LECTURE 420 – COMPENSATION OF OP AMPS-I
(READING: Text-Sec. 9.2, 9.3, 9.4)

INTRODUCTION

The objective of this presentation is to present the principles of compensating two-stage op amps.

Outline

- Compensation of Op Amps
  - General principles
  - Miller, Nulling Miller
  - Self-compensation
  - Feedforward
- Summary

GENERAL PRINCIPLES OF OP AMP COMPENSATION

Objective

Objective of compensation is to achieve stable operation when negative feedback is applied around the op amp.

Types of Compensation

1. Miller - Use of a capacitor feeding back around a high-gain, inverting stage.
    - Miller capacitor only
    - Miller capacitor with an unity-gain buffer to block the forward path through the compensation capacitor. Can eliminate the RHP zero.
    - Miller with a nulling resistor. Similar to Miller but with an added series resistance to gain control over the RHP zero.
2. Feedforward - Bypassing a positive gain amplifier resulting in phase lead. Gain can be less than unity.
3. Self compensating - Load capacitor compensates the op amp.

Single-Loop, Negative Feedback Systems

Block diagram:

$A(s)$ = differential-mode voltage gain of the op amp

$F(s)$ = feedback transfer function from the output of op amp back to the input.

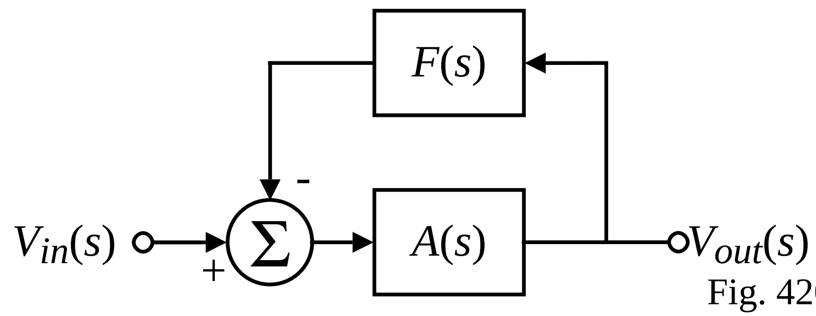

Fig. 420-01

Definitions:

- Open-loop gain = $L(s) = -A(s)F(s)$
- Closed-loop gain = $\dfrac{V_{out}(s)}{V_{in}(s)} = \dfrac{A(s)}{1+A(s)F(s)}$

Stability Requirements:

The requirements for stability for a single-loop, negative feedback system is,

$$|A(j\omega_{0^\circ})F(j\omega_{0^\circ})| = |L(j\omega_{0^\circ})| < 1$$

where ω_{0° is defined as

$$\mathrm{Arg}[-A(j\omega_{0^\circ})F(j\omega_{0^\circ})] = \mathrm{Arg}[L(j\omega_{0^\circ})] = 0°$$

Another convenient way to express this requirement is

$$\mathrm{Arg}[-A(j\omega_{0\mathrm{dB}})F(j\omega_{0\mathrm{dB}})] = \mathrm{Arg}[L(j\omega_{0\mathrm{dB}})] > 0°$$

where $\omega_{0\mathrm{dB}}$ is defined as

$$|A(j\omega_{0\mathrm{dB}})F(j\omega_{0\mathrm{dB}})| = |L(j\omega_{0\mathrm{dB}})| = 1$$

Illustration of the Stability Requirement using Bode Plots

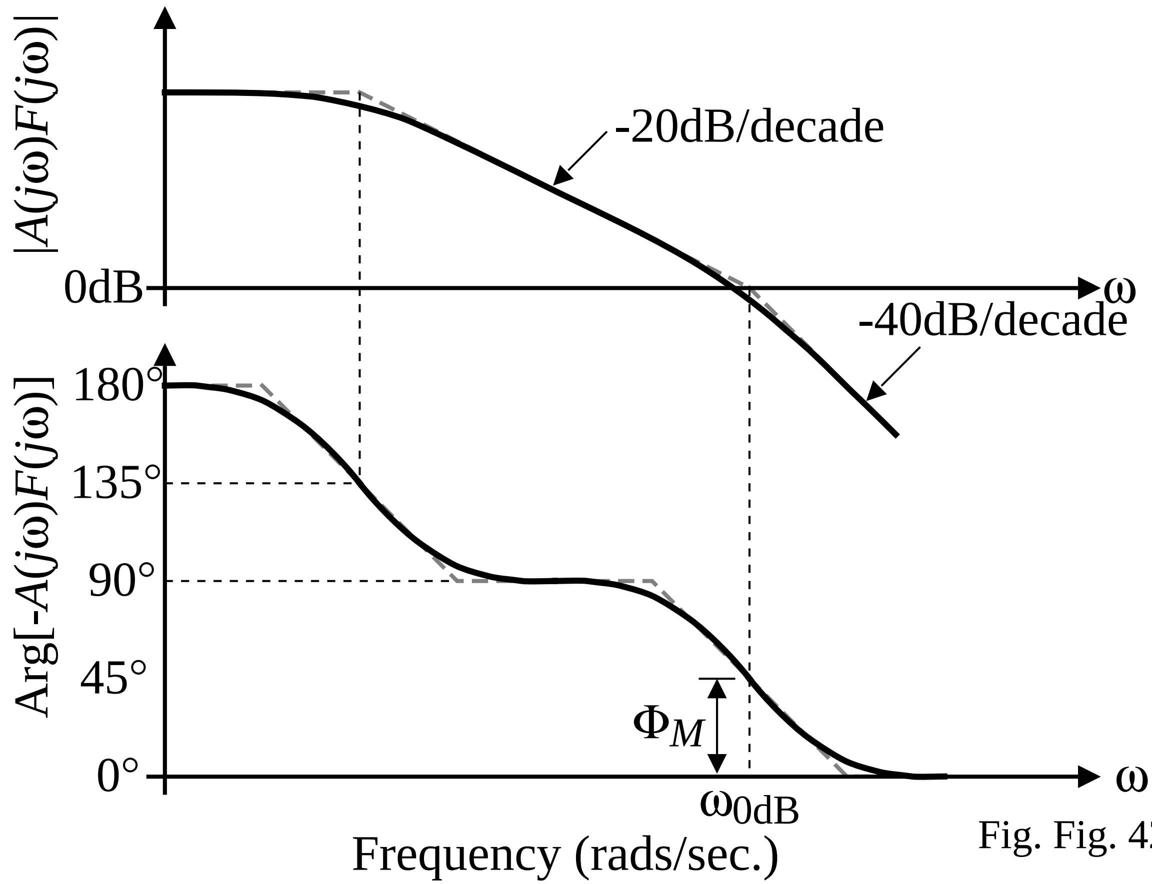

Fig. Fig. 420-02

A measure of stability is given by the phase when $|A(j\omega)F(j\omega)| = 1$. This phase is called *phase margin*.

$$\text{Phase margin} = \Phi_M = \text{Arg}[-A(j\omega_{0\text{dB}})F(j\omega_{0\text{dB}})] = \text{Arg}[L(j\omega_{0\text{dB}})]$$

Why Do We Want Good Stability?

Consider the step response of second-order system which closely models the closed-loop gain of the op amp.

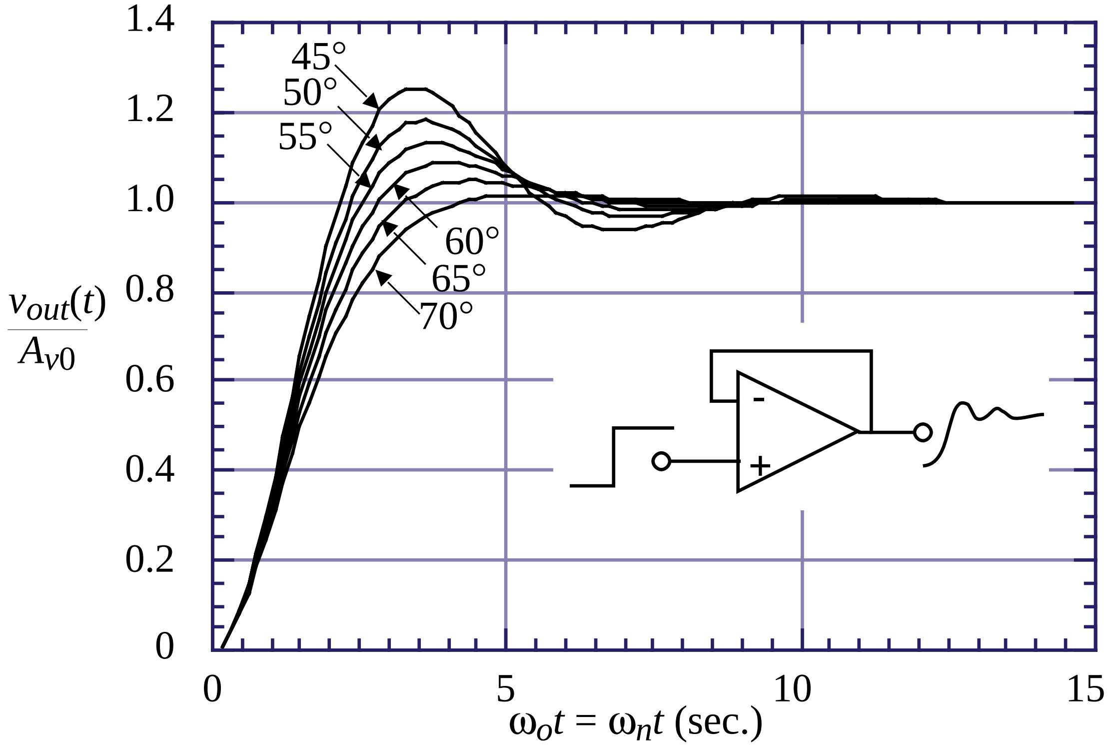

Fig. 420-03

A "good" step response is one that quickly reaches its final value.

Therefore, we see that phase margin should be at least 45° and preferably 60° or larger.

(A rule of thumb for satisfactory stability is that there should be less than three rings.)

Uncompensated Frequency Response of Two-Stage Op Amps

Two-Stage Op Amps:

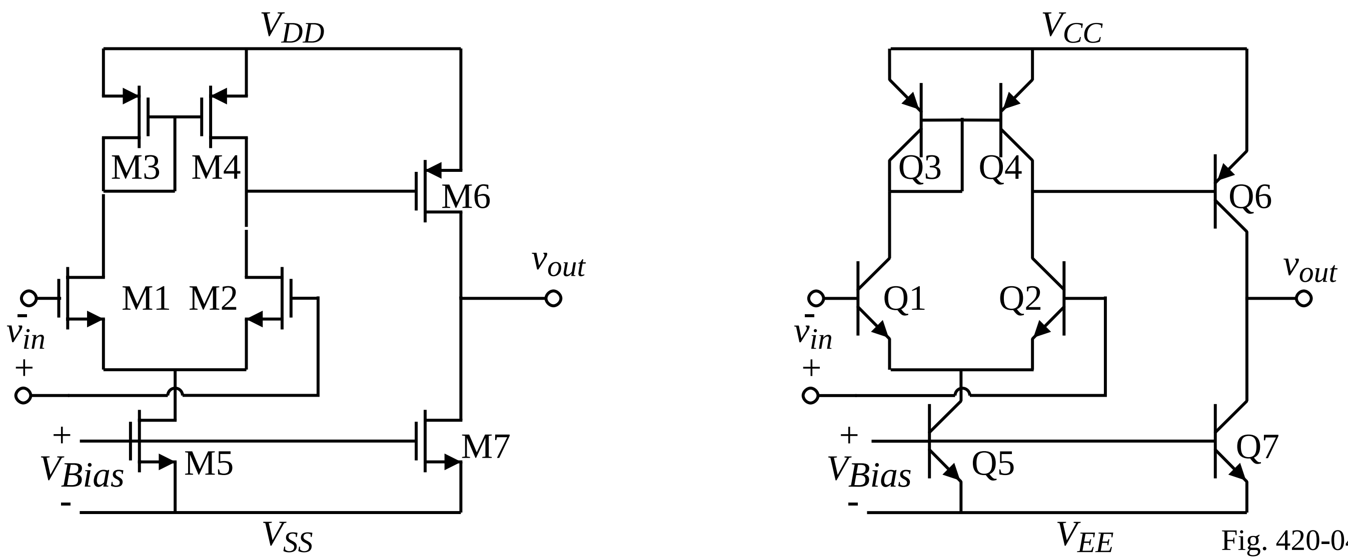

Fig. 420-04

Small-Signal Model:

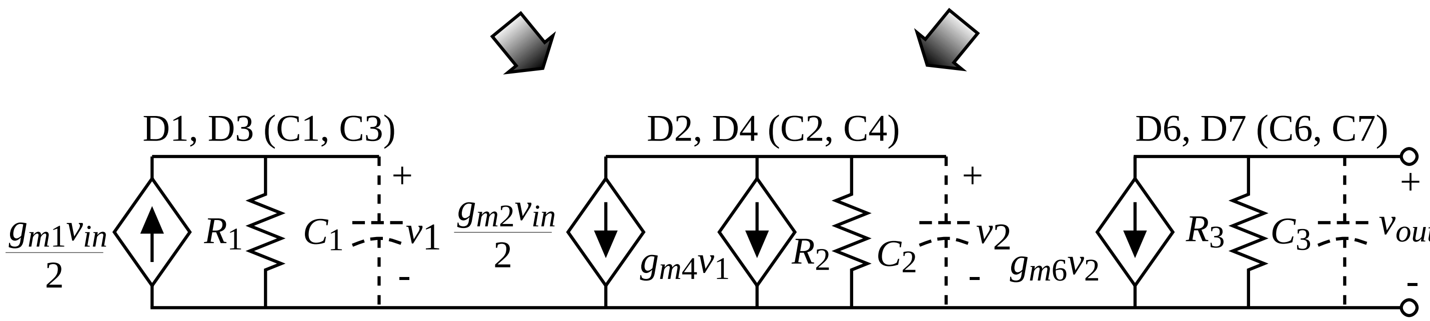

Fig. 420-05

Note that this model neglects the base-collector and gate-drain capacitances for purposes of simplification.

Uncompensated Frequency Response of Two-Stage Op Amps - Continued

For the MOS two-stage op amp:

$$R_1 \approx \frac{1}{g_{m3}} \| r_{ds3} \| r_{ds1} \approx \frac{1}{g_{m3}} \qquad R_2 = r_{ds2} \| r_{ds4} \qquad \text{and} \qquad R_3 = r_{ds6} \| r_{ds7}$$

$$C_1 = C_{gs3}+C_{gs4}+C_{bd1}+C_{bd3} \qquad C_2 = C_{gs6}+C_{bd2}+C_{bd4} \qquad \text{and} \quad C_3 = C_L + C_{bd6}+C_{bd7}$$

For the BJT two-stage op amp:

$$R_1 = \frac{1}{g_{m3}} \| r_{\pi 3} \| r_{\pi 4} \| r_{o3} \approx \frac{1}{g_{m3}} \qquad R_2 = r_{\pi 6} \| r_{o2} \| r_{o4} \approx r_{\pi 6} \quad \text{and} \qquad R_3 = r_{o6} \| r_{o7}$$

$$C_1 = C_{\pi 3}+C_{\pi 4}+C_{cs1}+C_{cs3} \qquad C_2 = C_{\pi 6}+C_{cs2}+C_{cs4} \qquad \text{and} \quad C_3 = C_L+C_{cs6}+C_{cs7}$$

Assuming the pole due to C_1 is much greater than the poles due to C_2 and C_3 gives,

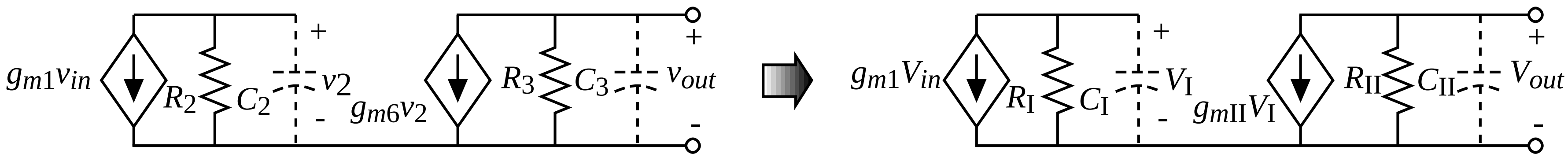

Fig. 420-06

The locations for the two poles are given by the following equations

$$p'_1 = \frac{-1}{R_{\mathrm{I}}C_{\mathrm{I}}} \quad \text{and} \quad p'_2 = \frac{-1}{R_{\mathrm{II}}C_{\mathrm{II}}}$$

where R_I (R_{II}) is the resistance to ground seen from the output of the first (second) stage and C_I (C_{II}) is the capacitance to ground seen from the output of the first (second) stage.

Uncompensated Frequency Response of an Op Amp

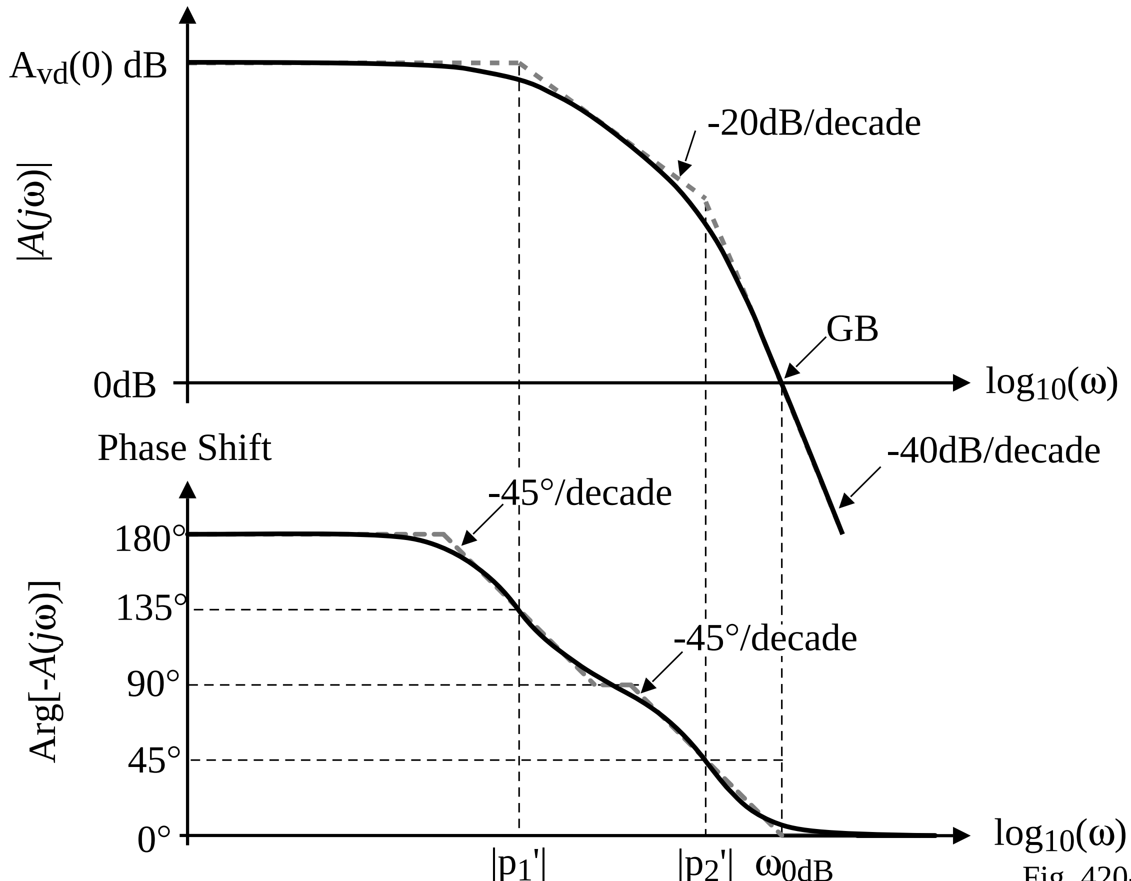

Fig. 420-07

If we assume that $F(s) = 1$ (this is the worst case for stability considerations), then the above plot is the same as the loop gain.

Note that the phase margin is much less than 45°.

Therefore, the op amp must be compensated before using it in a closed-loop configuration.

MILLER COMPENSATION

Two-Stage Op Amp

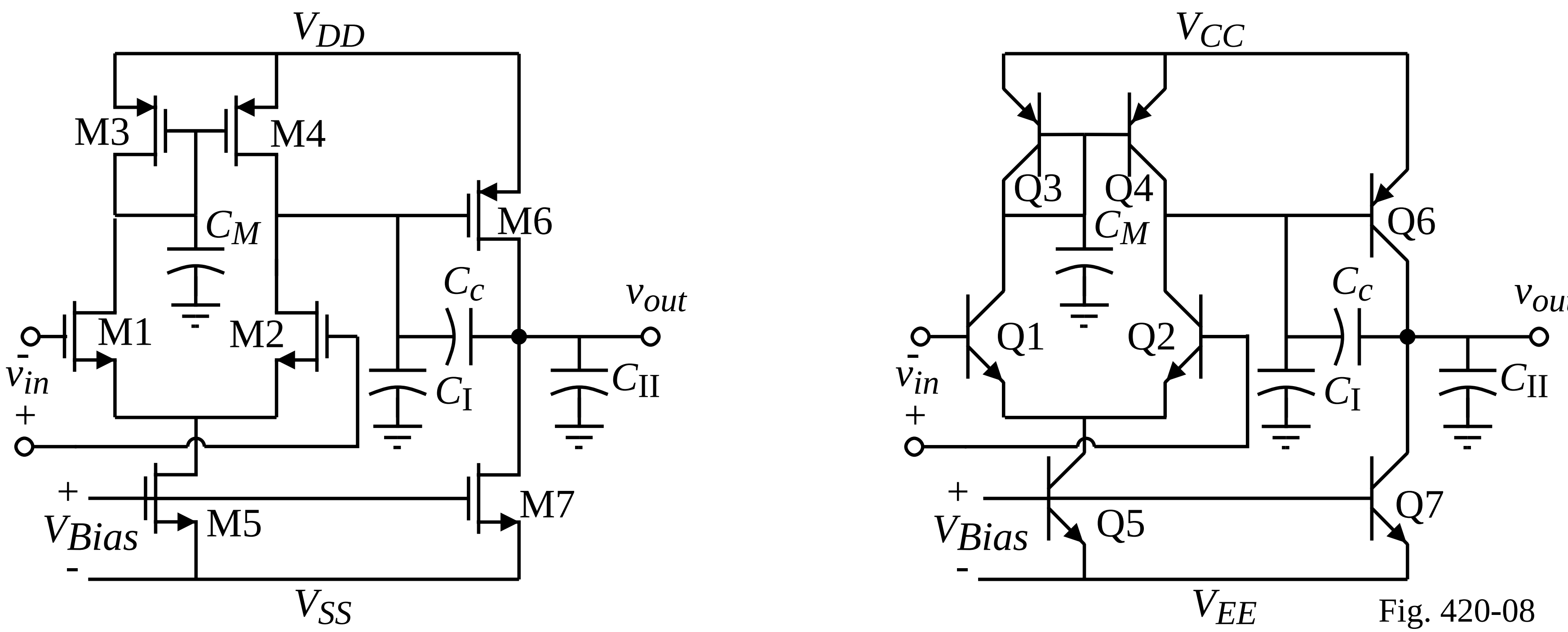

Fig. 420-08

The various capacitors are:

C_c = accomplishes the Miller compensation

C_M = capacitance associated with the first-stage mirror (mirror pole)

C_I = output capacitance to ground of the first-stage

C_{II} = output capacitance to ground of the second-stage

Compensated Two-Stage, Small-Signal Frequency Response Model Simplified

Use the CMOS op amp to illustrate:

1.) Assume that $g_{m3} >> g_{ds3} + g_{ds1}$

2.) Assume that $\dfrac{g_{m3}}{C_M} >> GB$

Therefore,

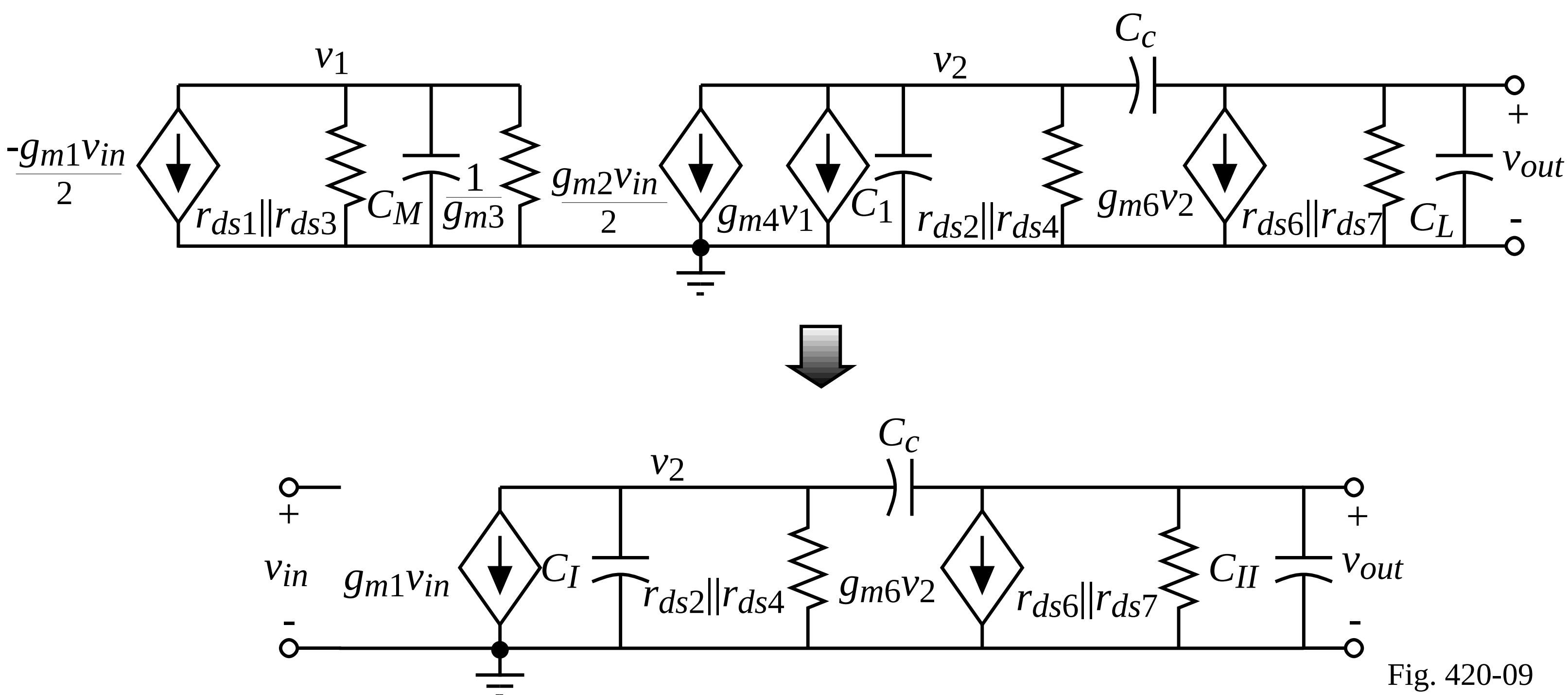

Fig. 420-09

Same circuit holds for the BJT op amp with different component relationships.

General Two-Stage Frequency Response Analysis

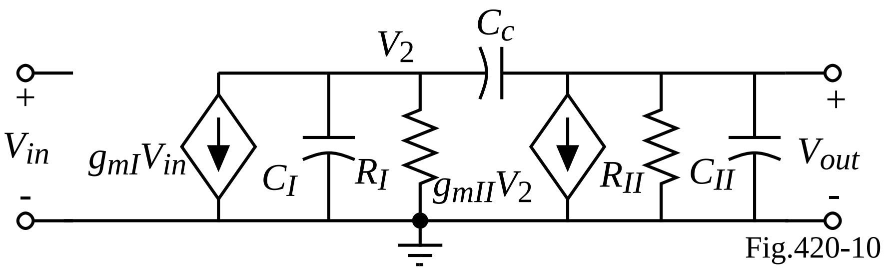

Fig.420-10

where

$$g_{mI} = g_{m1} = g_{m2},\ R_I = r_{ds2}||r_{ds4},\ C_I = C_1$$

and

$$g_{mII} = g_{m6},\ R_{II} = r_{ds6}||r_{ds7},\ C_{II} = C_2 = C_L$$

Nodal Equations:

$$-g_{mI}V_{in} = [G_I + s(C_I + C_c)]V_2 - [sC_c]V_{out} \quad \text{and} \quad 0 = [g_{mII} - sC_c]V_2 + [G_{II} + sC_{II} + sC_c]V_{out}$$

Solving using Cramer's rule gives,

$$\frac{V_{out}(s)}{V_{in}(s)} = \frac{g_{mI}(g_{mII} - sC_c)}{G_IG_{II}+s\,[G_{II}(C_I+C_{II})+G_I(C_{II}+C_c)+g_{mII}C_c]+s^2[C_IC_{II}+C_cC_I+C_cC_{II}]}$$

$$= \frac{A_o[1 - s\,(C_c/g_{mII})]}{1+s\,[R_I(C_I+C_{II})+R_{II}(C_2+C_c)+g_{mII}R_IR_{II}C_c]+s^2[R_IR_{II}(C_IC_{II}+C_cC_I+C_cC_{II})]}$$

where, $A_o = g_{mI}g_{mII}R_IR_{II}$

In general, $D(s) = \left(1-\frac{s}{p_1}\right)\left(1-\frac{s}{p_2}\right) = 1-s\left(\frac{1}{p_1}+\frac{1}{p_2}\right)+\frac{s^2}{p_1p_2} \;\rightarrow\; D(s) \approx 1-\frac{s}{p_1} + \frac{s^2}{p_1p_2}$, if $|p_2|>>|p_1|$

$$\therefore \quad \boxed{p_1 = \frac{-1}{R_I(C_I+C_{II})+R_{II}(C_{II}+C_c)+g_{mII}R_IR_{II}C_c} \approx \frac{-1}{g_{mII}R_IR_{II}C_c}}, \quad \boxed{z = \frac{g_{mII}}{C_c}}$$

$$\boxed{p_2 = \frac{-[R_I(C_I+C_{II})+R_{II}(C_{II}+C_c)+g_{mII}R_IR_{II}C_c]}{R_IR_{II}(C_IC_{II}+C_cC_I+C_cC_{II})} \approx \frac{-g_{mII}C_c}{C_IC_{II}+C_cC_I+C_cC_{II}} \approx \frac{-g_{mII}}{C_{II}}}, \quad C_{II} > C_c > C_I$$

Summary of Results for Miller Compensation of the Two-Stage Op Amp

There are three roots of importance:

1.) Right-half plane zero:

$$z_1 = \frac{g_{mII}}{C_c} = \frac{g_{m6}}{C_c}$$

This root is very undesirable- it boosts the magnitude while decreasing the phase.

2.) Dominant left-half plane pole (the Miller pole):

$$p_1 \approx \frac{-1}{g_{mII}R_I R_{II} C_c} = \frac{-(g_{ds2}+g_{ds4})(g_{ds6}+g_{ds7})}{g_{m6}C_c}$$

This root accomplishes the desired compensation.

3.) Left-half plane output pole:

$$p_2 \approx \frac{-g_{mII}}{C_{II}} \approx \frac{-g_{m6}}{C_L}$$

This pole must be ≥ unity-gainbandwidth or the phase margin will not be satisfied.

Root locus plot of the Miller compensation:

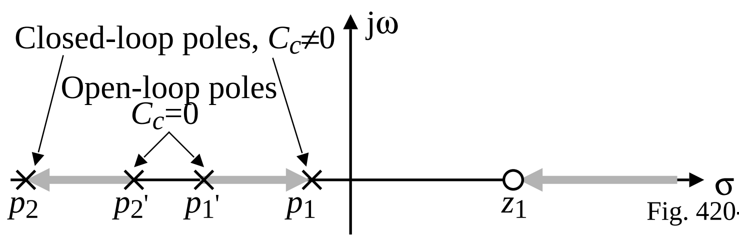

Fig. 420-11

Compensated Open-Loop Frequency Response of the Two-Stage Op Amp

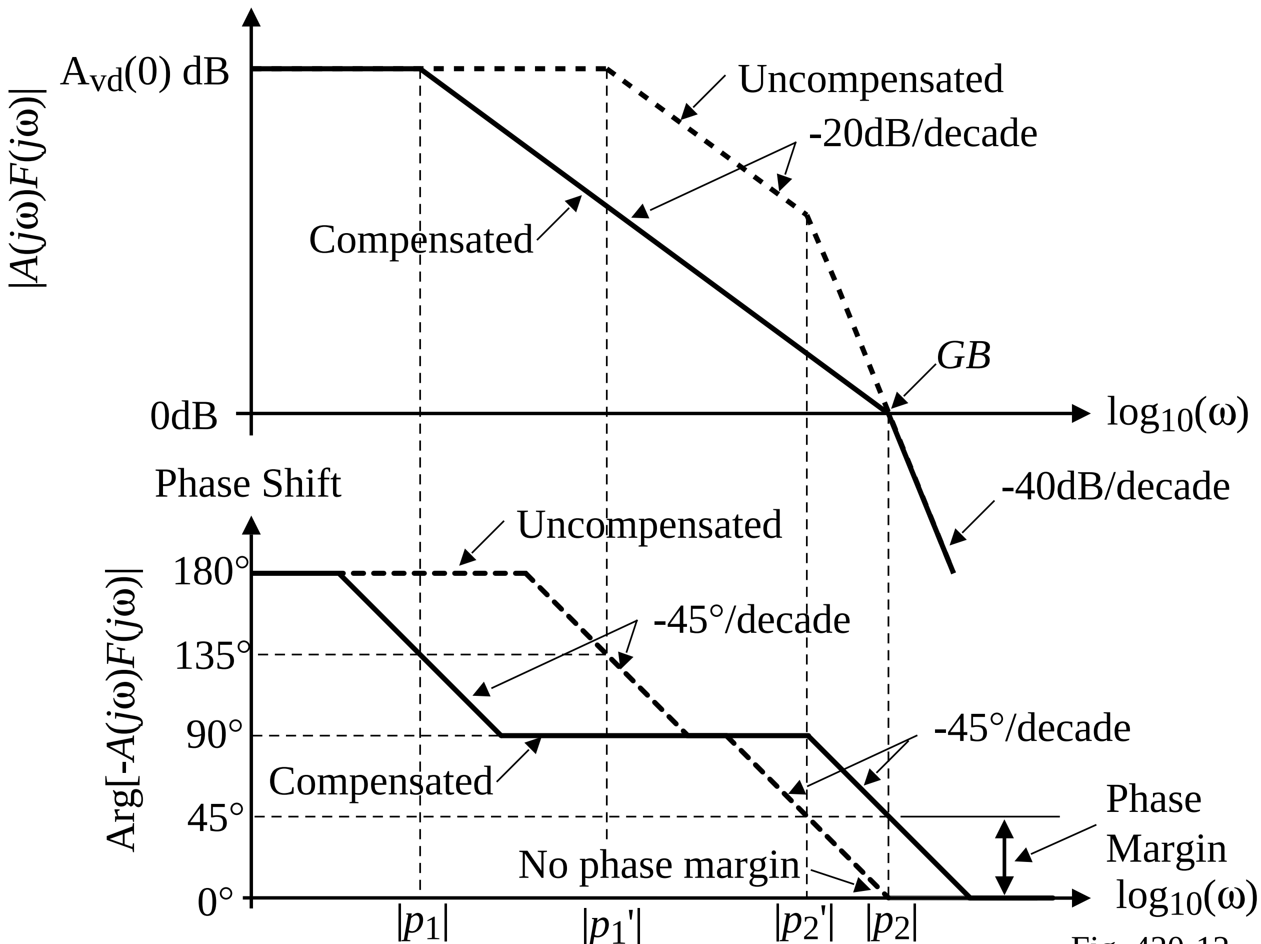

Fig. 420-12

Note that the unity-gainbandwidth, *GB*, is

$$GB = A_{vd}(0)\cdot|p_1| = (g_{mI}g_{mII}R_IR_{II})\frac{1}{g_{mII}R_IR_{II}C_c} = \frac{g_{mI}}{C_c} = \frac{g_{m1}}{C_c} = \frac{g_{m2}}{C_c}$$

Conceptually, where do these roots come from?

1.) The Miller pole:

$$|p_1| \approx \frac{1}{R_I(g_{m6}R_{II}C_c)}$$

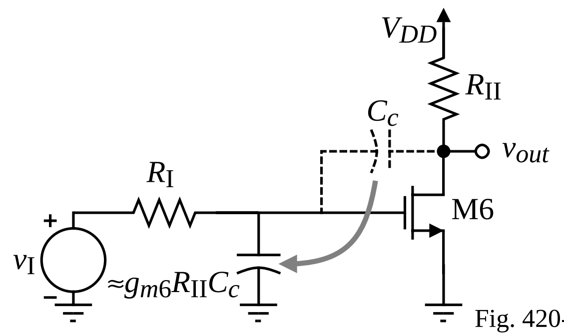

Fig. 420-13

2.) The left-half plane output pole:

$$|p_2| \approx \frac{g_{m6}}{C_{II}}$$

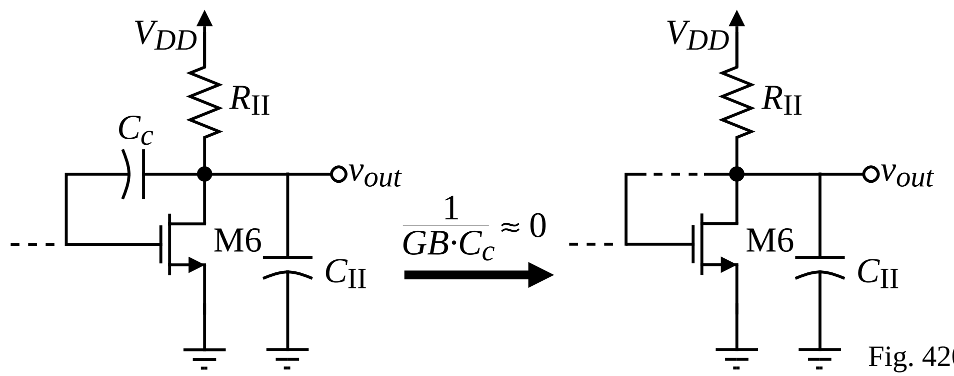

Fig. 420-14

3.) Right-half plane zero (*Zeros always arise from multiple paths from the input to output*):

$$v_{out} = \left(\frac{-g_{m6}R_{II}(1/sC_c)}{R_{II} + 1/sC_c}\right)v' + \left(\frac{R_{II}}{R_{II} + 1/sC_c}\right)v'' = \frac{-R_{II}\left(\frac{g_{m6}}{sC_c} - 1\right)}{R_{II} + 1/sC_c}\,v$$

where $v = v' = v''$.

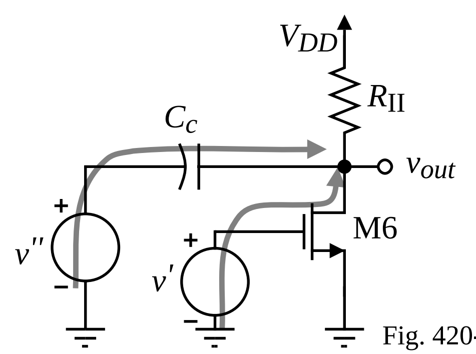

Fig. 420-15

Influence of the Mirror Pole

Up to this point, we have neglected the influence of the pole, p_3, associated with the current mirror of the input stage. If $|p_2| \approx |p_3|$, we have problems in compensation. This pole is given approximately as

$$p_3 \approx \frac{-g_{m3}}{C_M}$$

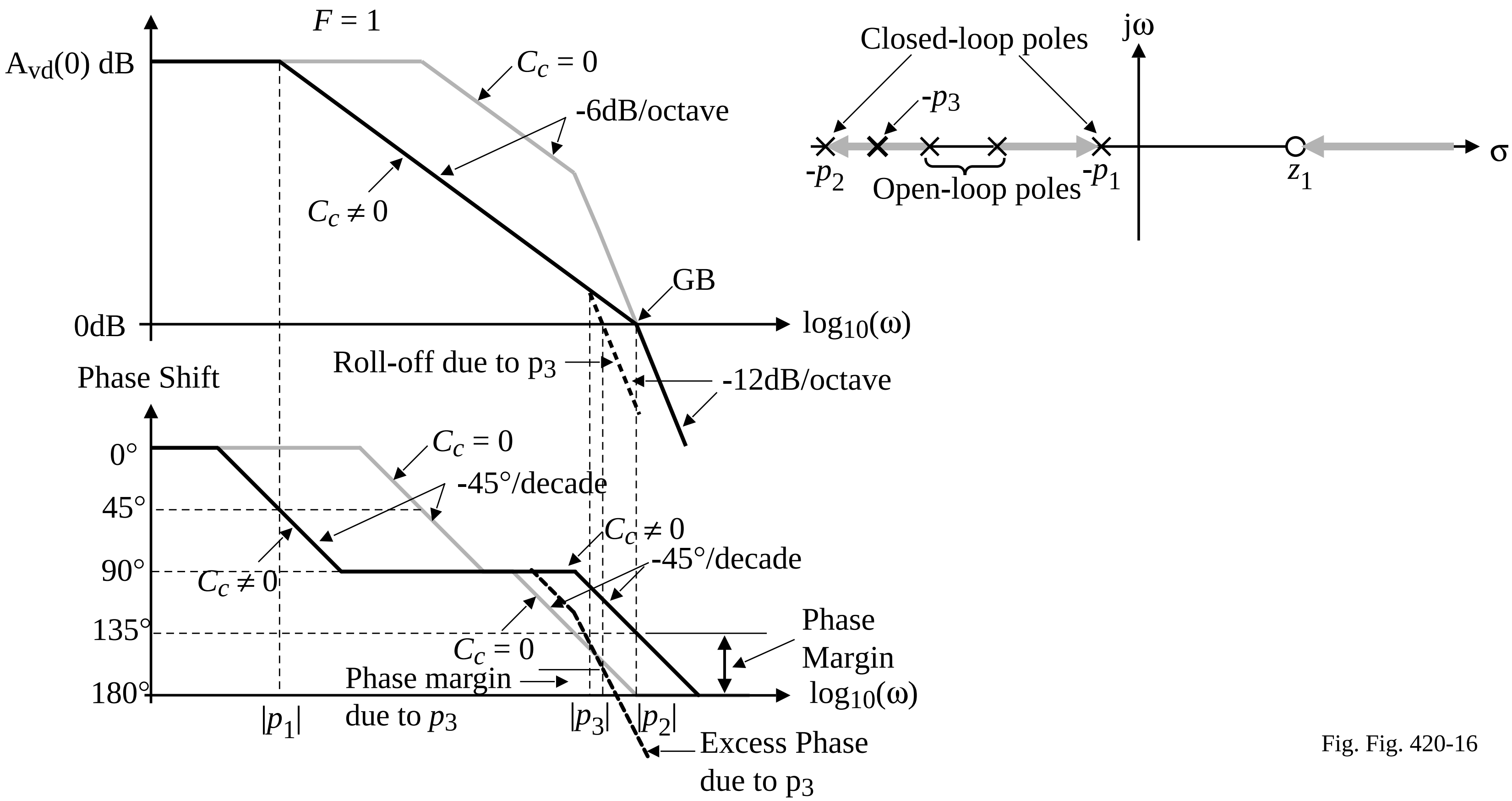

Fig. Fig. 420-16

SUMMARY

Compensation

- Designed so that the op amp with unity gain feedback (buffer) is stable
- Types
  - Miller
  - Miller with nulling resistors
  - Self Compensating
  - Feedforward

