

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

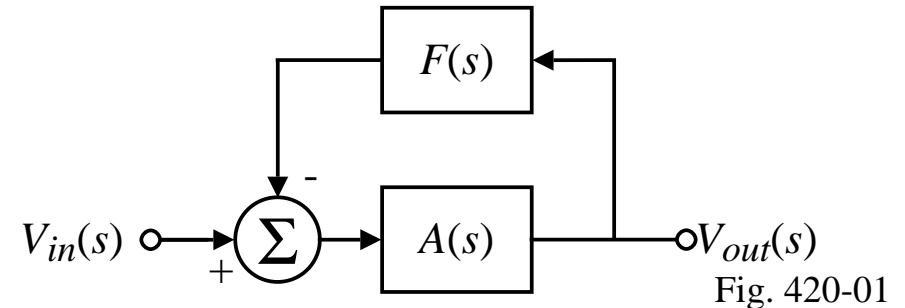
1. Miller - Use of a capacitor feeding back around a high-gain, inverting stage.
 - Miller capacitor only
 - Miller capacitor with an unity-gain buffer to block the forward path through the compensation capacitor. Can eliminate the RHP zero.
 - Miller with a nulling resistor. Similar to Miller but with 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.



Definitions:

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

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

$$\text{Arg}[-A(j\omega_0^\circ)F(j\omega_0^\circ)] = \text{Arg}[L(j\omega_0^\circ)] = 0^\circ$$

Another convenient way to express this requirement is

$$\text{Arg}[-A(j\omega_{0dB})F(j\omega_{0dB})] = \text{Arg}[L(j\omega_{0dB})] > 0^\circ$$

where ω_{0dB} is defined as

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

Illustration of the Stability Requirement using Bode Plots

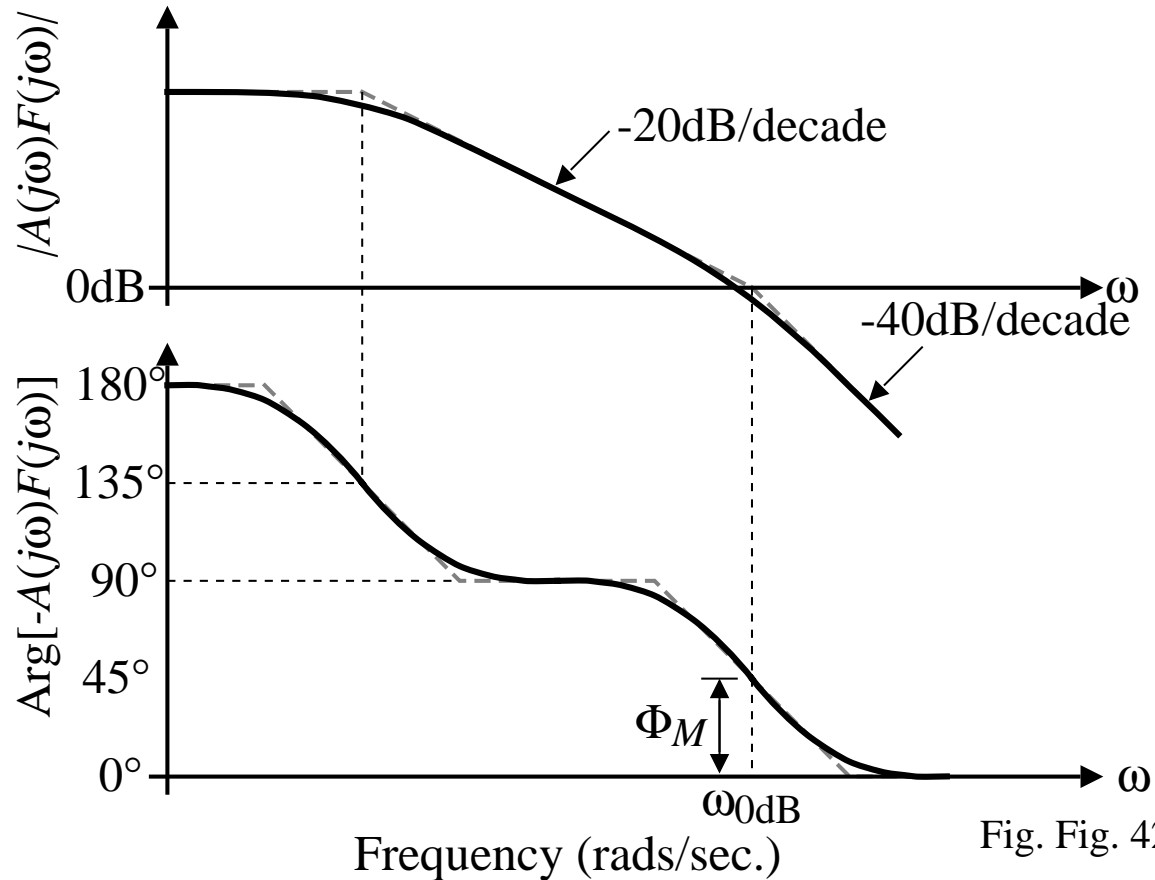


Fig. Fig. 420-02

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

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

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.

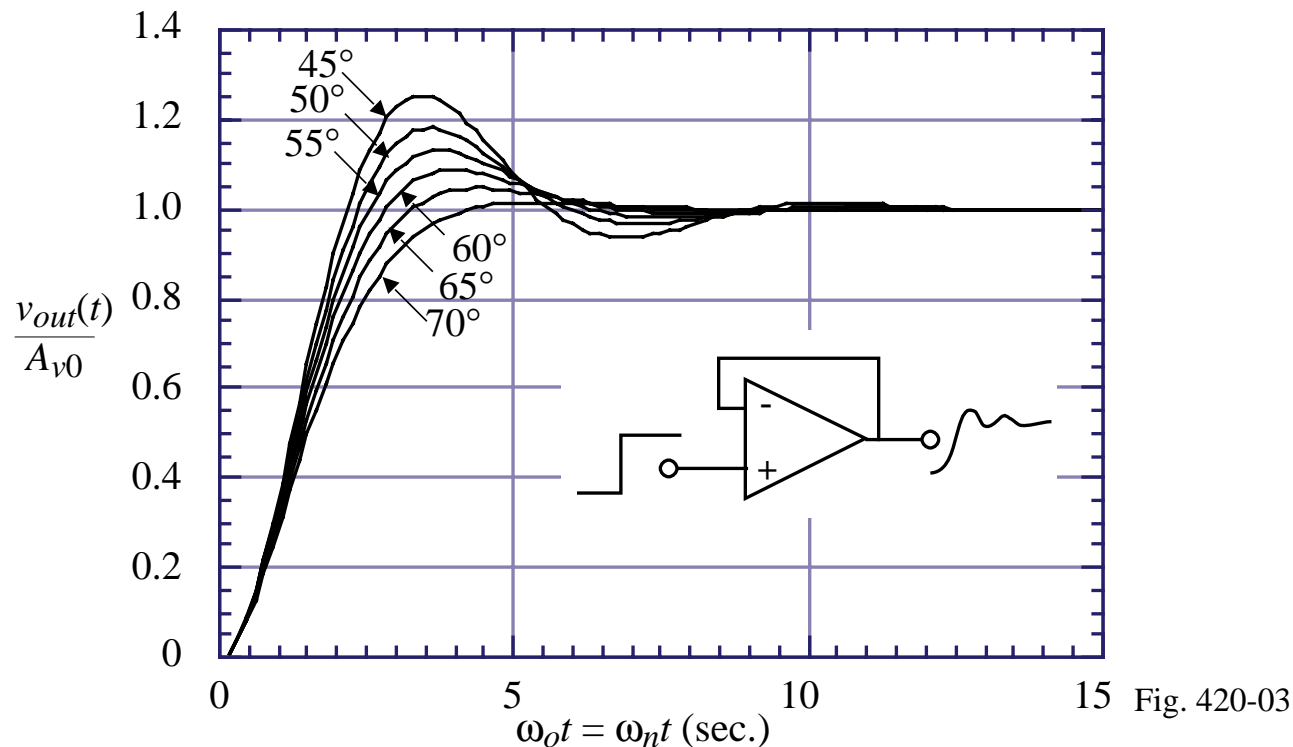


Fig. 420-03

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:

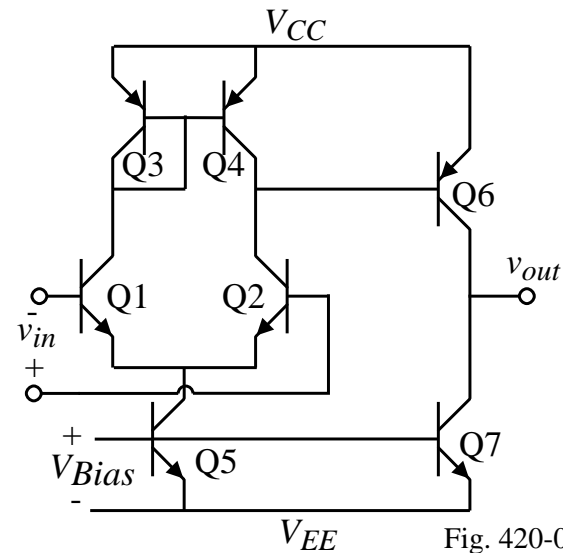
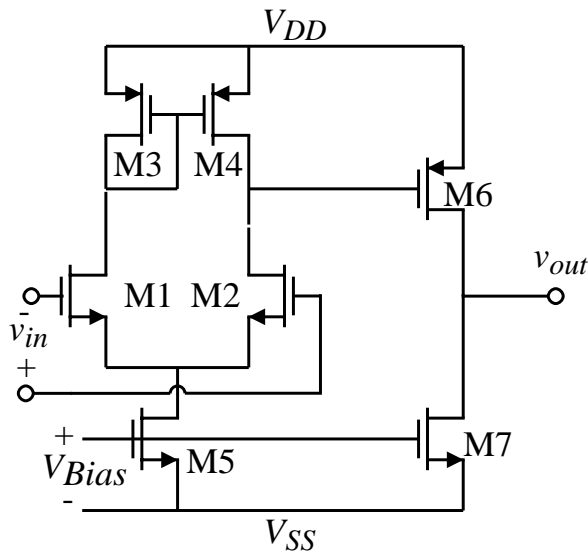


Fig. 420-04

Small-Signal Model:

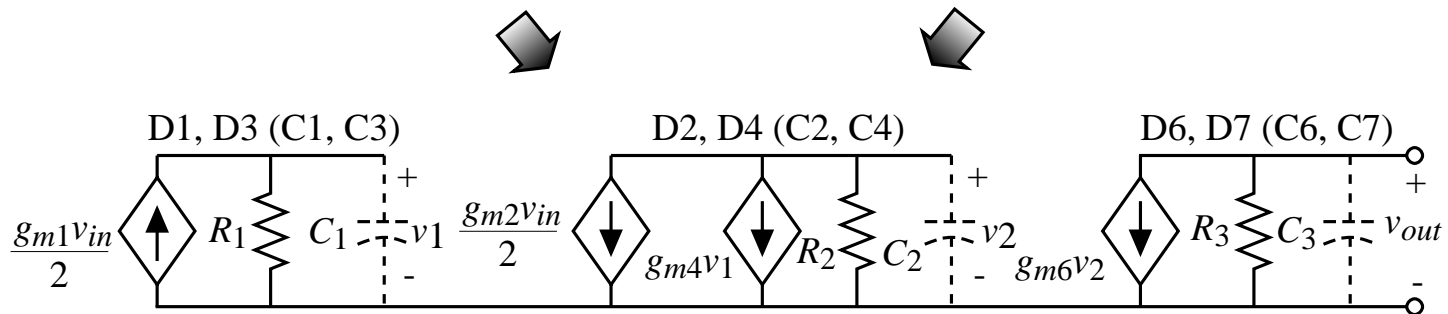


Fig. 420-05

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:

$$R_1 \approx \frac{1}{g_{m3}} \parallel r_{ds3} \parallel r_{ds1} \approx \frac{1}{g_{m3}}$$

$$R_2 = r_{ds2} \parallel r_{ds4}$$

$$\text{and } R_3 = r_{ds6} \parallel r_{ds7}$$

$$C_1 = C_{gs3} + C_{gs4} + C_{bd1} + C_{bd3}$$

$$C_2 = C_{gs6} + C_{bd2} + C_{bd4}$$

$$\text{and } C_3 = C_L + C_{bd6} + C_{bd7}$$

For the BJT two-stage op amp:

$$R_1 = \frac{1}{g_{m3}} \parallel r_{\pi3} \parallel r_{\pi4} \parallel r_{o3} \approx \frac{1}{g_{m3}}$$

$$R_2 = r_{\pi6} \parallel r_{o2} \parallel r_{o4} \approx r_{\pi6}$$

$$\text{and } R_3 = r_{o6} \parallel r_{o7}$$

$$C_1 = C_{\pi3} + C_{\pi4} + C_{cs1} + C_{cs3}$$

$$C_2 = C_{\pi6} + C_{cs2} + C_{cs4}$$

$$\text{and } C_3 = C_L + C_{cs6} + C_{cs7}$$

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

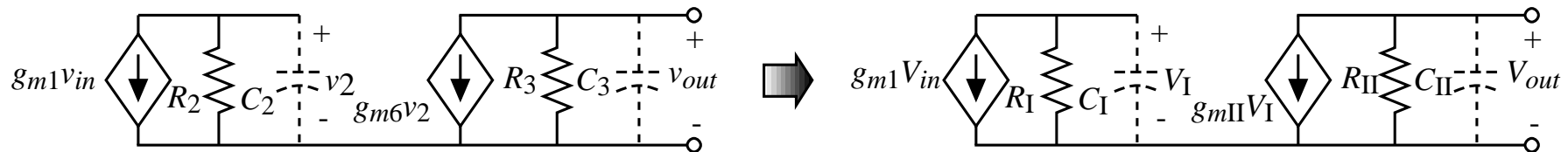


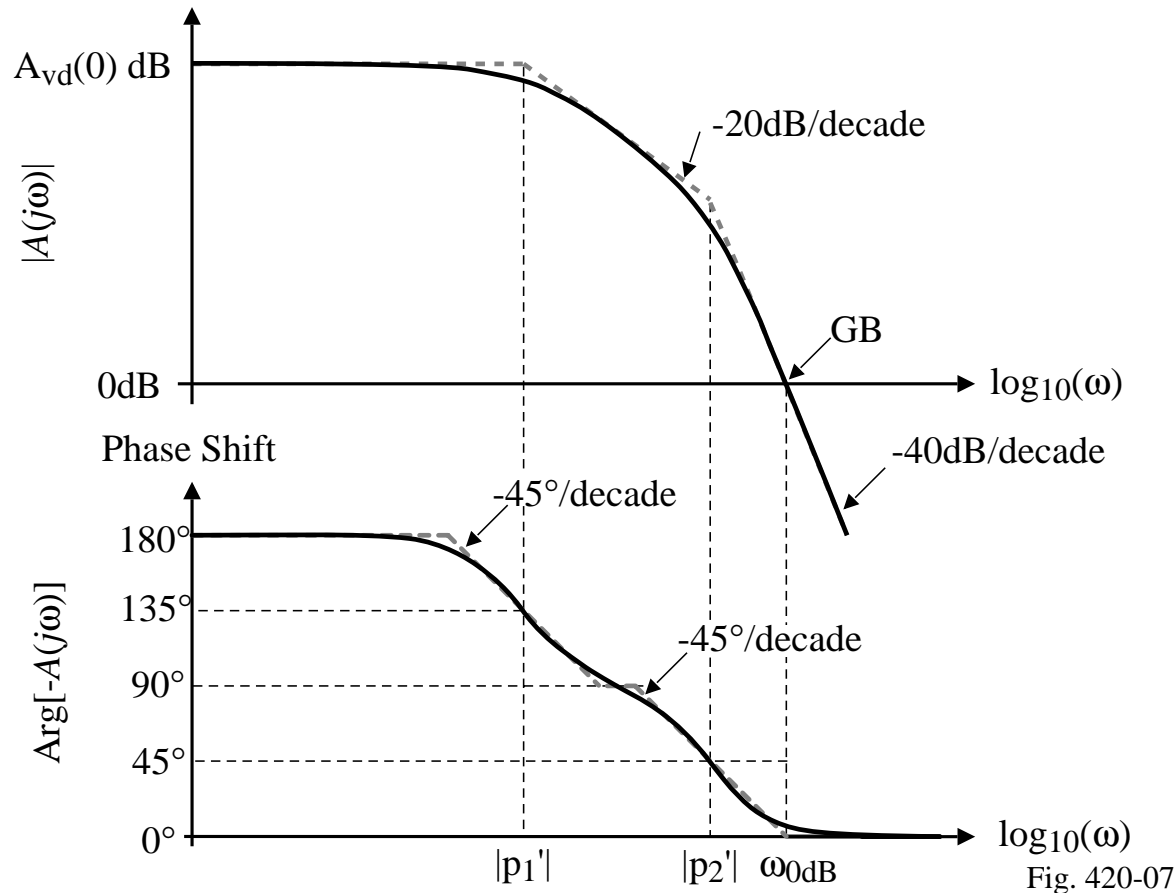
Fig. 420-06

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

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

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



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

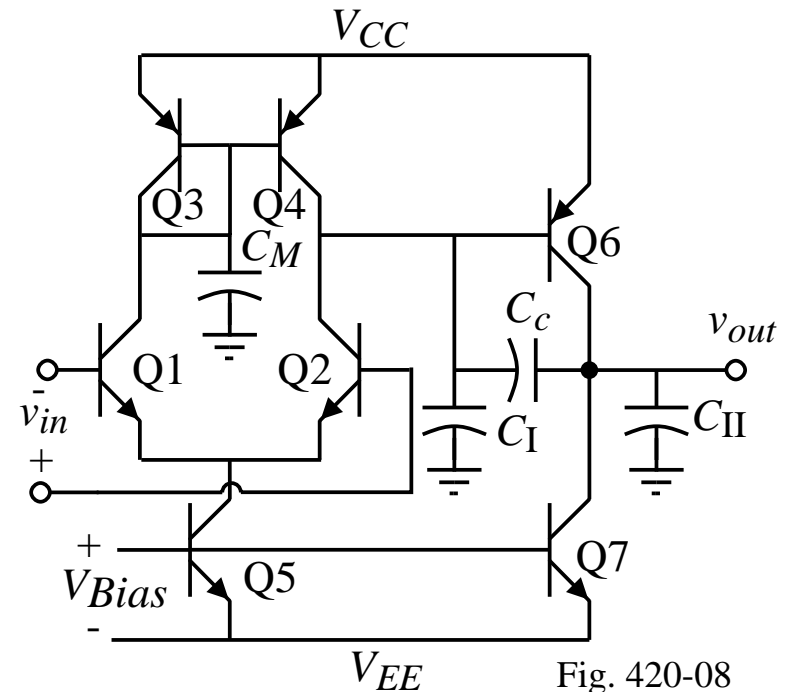
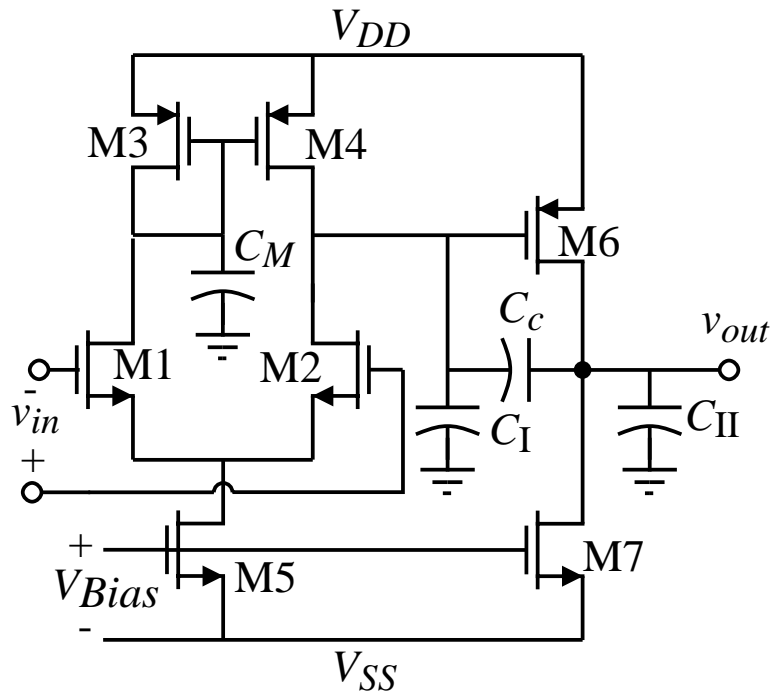


Fig. 420-08

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 $g_{m3} \gg g_{ds3} + g_{ds1}$

2.) Assume that $\frac{g_{m3}}{C_M} \gg GB$

Therefore,

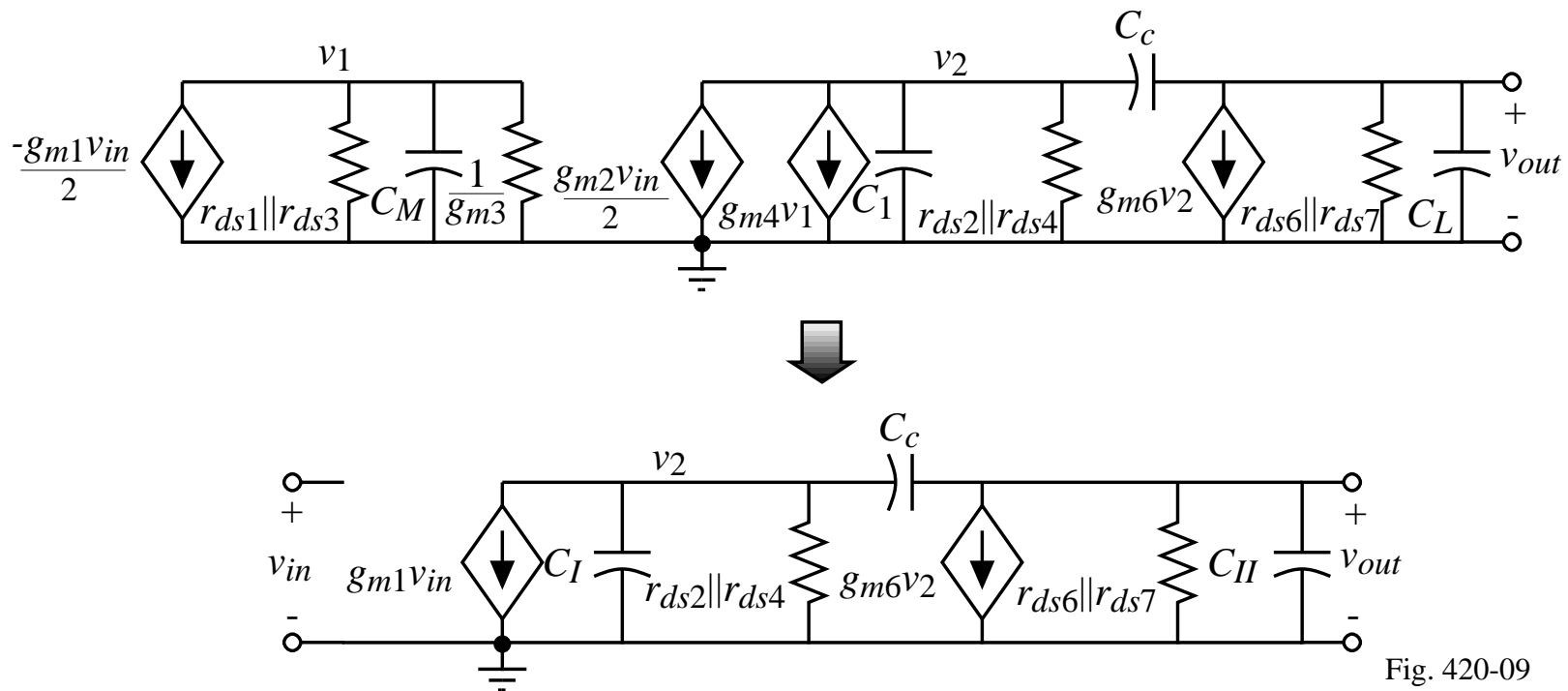
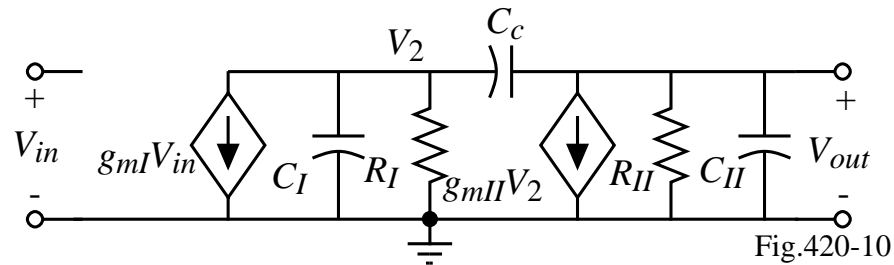


Fig. 420-09

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

General Two-Stage Frequency Response Analysis



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,

$$\begin{aligned} \frac{V_{out}(s)}{V_{in}(s)} &= \frac{g_{mI}(g_{mII} - sC_c)}{G_I G_{II} + s [G_{II}(C_I + C_{II}) + G_I(C_{II} + C_c) + g_{mII}C_c] + s^2 [C_I C_{II} + C_c C_I + C_c C_{II}]} \\ &= \frac{A_o [1 - s(C_c/g_{mII})]}{1 + s [R_I(C_I + C_{II}) + R_{II}(C_{II} + C_c) + g_{mII}R_I R_{II} C_c] + s^2 [R_I R_{II} (C_I C_{II} + C_c C_I + C_c C_{II})]} \end{aligned}$$

where, $A_o = g_{mI} g_{mII} R_I R_{II}$

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

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

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

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):

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

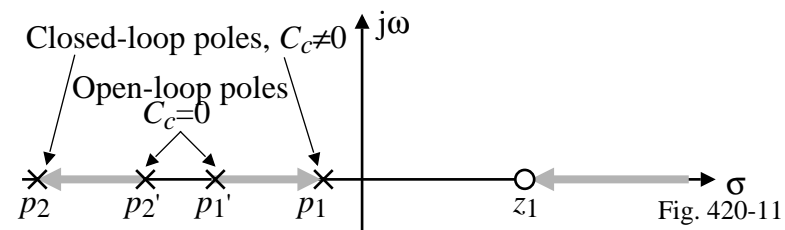
This root accomplishes the desired compensation.

3.) Left-half plane output pole:

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

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

Root locus plot of the Miller compensation:



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

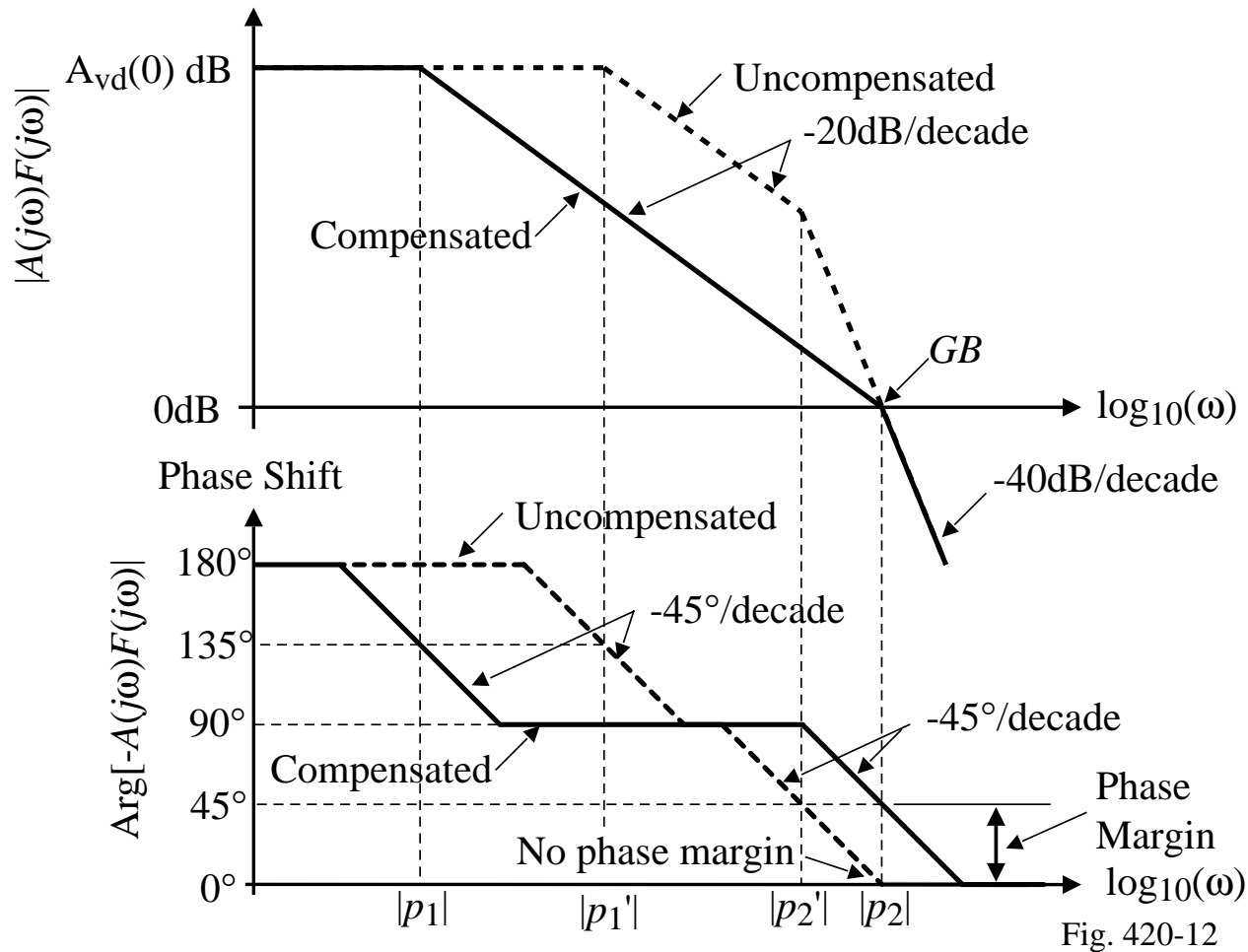


Fig. 420-12

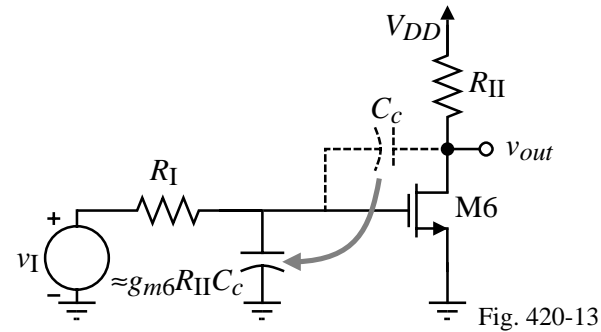
Note that the unity-gainbandwidth, GB , is

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

Conceptually, where do these roots come from?

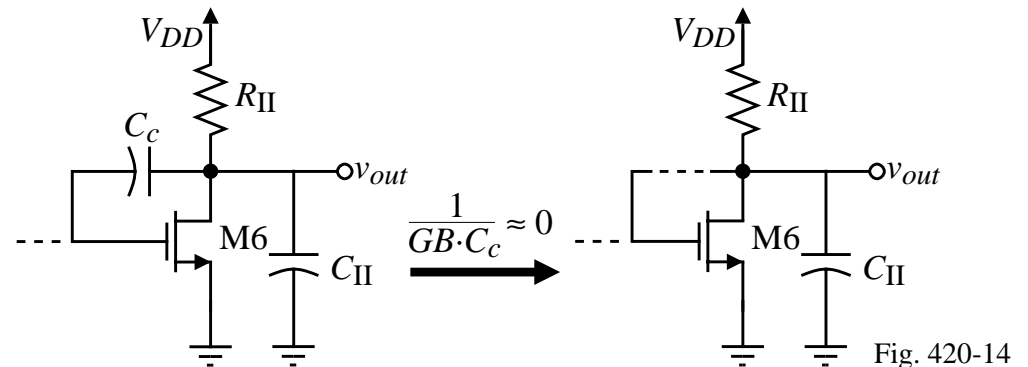
1.) The Miller pole:

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



2.) The left-half plane output pole:

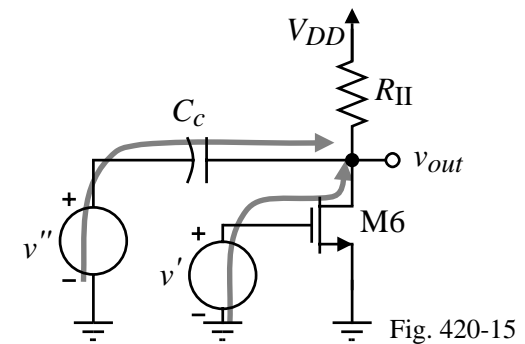
$$|p_2| \approx \frac{g_{m6}}{C_{II}}$$



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 $v = v' = v''$.



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

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

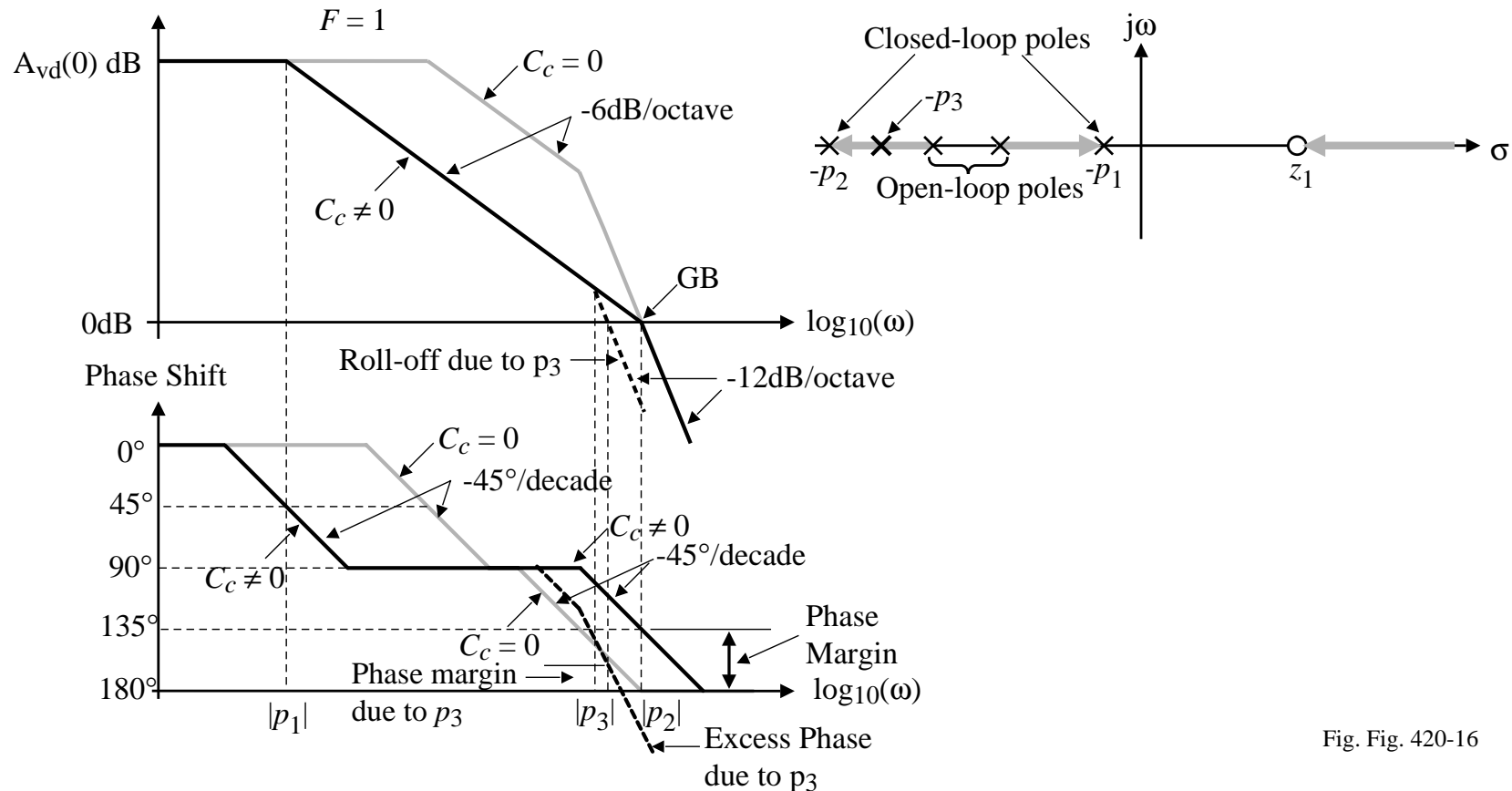


Fig. Fig. 420-16

SUMMARY

Compensation

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