LECTURE 150 – SIMPLE BJT OP AMPS
(READING: Text-GHLM – 425-434, 453-454, AH – 249-253)

INTRODUCTION

The objective of this presentation is:

1.) Illustrate the analysis of BJT op amps

2.) Prepare for the design of BJT op amps

Outline

- Simple BJT Op Amps
  - Two-stage
  - Folded-cascode
- Summary

SIMPLE TWO-STAGE BJT OP AMPS

BJT Two-Stage Op Amp

Circuit:

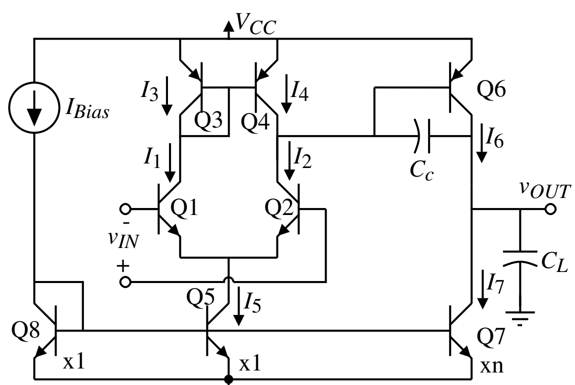


Fig. 150-01

DC Conditions:

$I_5 = I_{bias}$, $I_1 = I_2 = 0.5I_5 = 0.5I_{bias}$, $I_7 = I_6 = nI_{Bias}$

$V_{icm}(\text{max}) = V_{CC} - V_{EB3} - V_{CE1}(\text{sat}) + V_{BE1}$

$V_{icm}(\text{min}) = V_{EE} + V_{CE5}(\text{sat}) + V_{BE1}$

$V_{out}(\text{max}) = V_{CC} - V_{EC6}(\text{sat})$

$V_{out}(\text{min}) = V_{EE} + V_{CE7}(\text{sat})$

Notice that the output stage is class A $\Rightarrow$ $I_{sink} = I_7$ and $I_{source} = \beta_F I_5 - I_7$

Two-Stage BJT Op Amp - Continued

Small Signal Performance:

Assuming differential mode operation, we can write the small-signal model as,

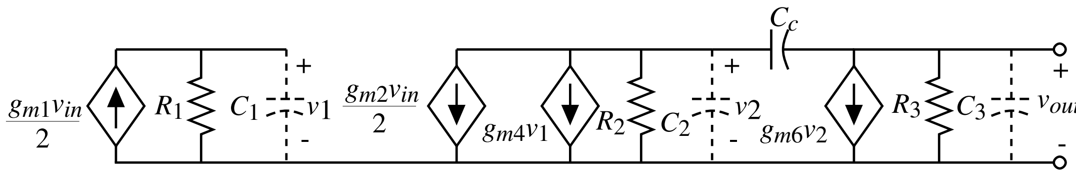


Fig. 150-02

where,

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

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

Note that we have ignored the base-collector capacitors, C_μ, except for M6, which is called C_c.

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

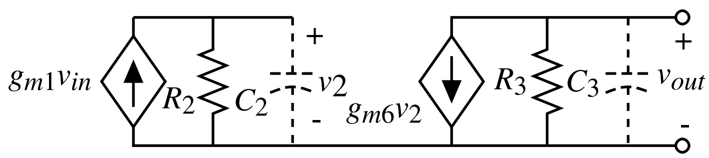


Fig. 150-03

Two-Stage BJT Op Amp - Continued

Summary of the small signal performance:

Midband performance-

$A_o = g_{mI}g_{mII}R_IR_{II} \approx g_{m1}g_{m6}r_{\pi 6}(r_{o6}||r_{o7}) = g_{m1}\beta_{F6}(r_{o6}||r_{o7})$, $R_{out} = r_{o6}||r_{o7}$, $R_{in} = 2r_{\pi 1}$

Roots-

$$\text{Zero} = \frac{g_{mII}}{C_c} = \frac{g_{m6}}{C_c}$$

Poles at $p_1 \approx \frac{-1}{g_{mII}R_IR_{II}C_c} = \frac{-1}{g_{m6}r_{\pi 6}(r_{o6}||r_{o7})C_c} = \frac{-g_{m1}}{A_oC_c}$ and $p_2 \approx \frac{-g_{mII}}{C_{II}} \approx \frac{-g_{m6}}{C_L}$

Assume that β_F =100, g_{m1}=1mS, g_{m6} =10mS, r_{o6}=r_{o7}=0.5MΩ, C_c=5pF and C_L=10pF:

A_o=(1mS)(100)(250kΩ)=25,000V/V, R_{in} 2(β_F/g_{m1})2(100kΩ)=200kΩ, R_{out}=250kΩ

$$\text{Zero} = \frac{10\text{mS}}{5\text{pF}} = 2\text{x}10^9 \text{ rads/sec}$$

or 318.3MHz,

$$p_1 = \frac{-1\text{mS}}{(25{,}000)5\text{pF}} = \frac{-2\text{x}10^8}{25{,}000}$$

= -8000 rads/sec or 1273Hz,

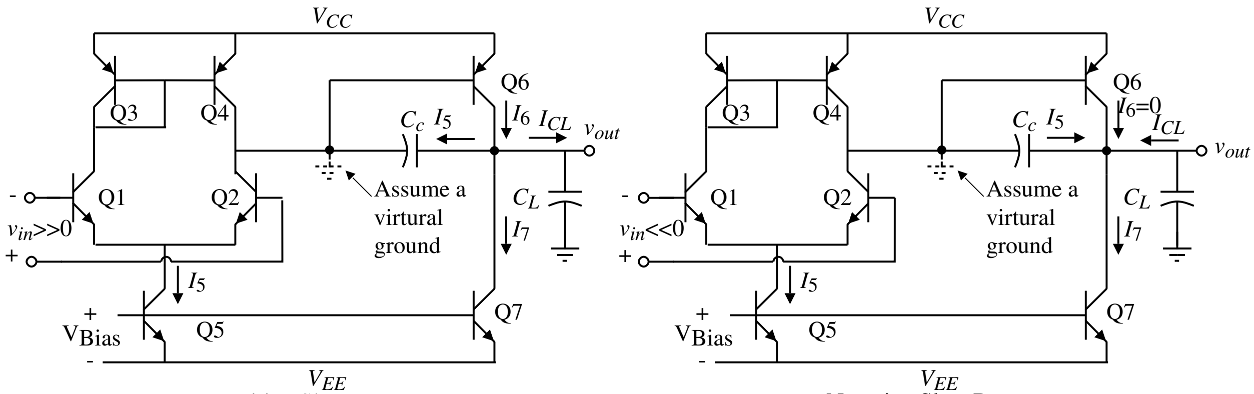
and p_2 = -10mS/10pF = -10^9 rads/sec or 159.15MHz

Fig. 150-04

Slew Rate of the Two-Stage BJT Op Amp

Remember that slew rate occurs when currents flowing in a capacitor become limited and is given as

$$I_{lim} = C\frac{dv_C}{dt} \text{ where } v_C \text{ is the voltage across the capacitor } C.$$



Positive Slew Rate

Negative Slew Rate

Fig. 150-05

$$SR^{+} = \min\left[\frac{I_5}{C_c}, \frac{I_6-I_5-I_7}{C_L}\right] = \frac{I_5}{C_c} \text{ because } I_6>>I_5 \qquad SR^{-} = \min\left[\frac{I_5}{C_c}, \frac{I_7-I_5}{C_L}\right] = \frac{I_5}{C_c} \text{ if } I_7>>I_5.$$

Therefore, if C_L is not too large and if I_7 is significantly greater than I_5, then the slew rate of the two-stage op amp should be,

$$SR = \frac{I_5}{C_c}$$

Folded-Cascode BJT Op Amp

Circuit

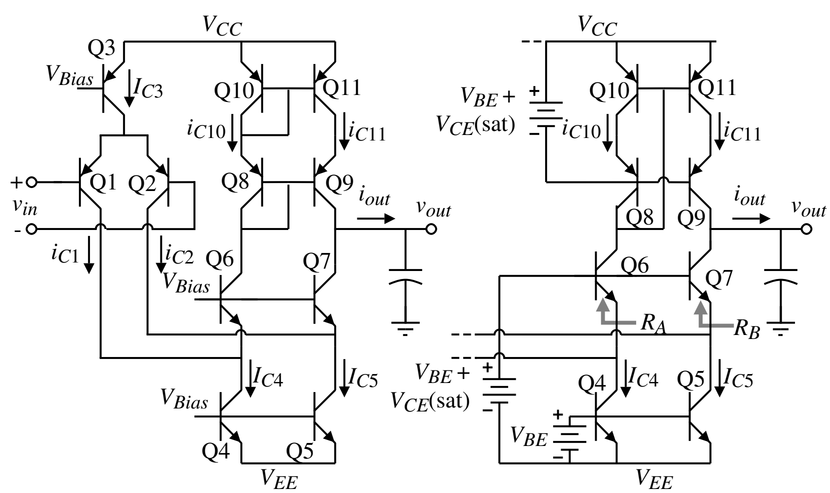


Fig. 150-06 Simplified circuit Biasing details of the output

DC Conditions:

$I_3 = I_{bias}$, $I_1 = I_2 = 0.5I_5 = 0.5I_{bias}$, $I_4 = I_5 = kI_{Bias}$, $I_{10} = I_{11} = kI_{Bias}\text{-}0.5I_{bias}$ $(k>1)$

$V_{icm}(\max) = V_{CC}\text{-}V_{CE3}(\text{sat})+V_{EB1}$ $\qquad V_{icm}(\min) = V_{EE}+V_{CE4}(\text{sat})+V_{EC1}(\text{sat})\text{-}V_{BE1}$

$V_{out}(\max) = V_{CC}\text{-}V_{EC9}(\text{sat})\text{-}V_{EC11}(\text{sat})$ $\qquad V_{out}(\min) = V_{EE}+V_{CE5}(\text{sat})+V_{CE7}(\text{sat})$

Notice that the output stage is push-pull ⇒ I_{sink} and I_{source} are limited by the base current.

Folded-Cascode BJT Op Amp - Continued

Small-Signal Analysis:

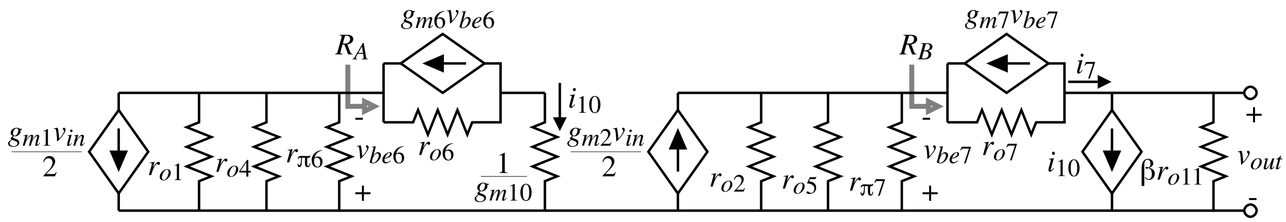


Fig. 150-07

where $R_A \approx 1/g_{m6}$ and $R_B \approx \dfrac{r_{o7}+\beta_P r_{o11}/2}{1+g_{m7}r_{o7}} \approx \dfrac{r_{\pi 7}}{2}$ if $r_{o7} \approx r_{o11}$

$$i_{10} \approx \frac{-g_{m1}r_{\pi 6}v_{in}}{2(r_{\pi 6}+R_A)} \approx \frac{-g_{m1}v_{in}}{2} \qquad i_7 \approx \frac{g_{m2}r_{\pi 7}v_{in}}{2(r_{\pi 7}+R_B)} \approx \frac{g_{m2}r_{\pi 7}v_{in}}{2(r_{\pi 7}+0.5r_{\pi 7})} = \frac{g_{m2}v_{in}}{3}$$

$\therefore \quad v_{out} = (i_7 - i_{10})R_{out}v_{in} = \dfrac{5}{6}(g_{m1}R_{out})v_{in}$ if $g_{m1} = g_{m2} \Rightarrow \dfrac{v_{out}}{v_{in}} = \dfrac{5}{6}(g_{m1}R_{out})$

$R_{out} = \beta_P r_{o11} || [\beta_N(r_{o5}||r_{o2})]$ and $R_{in} = 2r_{\pi 1}$

Assume that β_{FN} =100, β_{FP} =50, $g_{m1} = g_{m2}$ =1mS, r_{oN} = 1MΩ, and r_{oP} = 0. 5MΩ:

$\dfrac{v_{out}}{v_{in}}$ = 14,285V/V $\qquad R_{out}$ = 14.285 MΩ $\qquad$ and R_{in} = 100kΩ

Folded-Cascode BJT Op Amp - Continued

Frequency response includes only 1 dominant pole at the output (self-compensation),

$$p_1 = \frac{-1}{R_{out}\,C_L}$$

There are other poles but we shall assume that they are less than *GB*

If C_L = 25pF, then $|p_1|$ = 2800 rads/sec. or 446Hz ⇒ *GB* = 6.371 MHz

Checking some of the nondominant poles gives:

$$|p_A| = \frac{1}{R_A C_A} = \frac{g_{m6}}{C_A} \Rightarrow \text{159MHz if } C_A = 1\text{pf}$$

(the capacitance to ac ground at the emitter of Q6)

$|p_B| = \dfrac{1}{R_B C_B} = \dfrac{2}{r_{\pi 7}C_B} \Rightarrow$ 6.37MHz if C_B = 1pf (the capacitance to ac ground at the emitter of Q7)

This indicates that for small capacitive loads, this op amp will suffer from higher poles with respect to phase margin. Capacitive loads greater than 25pF, will have better stability (and less *GB*).

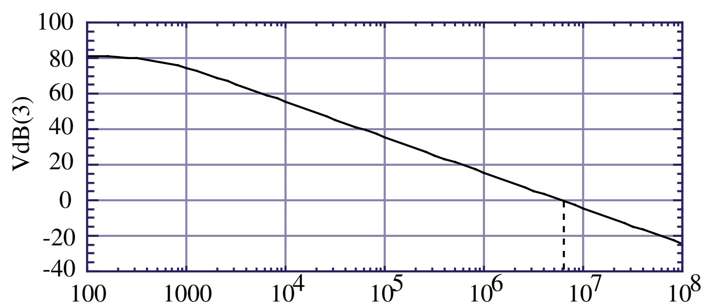


Fig. 150-08

SUMMARY

- Two stage op amp gives reasonably robust performance as an “on-chip” op amp
- DC balance conditions insure proper mirroring and all transistors in saturation
- Slew rate of the two-stage op amp is I_5/C_c
- Folded cascode op amp offers wider input common voltage range
- Folded cascode op amp is a self-compensated op amp because the dominant pole at the output and proportional to the load capacitor