LECTURE 200 – CASCODE OP AMPS II
(READING: GHLM – 443-453, AH – 293-309)

Objective

The objective of this presentation is:

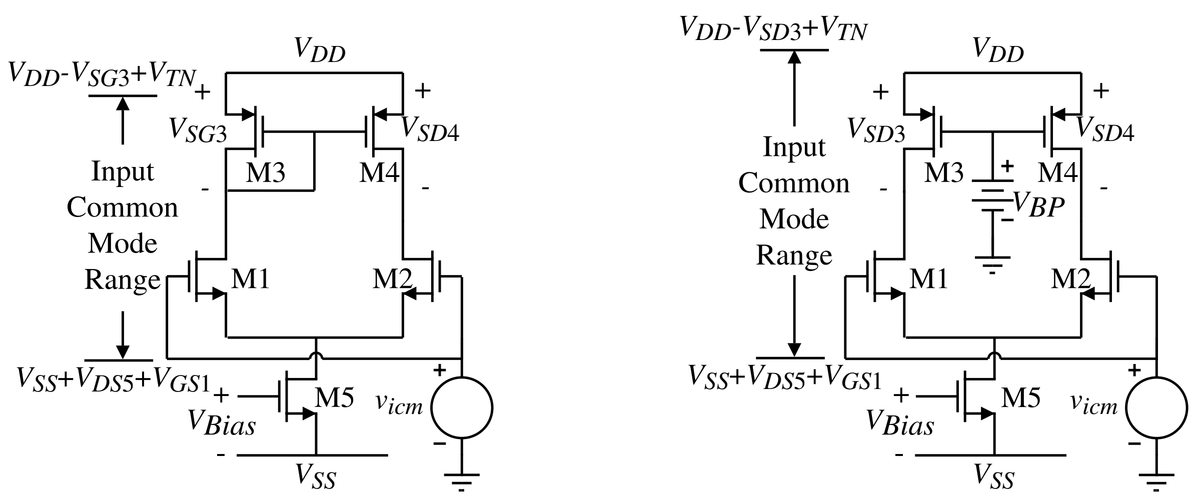
1.) Develop cascode op amp architectures

2.) Show how to design with the cascode op amps

Outline

- Op amps with cascoding in the first stage
- Op amps with cascoding in the second stage
- Folded cascode op amp
- Summary

Input Common Mode Range for Two Types of Differential Amplifier Loads



Differential amplifier with a current mirror load.

Differential amplifier with current source loads. Fig. 200-01

In order to improve the ICMR, it is desirable to use current source (sink) loads without losing half the gain.

The resulting solution is the *folded* cascode op amp.

The Folded Cascode Op Amp

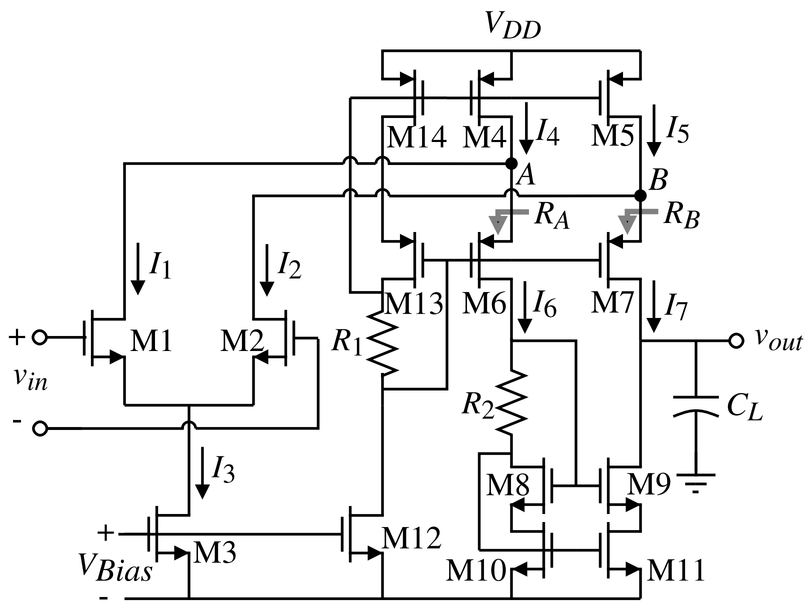


Fig. 200-02

We have examined the small signal performance and the frequency response in an earlier lecture.

PSRR of the Folded Cascode Op Amp

Consider the following circuit used to model the $PSRR^-$:

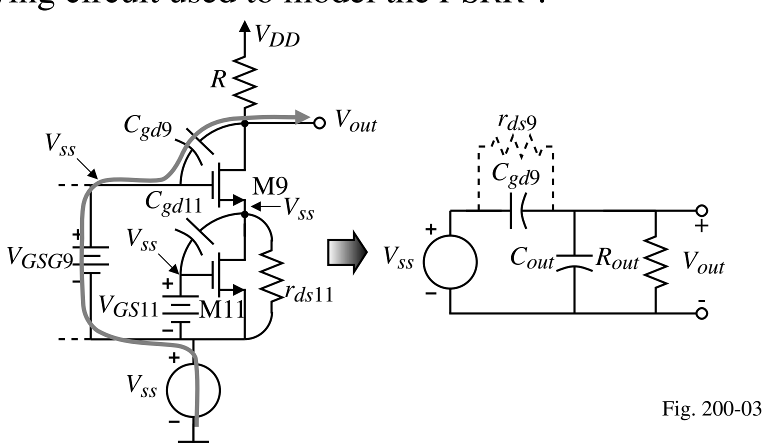


Fig. 200-03

This model assumes that gate, source and drain of M11 and the gate and source of M9 all vary with V_{SS}.

We shall examine V_{out}/V_{ss} rather than $PSRR^-$. (Small V_{out}/V_{ss} will lead to large $PSRR^-$.)

The transfer function of V_{out}/V_{ss} can be found as

$$\frac{V_{out}}{V_{ss}} \approx \frac{sC_{gd9}R_{out}}{sC_{out}R_{out}+1} \quad \text{for } C_{gd9} < C_{out}$$

The approximate PSRR$^-$ is sketched on the next page.

Frequency Response of the PSRR⁻ of the Folded Cascode Op Amp

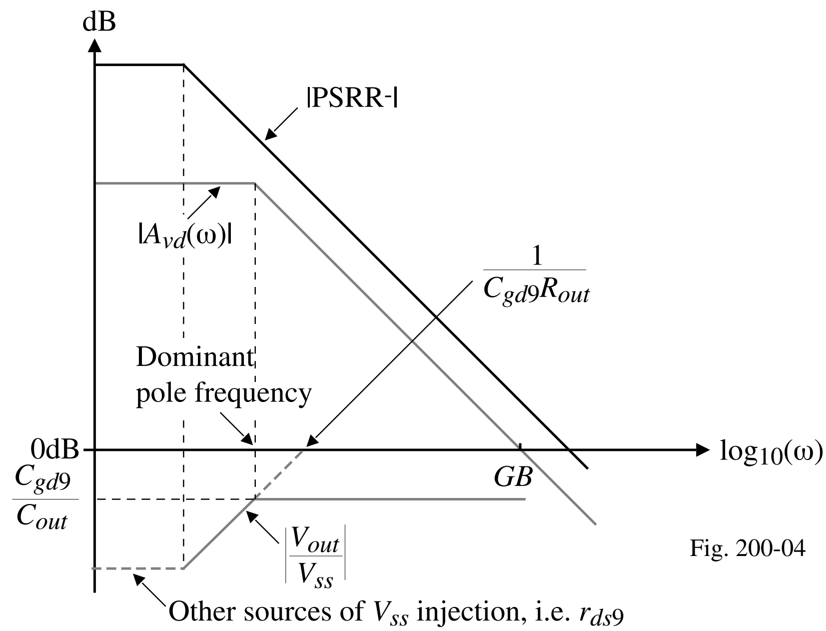


Fig. 200-04

We see that the PSRR of the cascode op amp is much better than the two-stage op amp.

Design Approach for the Folded-Cascode Op Amp

Step	Relationship/ Requirement	Design Equation/Constraint	Comments
1	Slew Rate	$I_3 = SR\cdot C_L$	
2	Bias currents in output cascodes	$I_4 = I_5 = 1.2I_3$ to $1.5I_3$	Avoid zero current in cascodes
3	Maximum output voltage, v_{out}(max)	$S_5=\frac{8I_5}{K_P' V_{SD5}^2}$, $S_7=\frac{8I_7}{K_P' V_{SD7}^2}$ Let $S_4=S_{14}=S_5$ & $S_{13}=S_6=S_7$	$V_{SD5}(sat) = V_{SD7}(sat) = 0.5[V_{DD}-V_{out}(min)]$
4	Minimum output voltage, v_{out}(min)	$S_{11}=\frac{8I_{11}}{K_N' V_{DS11}^2}$, $S_9 = \frac{8I_9}{K_N' V_{DS9}^2}$ Let $S_{10}=S_{11}$ & $S_8=S_9$	$V_{DS9}(sat) = V_{DS11}(sat) = 0.5(V_{out}(min)-\|V_{SS}\|)$
5	Self-bias cascode	$R_1 = V_{SD14}(sat)/I_{14}$ and $R_2 = V_{DS8}(sat)/I_6$	
6	$GB = \frac{g_{m1}}{C_L}$	$S_1=S_2=\frac{g_{m1}^2}{K_N' I_3}=\frac{GB^2 C_L^2}{K_N' I_3}$	
7	Minimum input CM	$S_3 = \frac{2I_3}{K_N'\left(V_{in}(min)-V_{SS}-\sqrt{\frac{I_3}{K_N' S_1}}-V_{T1}\right)^2}$	
8	Maximum input CM	$S_4 = S_5 = \frac{2I_4}{K_P'(V_{DD}-V_{in}(max)+V_{T1})^2}$	S_4 and S_5 must meet or exceed the value in step 3
9	Differential Voltage Gain	$\frac{v_{out}}{v_{in}} = \left(\frac{g_{m1}}{2}+\frac{g_{m2}}{2(1+k)}\right)R_{out} = \left(\frac{2+k}{2+2k}\right) g_{mI}R_{out}$	
10	Power dissipation	$P_{diss} = (V_{DD}-V_{SS})(I_3+I_{12}+I_{10}+I_{11})$	

Example 3 - Design of a Folded-Cascode Op Amp

Follow the procedure given to design the folded-cascode op amp when the slew rate is 10V/µs, the load capacitor is 10pF, the maximum and minimum output voltages are ±2V for ±2.5V power supplies, the *GB* is 10MHz, the minimum input common mode voltage is -1.5V and the maximum input common mode voltage is 2.5V. The differential voltage gain should be greater than 5,000V/V and the power dissipation should be less than 5mW. Use channel lengths of 1µm.

Solution

Following the approach outlined above we obtain the following results.

$$I_3 = SR\cdot C_L = 10\text{x}10^6\cdot 10^{-11} = 100\mu\text{A}$$

Select $I_4 = I_5 = 125\mu$A.

Next, we see that the value of $0.5(V_{DD}\text{-}V_{out}(\text{max}))$ is 0.5V/2 or 0.25V. Thus,

$$S_4 = S_5 = S_{14} = \frac{2\cdot 125\mu\text{A}}{50\mu\text{A/V}^2\cdot(0.25\text{V})^2} = \frac{2\cdot 125\cdot 16}{50} = 80$$

and assuming worst case currents in M6 and M7 gives,

$$S_6 = S_7 = S_{13} = \frac{2\cdot 125\mu\text{A}}{50\mu\text{A/V}^2(0.25\text{V})^2} = \frac{2\cdot 125\cdot 16}{50} = 80$$

The value of $0.5(V_{out}(\text{min})\text{-}|V_{SS}|)$ is also 0.25V which gives the value of S_8, S_9, S_{10} and S_{11} as

$$S_8 = S_9 = S_{10} = S_{11} = \frac{2\cdot I_8}{K_N' V_{DS8}{}^2} = \frac{2\cdot 125}{110\cdot(0.25)^2} = 36.36$$

Example 3 - Continued

The value of R_1 and R_2 is equal to 0.25V/125µA or 2kΩ. In step 6, the value of *GB* gives S_1 and S_2 as

$$S_1 = S_2 = \frac{GB^2\cdot C_L{}^2}{K_N' I_3} = \frac{(20\pi\text{x}10^6)^2(10^{-11})^2}{110\text{x}10^{-6}\cdot 100\text{x}10^{-6}} = 35.9$$

The minimum input common mode voltage defines S_3 as

$$S_3 = \frac{2I_3}{K_N'\left(V_{in}(\text{min})\text{-}V_{SS}\text{-}\sqrt{\frac{I_3}{K_N' S_1}} - V_{T1}\right)^2} = \frac{200\text{x}10^{-6}}{110\text{x}10^{-6}\left(-1.5+2.5-\sqrt{\frac{100}{110\cdot 35.9}}-0.75\right)^2} = 20$$

We need to check that the values of S_4 and S_5 are large enough to satisfy the maximum input common mode voltage. The maximum input common mode voltage of 2.5 requires

$$S_4 = S_5 \geq \frac{2I_4}{K_P'[V_{DD}\text{-}V_{in}(\text{max})+V_{T1}]^2} = \frac{2\cdot 125\mu\text{A}}{50\text{x}10^{-6}\mu\text{A/V}^2[0.7\text{V}]^2} = 10.2$$

which is much less than 80. In fact, with $S_4 = S_5 = 80$, the maximum input common mode voltage is 3V. Finally, S_{12}, is given as

$$S_{12} = \frac{125}{100} S_3 = 25$$

The power dissipation is found to be

$$P_{diss} = 5\text{V}(125\mu\text{A}+125\mu\text{A}+125\mu\text{A}) = 1.875\text{mW}$$

Example 3 - Continued

The small-signal voltage gain requires the following values to evaluate:

S_4, S_5, S_{13}, S_{14}: $g_m = \sqrt{2\cdot125\cdot50\cdot80} = 1000\mu S$ and $g_{ds} = 125\text{x}10^{-6}\cdot0.05 = 6.25\mu S$

S_6, S_7: $g_m = \sqrt{2\cdot75\cdot50\cdot80} = 774.6\mu S$ and $g_{ds} = 75\text{x}10^{-6}\cdot0.05 = 3.75\mu S$

S_8, S_9, S_{10}, S_{11}: $g_m = \sqrt{2\cdot75\cdot110\cdot36.36} = 774.6\mu S$ and $g_{ds} = 75\text{x}10^{-6}\cdot0.04 = 3\mu S$

S_1, S_2: $g_{mI} = \sqrt{2\cdot50\cdot110\cdot35.9} = 628\mu S$ and $g_{ds} = 50\text{x}10^{-6}(0.04) = 2\mu S$

Thus,

$$R_{II} \approx g_{m9}r_{ds9}r_{ds11} = (774.6\mu S)\left(\frac{1}{3\mu S}\right)\left(\frac{1}{3\mu S}\right) = 86.07M\Omega$$

$$R_{out} \approx 86.07M\Omega || (774.6\mu S)\left(\frac{1}{3.75\mu S}\right)\left(\frac{1}{2\mu S+6.25\mu S}\right) = 19.40M\Omega$$

$$k = \frac{R_{II}(g_{ds2}+g_{ds4})}{g_{m7}r_{ds7}} = \frac{86.07M\Omega(2\mu S+6.25\mu S)(3.75\mu S)}{774.6\mu S} = 3.4375$$

The small-signal, differential-input, voltage gain is

$$A_{vd} = \left(\frac{2+k}{2+2k}\right) g_{mI}R_{out} = \left(\frac{2+3.4375}{2+6.875}\right) 0.628\text{x}10^{-3}\cdot19.40\text{x}10^{6} = 7{,}464 \text{ V/V}$$

The gain is larger than required by the specifications which should be okay.

Comments on Folded Cascode Op Amps

- Good PSRR
- Good ICMR
- Self compensated
- Can cascade an output stage to get extremely high gain with lower output resistance (use Miller compensation in this case)
- Need first stage gain for good noise performance
- Widely used in telecommunication circuits where large dynamic range is required

SUMMARY

- Cascode op amps offer an alternate architecture to the two-stage op amp
- The cascode op amp is typically self-compensating
- The cascode op amp generally has better PSRR