LECTURE 180 – POWER SUPPLY REJECTION RATIO
(READING: GHLM – 434-439, AH – 286-293)

Objective

The objective of this presentation is:

1.) Illustrate the calculation of PSRR

2.) Examine the PSRR of the two-stage, Miller compensated op amp

Outline

- Definition of PSRR
- Calculation of PSRR for the two-stage op amp
- Conceptual reason for PSRR
- Summary

What is *PSRR*?

$$PSRR = \frac{A_v(V_{dd}=0)}{A_{dd}(V_{in}=0)}$$

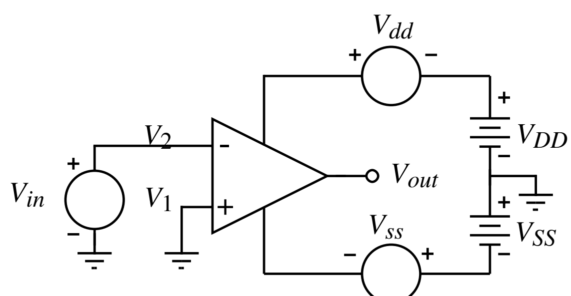

Fig.180-01

How do you calculate *PSRR*?

You could calculate A_v and A_{dd} and divide, however

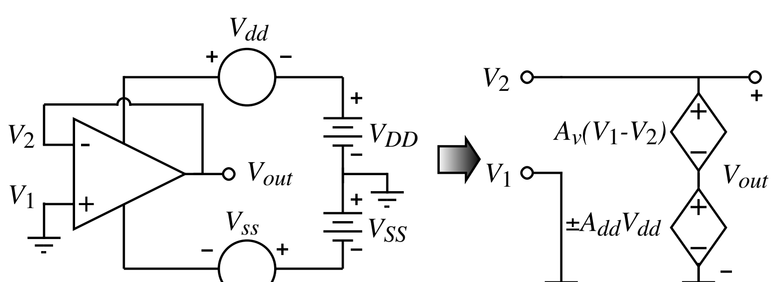

Fig. 180-02

$$V_{out} = A_{dd}V_{dd} + A_v(V_1 - V_2) = A_{dd}V_{dd} - A_vV_{out} \quad \rightarrow \quad V_{out}(1+A_v) = A_{dd}V_{dd}$$

$$\therefore \frac{V_{out}}{V_{dd}} = \frac{A_{dd}}{1+A_v} \approx \frac{A_{dd}}{A_v} = \frac{1}{PSRR^+} \quad \text{(Good for frequencies up to } GB\text{)}$$

Positive *PSRR* of the Two-Stage Op Amp

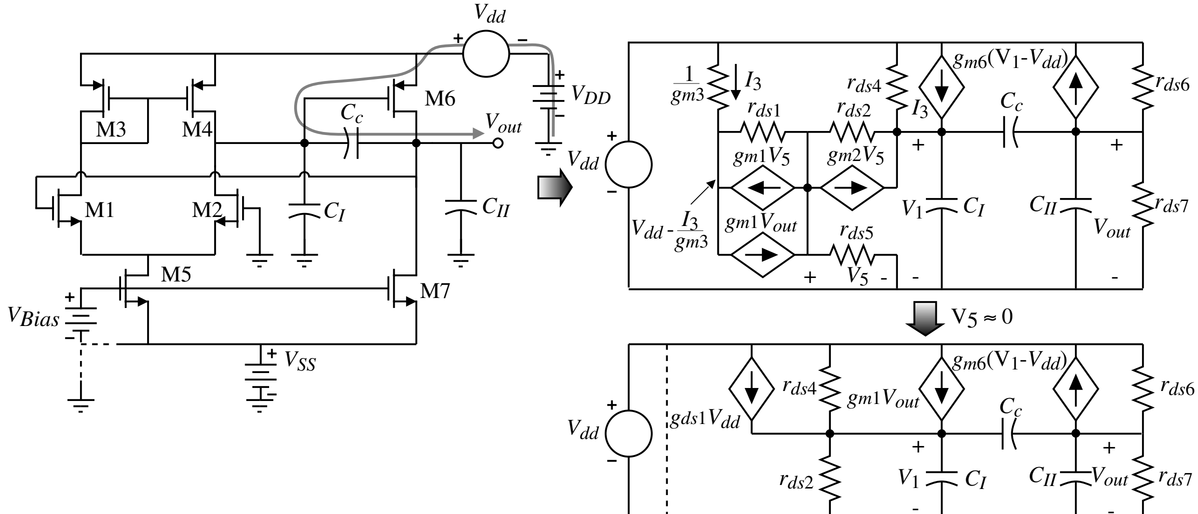

Fig. 180-03

The nodal equations are:

$$(g_{ds1} + g_{ds4})V_{dd} = (g_{ds2} + g_{ds4} + sC_c + sC_I)V_1 - (g_{m1} + sC_c)V_{out}$$

$$(g_{m6} + g_{ds6})V_{dd} = (g_{m6} - sC_c)V_1 + (g_{ds6} + g_{ds7} + sC_c + sC_{II})V_{out}$$

Using the generic notation the nodal equations are:

$$G_IV_{dd} = (G_I + sC_c + sC_I)V_1 - (g_{mI} + sC_c)V_{out}$$

$$(g_{mII} + g_{ds6})V_{dd} = (g_{mII} - sC_c)V_1 + (G_{II} + sC_c + sC_{II})V_{out}$$

where $G_I = g_{ds1} + g_{ds4} = g_{ds2} + g_{ds4}$, $G_{II} = g_{ds6} + g_{ds7}$, $g_{mI} = g_{m1} = g_{m2}$ and $g_{mII} = g_{m6}$

Positive *PSRR* of the Two-Stage Op Amp - Continued

Using Cramer's rule to solve for the transfer function, V_{out}/V_{dd}, and inverting the transfer function gives the following result.

$$\frac{V_{dd}}{V_{out}} = \frac{s^2[C_cC_I+C_IC_{II} + C_{II}C_c]+ s[G_I(C_c+C_{II}) + G_{II}(C_c+C_I) + C_c(g_{mII} - g_{mI})] + G_IG_{II}+g_{mI}g_{mII}}{s[C_c(g_{mII}+G_I+g_{ds6}) + C_I(g_{mII} + g_{ds6})] + G_Ig_{ds6}}$$

We may solve for the approximate roots of numerator as

$$PSRR+ = \frac{V_{dd}}{V_{out}} \cong \left(\frac{g_{mI}g_{mII}}{G_Ig_{ds6}}\right)\left[\frac{\left(\frac{sC_c}{g_{mI}} + 1\right)\left(\frac{s(C_cC_I+C_IC_{II}+C_cC_{II})}{g_{mII}\,C_c} + 1\right)}{\left(\frac{sg_{mII}C_c}{G_Ig_{ds6}} + 1\right)}\right]$$

where $g_{mII} > g_{mI}$ and that all transconductances are larger than the channel conductances.

$$\therefore \quad PSRR+ = \frac{V_{dd}}{V_{out}} = \left(\frac{g_{mI}g_{mII}}{G_Ig_{ds6}}\right)\left[\frac{\left(\frac{sC_c}{g_{mI}} + 1\right)\left(\frac{sC_{II}}{g_{mII}} + 1\right)}{\frac{sg_{mII}C_c}{G_Ig_{ds6}} + 1}\right] = \left(\frac{G_{II}A_{vo}}{g_{ds6}}\right)\frac{\left(\frac{s}{GB} + 1\right)\left(\frac{s}{|p_2|} + 1\right)}{\left(\frac{sG_{II}A_{vo}}{g_{ds6}GB} + 1\right)}$$

Positive *PSRR* of the Two-Stage Op Amp - Continued

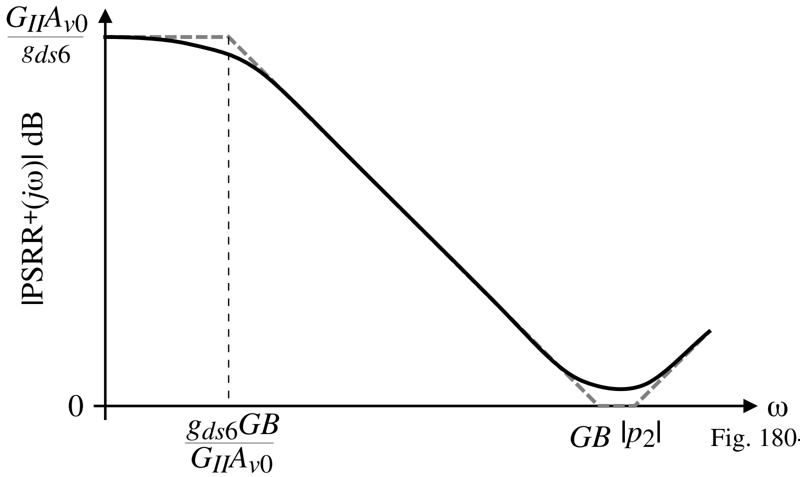

Fig. 180-04

At approximately the dominant pole, the *PSRR* falls off with a -20dB/decade slope and degrades the higher frequency $PSRR^+$ of the two-stage op amp.

Using the values of Example 6.3-1 we get:

$PSRR^+(0) = 68.8\text{dB}$, $z_1 = -5\text{MHz}$, $z_2 = -15\text{MHz}$ and $p_1 = -906\text{Hz}$

Concept of the $PSRR^+$ for the Two-Stage Op Amp

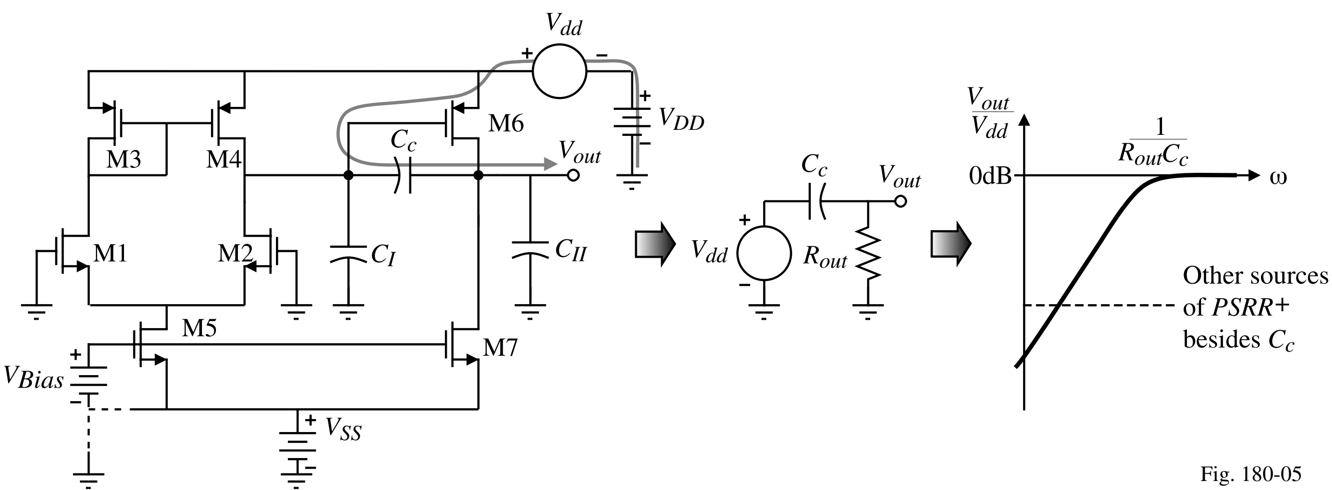

Fig. 180-05

1.) The M7 current sink causes V_{SG6} to act like a battery.
2.) Therefore, V_{dd} couples from the source to gate of M6.
3.) The path to the output is through any capacitance from gate to drain of M6.

Conclusion:

The Miller capacitor C_c couples the positive power supply ripple directly to the output. Must reduce or eliminate C_c.

Negative *PSRR* of the Two-Stage Op Amp with V_{Bias} Grounded

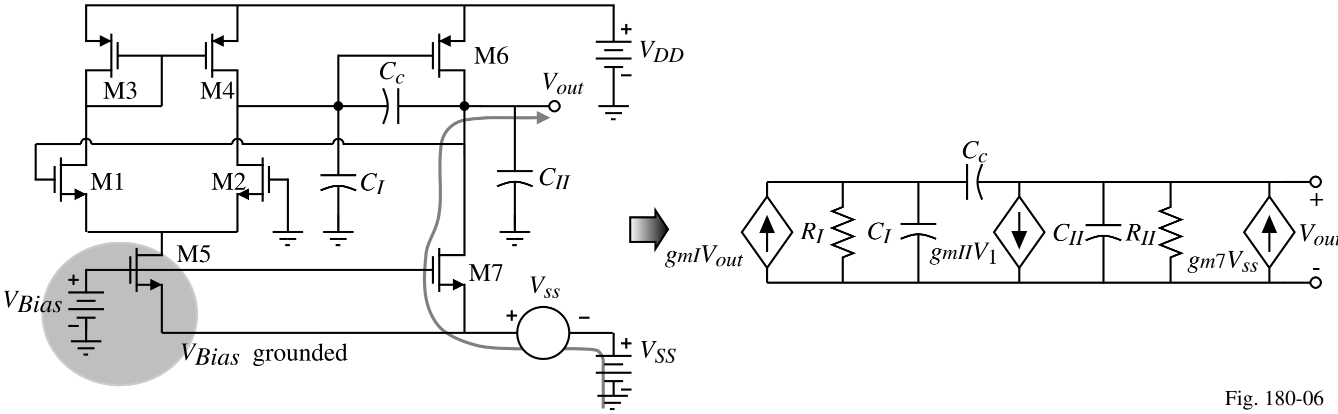

Fig. 180-06

Nodal equations for V_{Bias} grounded:

$$0 = (G_I + sC_c + sC_I)V_1 - (g_{mI} + sC_c)V_o$$

$$g_{m7}V_{ss} = (g_{MII} - sC_c)V_1 + (G_{II} + sC_c + sC_{II})V_o$$

Solving for V_{out}/V_{ss} and inverting gives

$$\frac{V_{ss}}{V_{out}} = \frac{s^2[C_cC_I + C_IC_{II} + C_{II}C_c] + s[G_I(C_c+C_{II}) + G_{II}(C_c+C_I) + C_c(g_{mII} - g_{mI})] + G_IG_{II} + g_{mI}g_{mII}}{[s(C_c+C_I)+G_I]g_{m7}}$$

Negative *PSRR* of the Two-Stage Op Amp with V_{Bias} Grounded - Continued

Again using techniques described previously, we may solve for the approximate roots as

$$PSRR^- = \frac{V_{ss}}{V_{out}} \cong \left(\frac{g_{mI}g_{mII}}{G_Ig_{m7}}\right)\left[\frac{\left(\frac{sC_c}{g_{mI}} + 1\right)\left(\frac{s(C_cC_I + C_IC_{II} + C_cC_{II})}{g_{mII}\,C_c} + 1\right)}{\left(\frac{s(C_c+C_I)}{G_I} + 1\right)}\right]$$

This equation can be rewritten approximately as

$$PSRR^- = \frac{V_{ss}}{V_{out}} \cong \left(\frac{g_{mI}g_{mII}}{G_Ig_{m7}}\right)\left[\frac{\left(\frac{sC_c}{g_{mI}} + 1\right)\left(\frac{sC_{II}}{g_{mII}} + 1\right)}{\left(\frac{sC_c}{G_I} + 1\right)}\right] = \left(\frac{G_{II}A_{v0}}{g_{m7}}\right)\left[\frac{\left(\frac{s}{GB} + 1\right)\left(\frac{s}{|p_2|} + 1\right)}{\left(\frac{s}{GB}\frac{g_{mI}}{G_I} + 1\right)}\right]$$

Comments:

- $PSRR^-$ zeros = $PSRR^+$ zeros
- DC gain ≈ Second-stage gain,
- $PSRR^-$ pole ≈ (Second-stage gain) x ($PSRR^+$ pole)

Assuming the values of Ex. 6.3-1 gives a gain of 23.7 dB and a pole -147 kHz. The dc value of $PSRR^-$ is very poor for this case, however, this case can be avoided by correctly implementing V_{Bias} which we consider next.

Negative *PSRR* of the Two-Stage Op Amp with V_{Bias} Connected to V_{SS}

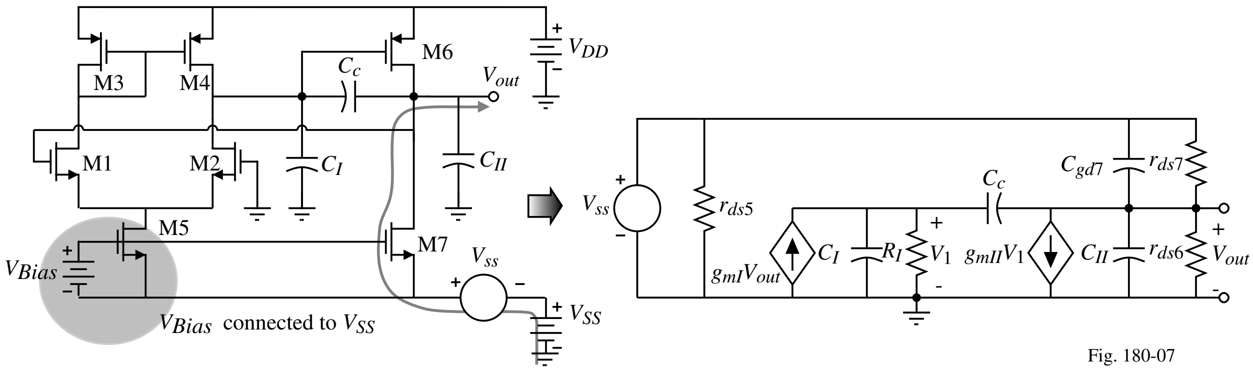

Fig. 180-07

If the value of V_{Bias} is independent of V_{ss}, then the model shown results. The nodal equations for this model are

$$0 = (G_I + sC_c + sC_I)V_1 - (g_{mI} + sC_c)V_{out}$$

and

$$(g_{ds7} + sC_{gd7})V_{ss} = (g_{mII} - sC_c)V_1 + (G_{II} + sC_c + sC_{II} + sC_{gd7})V_{out}$$

Again, solving for V_{out}/V_{ss} and inverting gives

$$\frac{V_{ss}}{V_{out}} = \frac{s^2[C_cC_I+C_IC_{II}+C_{II}C_c+C_IC_{gd7}+C_cC_{gd7}]+s[G_I(C_c+C_{II}+C_{gd7})+G_{II}(C_c+C_I)+C_c(g_{mII}-g_{mI})]+G_IG_{II}+g_{mI}g_{mII}}{(sC_{gd7}+g_{ds7})(s(C_I+C_c)+G_I)}$$

Negative *PSRR* of the Two-Stage Op Amp with V_{Bias} Connected to V_{SS} - Continued

Assuming that $g_{mII} > g_{mI}$ and solving for the approximate roots of both the numerator and denominator gives

$$PSRR^- = \frac{V_{ss}}{V_{out}} \cong \left(\frac{g_{mI}g_{mII}}{G_Ig_{ds7}}\right)\left[\frac{\left(\frac{sC_c}{g_{mI}}+1\right)\left(\frac{s(C_cC_I+C_IC_{II}+C_cC_{II})}{g_{mII}\,C_c}+1\right)}{\left(\frac{sC_{gd7}}{g_{ds7}}+1\right)\left(\frac{s(C_I+C_c)}{G_I}+1\right)}\right]$$

This equation can be rewritten as

$$PSRR^- = \frac{V_{ss}}{V_{out}} \approx \left(\frac{G_{II}A_{v0}}{g_{ds7}}\right)\left[\frac{\left(\frac{s}{GB}+1\right)\left(\frac{s}{|p_2|}+1\right)}{\left(\frac{sC_{gd7}}{g_{ds7}}+1\right)\left(\frac{sC_c}{G_I}+1\right)}\right]$$

Comments:

- DC gain has been increased by the ratio of G_{II} to g_{ds7}
- Two poles instead of one, however the pole at $-g_{ds7}/C_{gd7}$ is large and can be ignored.

Using the values of Ex. 6.3-1 and assume that C_{ds7} = 10fF, gives,

$PSRR^-(0)$ = 76.7dB and Poles at -71.2kHz and -149MHz

Frequency Response of the Negative *PSRR* of the Two-Stage Op Amp with V_{Bias} Connected to V_{SS}

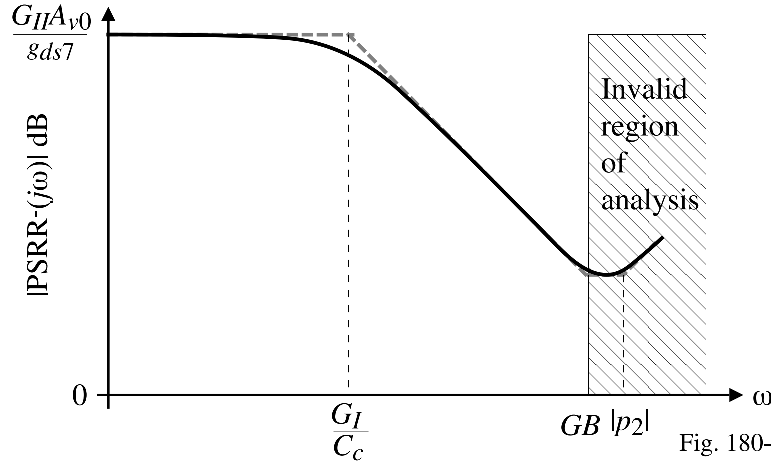

Fig. 180-08

Approximate Model for Negative *PSRR* with V_{Bias} Connected to Ground

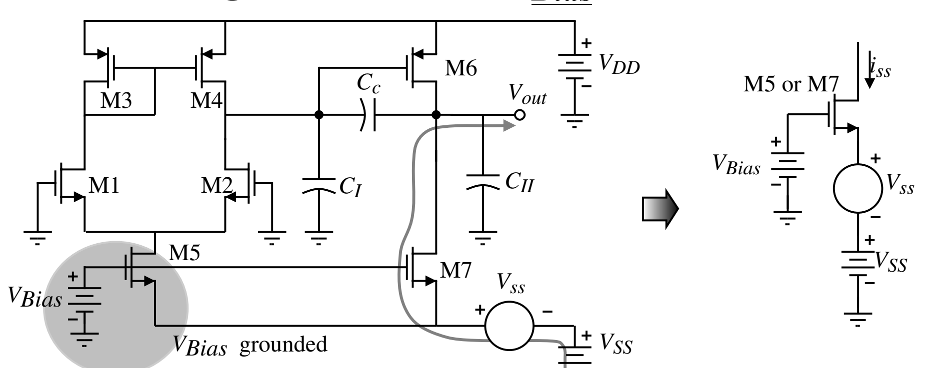

Fig. 180-09

Path through the input stage is not important as long as the *CMRR* is high.

Path through the output stage:

$$v_{out} \approx i_{ss}Z_{out} = g_{m7}Z_{out}V_{ss}$$

$$\therefore \quad \frac{V_{out}}{V_{ss}} = g_{m7}Z_{out} = g_{m7}R_{out}\left(\frac{1}{sR_{out}C_{out}+1}\right)$$

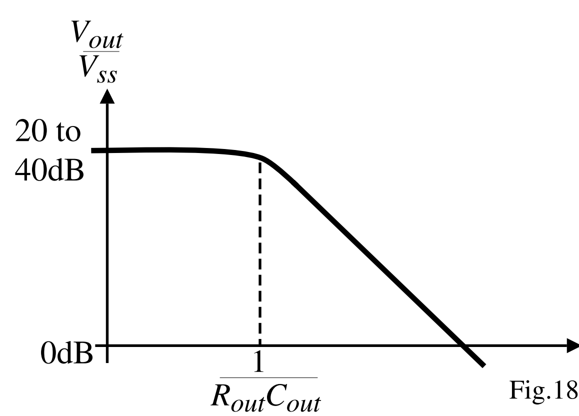

Fig.180-10

Approximate Model for Negative *PSRR* with V_{Bias} Connected to V_{SS}

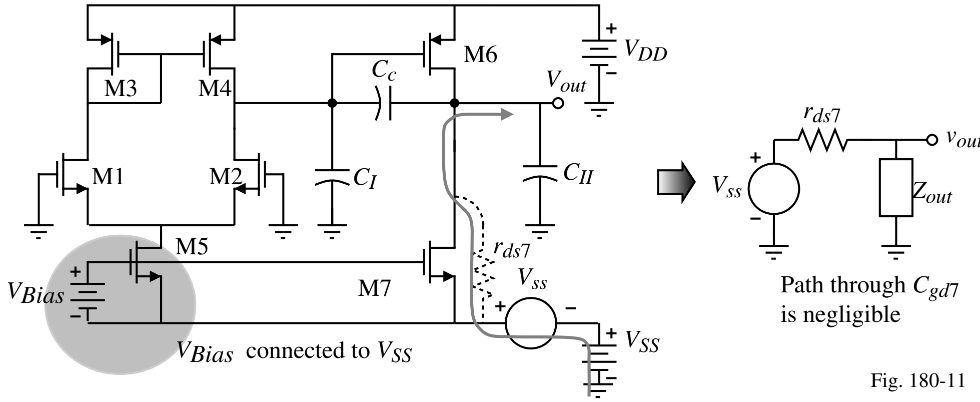

Fig. 180-11

What is Z_{out}?

$$Z_{out} = \frac{V_t}{I_t} \Rightarrow$$

$$I_t = g_{mII}V_1 = g_{mII}\left(\frac{g_{mI}V_t}{G_I+sC_I+sC_c}\right)$$

Thus, $$Z_{out} = \frac{G_I+s(C_I+C_c)}{g_{mI}g_{mII}}$$

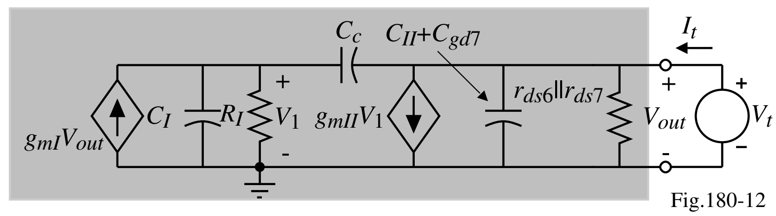

Fig.180-12

$$\therefore \quad \frac{V_{ss}}{V_{out}} = \frac{1+\frac{r_{ds7}}{Z_{out}}}{1} = \frac{s(C_c+C_I) + G_I+g_{mI}g_{mII}r_{ds7}}{s(C_c+C_I) + G_I} \quad \Rightarrow \quad \text{Pole at } \frac{-G_I}{C_c+C_I}$$

The two-stage op amp will never have good *PSRR* because of the Miller compensation.

SUMMARY

- PSRR is a measure of the influence of power supply ripple on the op amp output voltage
- PSRR can be calculated by putting the op amp in the unity-gain configuration with the input shorted.
- The Miller compensation capacitor allows the power supply ripple at the output to be large
- The two-stage op amp will never have good PSRR unless some modifications are made.

