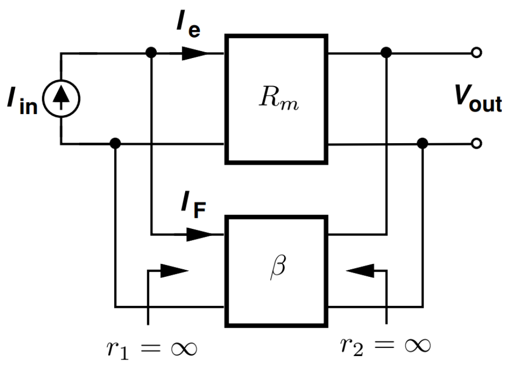

Figure 14

Closed loop gain:

$$R_{mf} = \frac{R_m}{1 + \beta R_m} \tag{22}$$

Input impedance:

$$R_{if} = \frac{R_i}{1 + \beta R_m} \tag{23}$$

Input impedance is enhanced (closer to the ideal case (0))

Output impedance:

$$R_{of} = \frac{R_o}{1 + \beta R_m} \tag{24}$$

Output impedance is enhanced (closer to the ideal case (0))

5.3 Current Voltage Feedback

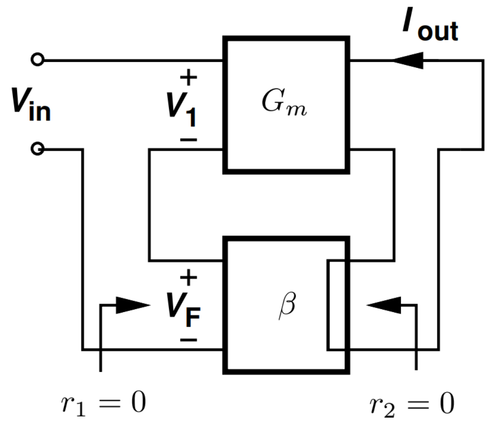

Figure 15

Closed loop gain:

$$G_{mf} = \frac{G_m}{1 + \beta G_m} \tag{25}$$

Input impedance:

$$R_{if} = R_i(1 + \beta G_m) \tag{26}$$

Input impedance is enhanced (closer to the ideal case (∞))

Output impedance:

$$R_{of} = R_o(1 + \beta G_m) \tag{27}$$

Output impedance is enhanced (closer to the ideal case (∞))

5.4 Current Current Feedback

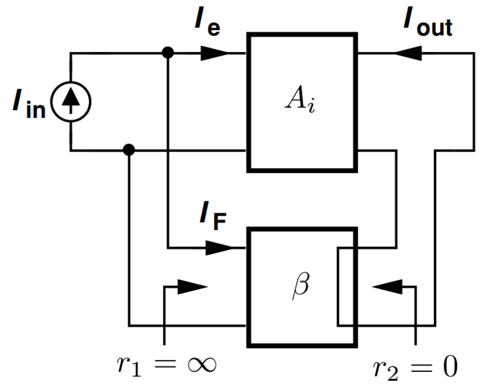

Figure 16

Closed loop gain:

$$A_{if} = \frac{A_i}{1 + \beta A_i} \tag{28}$$

Input impedance:

$$R_{if} = \frac{R_i}{1 + \beta A_i} \tag{29}$$

Input impedance is enhanced (closer to the ideal case (0))

Output impedance:

$$R_{of} = R_o(1 + \beta A_i) \tag{30}$$

Output impedance is enhanced (closer to the ideal case (∞))

6 Amplifier Frequency Response

7 Amplifier Gain

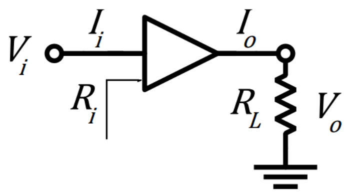

Figure 17

7.1 Gain as Ratio

Voltage Gain:

$$A_v = \frac{V_o}{V_i} \tag{31}$$

Current Gain:

$$A_i = \frac{I_o}{I_i} \tag{32}$$

Power Gain:

$$A_p = \frac{P_o}{P_i} = \frac{V_o I_o}{V_i I_i} = A_v \times A_i \tag{33}$$

If $R_i = R_L$:

$$A_p = A_v^2 = A_i^2 \tag{34}$$

7.2 Gain in Decibel

Power gain in (dB):

$$A_{p,\,\mathrm{dB}} = 10\log_{10}(A_p) \quad \text{(dB)} \tag{35}$$

Voltage gain in (dB):

$$A_{v,\,\mathrm{dB}} = 20\log_{10}(A_v) \quad \text{(dB)} \tag{36}$$

Current gain in (dB):

$$A_{i,\,\mathrm{dB}} = 20\log_{10}(A_i) \quad \text{(dB)} \tag{37}$$

In cascaded amplifiers:

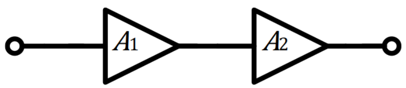

Figure 18

$$\begin{aligned} A_{\text{total}} &= A_1 \times A_2 \\ A_{\text{total, dB}} &= A_{1,\,\text{dB}} + A_{2,\,\text{dB}} \end{aligned} \tag{38}$$

- When A_p **increases** by (3dB), it means it is **multiplied** by 2
- When A_p **decreases** by (3dB), it means it is **divided** by 2

- When A_v **increases** by (3dB), it means it is **multiplied** by $\sqrt{2}$
- When A_v **decreases** by (3dB), it means it is **divided** by $\sqrt{2}$

- When A_i **increases** by (3dB), it means it is **multiplied** by $\sqrt{2}$
- When A_i **decreases** by (3dB), it means it is **divided** by $\sqrt{2}$

8 dBm Power Measurement

$$P_{\mathrm{dBm}} = 10\log_{10}\left(\frac{P(\mathrm{mW})}{1(\mathrm{mW})}\right) \quad \text{(dBm)} \tag{39}$$

$$P_{\mathrm{dB}\mu} = 10\log_{10}\left(\frac{P(\mathrm{mW})}{1(\mu\mathrm{W})}\right) \quad (\mathrm{dB}\mu) \tag{40}$$

9 Frequency Response

$$H(j\omega) = A(\omega)e^{j\phi(\omega)} \tag{41}$$

$A(\omega)$: Magnitude response.
$\phi(\omega)$: phase response.

$$Y(j\omega) = H(j\omega)X(j\omega) \tag{42}$$

$Y(j\omega)$: Output signal.
$H(j\omega)$: Frequency response.
$X(j\omega)$: Input signal.

10 Transfer Function

Notice that Fourier transform does not exist for many signals of interest.
For a wider class of signals, Laplace transform can be used by replace each $j\omega$ by $s = \sigma + j\omega$

$$H(s) = A(s)e^{\phi(s)} \tag{43}$$

$$Y(s) = H(s)X(s) \tag{44}$$

Transfer function in fraction form :

$$H(s) = K\frac{(s-s_{z_1})(s-s_{z_2})\cdots(s-s_{z_M})}{(s-s_{p_1})(s-s_{p_2})\cdots(s-s_{p_M})} = K\frac{\Pi_m(s-s_{z_m})}{\Pi_n(s-s_{p_n})} \tag{45}$$

11 Relation Between Frequency Response and Transfer Function

$$H(j\omega) = H(s)|_{s=0+j\omega} \tag{46}$$

12 Bode Plot: Real Zeros and Poles

Transfer function:

$$H(s) = K_o\frac{\left(\frac{s}{\omega_z}+1\right)}{\left(\frac{s}{\omega_p}+1\right)} \begin{cases} \text{zero} = & -\omega_z \\ \text{pole} = & -\omega_p \end{cases} \tag{47}$$

(48)

Frequency response:

$$H(j\omega) = K_o\frac{\left(\frac{j\omega}{\omega_z}+1\right)}{\left(\frac{j\omega}{\omega_p}+1\right)} \tag{49}$$

Magnitude response :

$$|H(j\omega)| = |K_o|\frac{\sqrt{1+\left(\frac{\omega}{\omega_z}\right)^2}}{\sqrt{1+\left(\frac{\omega}{\omega_p}\right)^2}} \tag{50}$$

Magnitude plot: Magnitude response in dB:

$$|H(j\omega)|_{\mathrm{dB}} = 20\log|K_0| + 20\log\sqrt{1+\left(\frac{\omega}{\omega_z}\right)^2} - 20\log|K_0|\sqrt{1+\left(\frac{\omega}{\omega_p}\right)^2} \tag{51}$$

Let $(\pm)$ sign refers to zero/pole terms. Straight line approximation is given by:

$$20\log|K_0| \begin{cases} <0 & |K_0|<1 \\ =0 & |K_0|=1 \\ >0 & |K_0|>1 \end{cases} \tag{52}$$

$$\pm 20\log\sqrt{1+\left(\frac{\omega}{\omega_c}\right)^2} = \begin{cases} 0 & \omega << \omega_c \\ \pm 3\text{ dB} & \omega = \omega_c \\ \pm 20\log\left(\frac{\omega}{\omega_c}\right) & \omega >> \omega_c \end{cases} \tag{53}$$

Phase plot: Phase response:

$$\phi(j\omega) = \tan^{-1}\left(\frac{\omega}{\omega_z}\right) - \tan^{-1}\left(\frac{\omega}{\omega_p}\right) \tag{54}$$

$$\phi(j\omega) \begin{cases} = 0^\circ & \omega < 0.1\,\omega_c \\ = \pm 5.7^\circ & \omega = 0.1\,\omega_c \\ = \pm 45^\circ & \omega = \omega_c \\ = \pm(90^\circ - 5.7^\circ) & \omega = 10\,\omega_c \\ = \pm 90^\circ & \omega > 10\,\omega_c \end{cases} \tag{55}$$

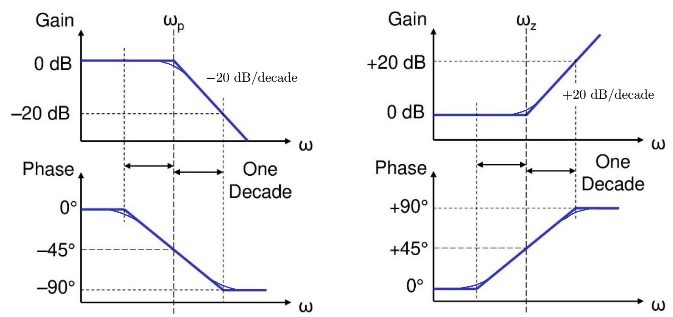

Figure 19: Magnitude plot and phase plot (assume $|K_0| = 1$)

13 Common Source (CS) Amplifier

13.1 DC Biasing

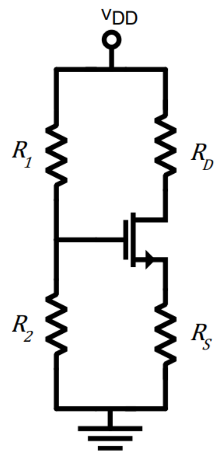

Figure 20

From circuit analysis :

$$V_{GS} = \frac{R_2}{R_1 + R_2} V_{DD} - I_D R_s \tag{56}$$

$$V_{DS} = V_{DD} - I_D(R_D + R_S) \tag{57}$$

From the MOSFET characteristics curves :

$$I_D = k(V_{GS} - V_T)^2 \tag{58}$$

By solving, we get the DC biasing Q-point :

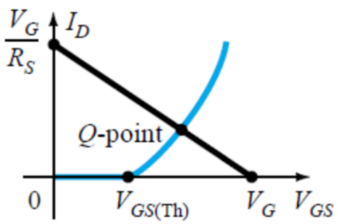

Figure 21

13.2 AC Amplifier Capacitance

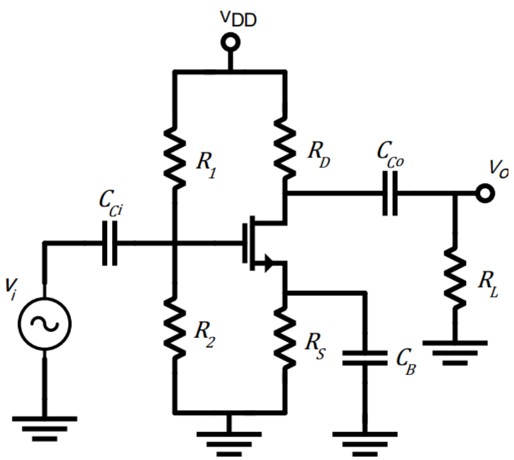

Figure 22

13.2.1 Capacitance Types

Coupling capacitors:
Block the DC, pass the AC

Bypass capacitors:
bypass the AC to the ground.

Internal capacitance:

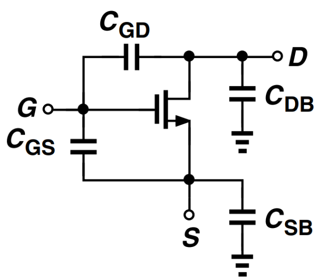

Figure 23: MOSFET internal capacitors

13.2.2 Capacitance Effect

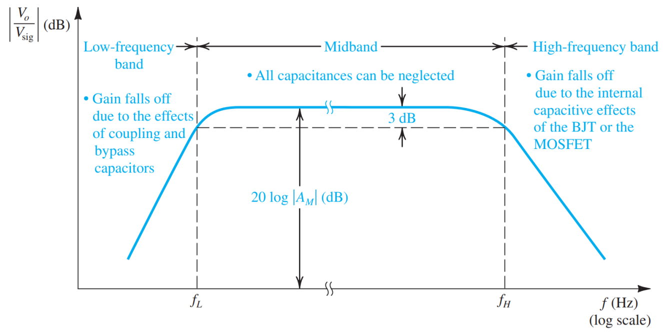

Figure 24

14 Frequency Response of a CS Amplifier

14.1 Low Frequency Response

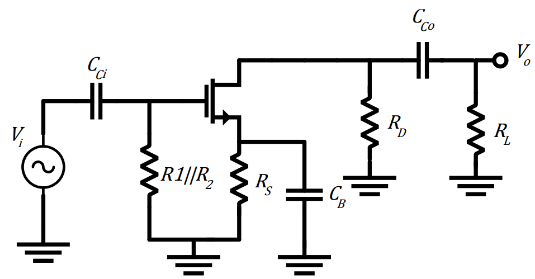

Figure 25

Transfer function :

$$H(s) = \frac{V_0(s)}{V_i(s)} = \frac{V_o(s)}{I_d(s)} \times \frac{I_d(s)}{V_g(s)} \times \frac{V_g(s)}{V_i(s)}$$

The output circuit:

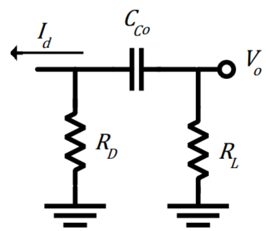

Figure 26

From current divider:

$$\frac{V_o(s)}{R_L} = -\frac{R_D}{R_D + \left(R_L + \frac{1}{sC_{co}}\right)} I_d(s)$$
$$\frac{V_o(s)}{I_d(s)} = \frac{-R_d||R_L}{1+\frac{\omega_{p1}}{s}} \tag{59}$$
$$\omega_{p1} = \frac{1}{(R_D + R_L)C_{co}}$$

Pole $s_p = -\omega_{p1}$ and zero $s_z = 0$

The bypass circuit:

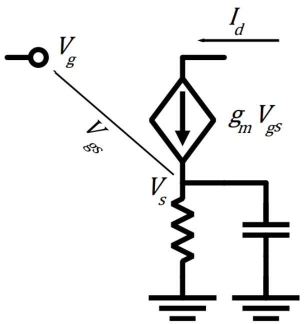

Figure 27

$$I_d(s) = g_m V_{gs}(s) = g_m V_g(s) - g_m I_d(s)\left(R_s \Big|\Big| \frac{1}{sC_b}\right)$$
$$\frac{I_d(s)}{V_g(s)} = g_m \frac{1+\frac{\omega_{z2}}{s}}{1+\frac{\omega_{p2}}{s}} \tag{60}$$
$$\omega_{z2} = \frac{1}{R_sC_b} \qquad \omega_{p2} = \frac{1+g_mR_s}{R_sC_b}$$

Pole $s_p = -\omega_{p2}$ and zero $s_z = -\omega_{z2}$

The input circuit:

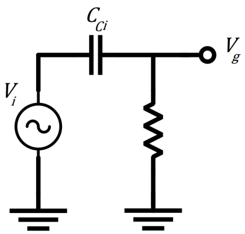

Figure 28

From voltage divider:

$$\frac{V_g(s)}{V_i(s)} = \frac{R_1||R_2}{R_1||R_2 + \frac{1}{sC_{ci}}} = \frac{1}{1+\frac{\omega_{p3}}{s}} \tag{61}$$
$$\omega_{p3} = \frac{1}{(R_1||R_2)C_{ci}}$$

Pole $s_p = -\omega_{p3}$ and zero $s_z = 0$

The overall transfer function:

$$H(s) = \frac{-R_D||R_L}{1+\frac{\omega_{p1}}{s}} \times g_m \frac{1+\frac{\omega_{z2}}{s}}{1+\frac{\omega_{p2}}{s}} \times \frac{1}{1+\frac{\omega_{p3}}{s}} \tag{62}$$

Frequency response:

$$H(j\omega) = H(s)|_{s=j\omega}$$

Bode plot:

Assume $\omega_{z2} < \omega_{p1} < \omega_{p2} < \omega_{p3}$

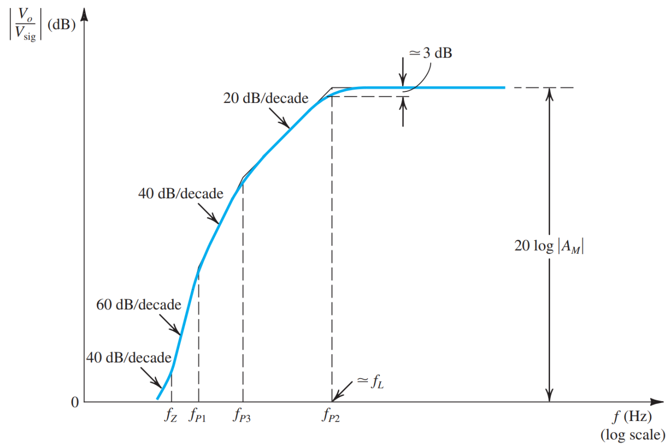

Figure 29

14.2 Mid Band Gain:

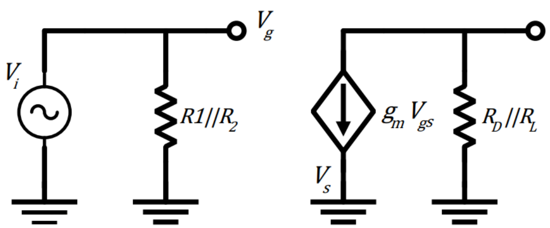

Figure 30

Resolve the circuit or substitute in Equation ?? with $s = \infty$

$$A_M = \frac{v_d}{v_g} = -g_m R_D||R_L \tag{63}$$

14.3 High Frequency Response

We consider the effect of internal transistor capacitance

14.3.1 Miller's Theorem

A method that transforms a floating impedance (Z_f) to two grounded impedances.

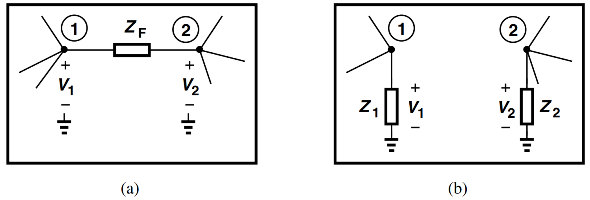

Figure 31: (a) General circuit including a floating impedance, (b) equivalent of (a) as obtained from Miller's theorem.

$$Z_1 = \frac{Z_f}{1-A_v} \qquad Z_2 = \frac{Z_f}{1-\frac{1}{A_v}} \tag{64}$$
$$A_v = \frac{V_2}{V_1}$$

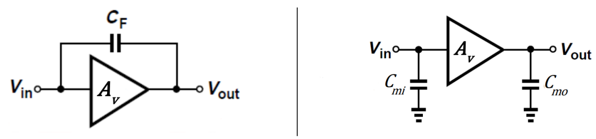

Figure 32

$$C_{mi} = C_F(1 - A_M) \qquad C_{mo} = C_F\left(1 - \frac{1}{A_M}\right) \tag{65}$$

A_M : Mid band gain.

Miller approximation :

$$A_v(s) \approx A_M \tag{66}$$

Circuit analysis:

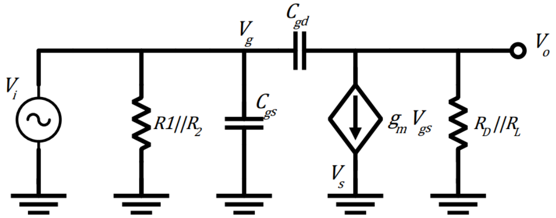

Figure 33

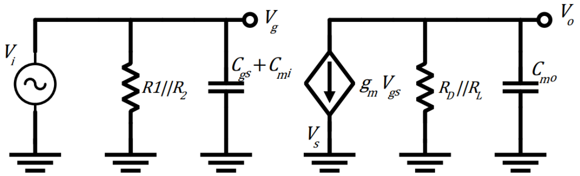

Figure 34

Transfer function:

$$H(s) = \frac{V_o(s)}{V_i(s)} = \frac{V_o(s)}{V_{gs}(s)} \times \frac{V_{gs}(s)}{V_i(s)}$$

Input circuit:

$$\frac{V_{gs}}{V_i} = 1 \tag{67}$$

Output circuit:

$$V_o(s) = -g_m V_{gs} \left(R_d || R_L || \frac{1}{sC_{mo}} \right)$$

$$\frac{V_o(s)}{V_i(s)} = -\frac{g_m(R_D||R_L)}{1 + \frac{s}{\omega_H}} \tag{68}$$

$$\omega_H = \frac{1}{(R_D||R_L)C_{om}}$$

Frequency response:

$$H(j\omega) = H(s)|_{s=j\omega}$$

Transfer function:

$$H(s) = -\frac{g_m(R_D||R_L)}{1 + \frac{s}{\omega_H}} \tag{69}$$

Pole $s_{pH} = -\omega_H$

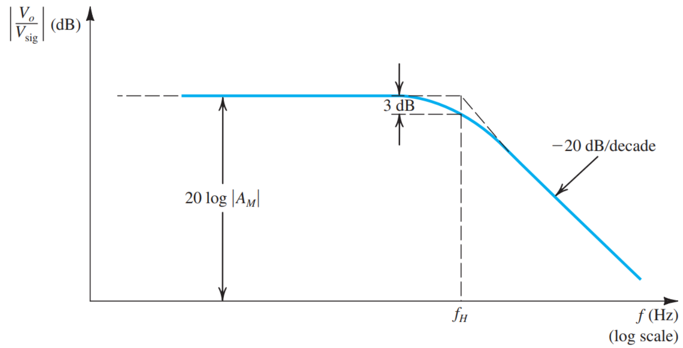

Figure 35: High frequency response