LECTURE 150 – SIMPLE BJT OP AMPS

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:

DC Conditions:
- $I_5 = I_{bias}$, $I_1 = I_2 = 0.5I_5 = 0.5I_{bias}$, $I_7 = I_6 = nI_{bias}$
- $V_{icm\text{(max)}} = V_{CC} - V_{EB3} - V_{CE1\text{(sat)}} + V_{BE1}$
- $V_{icm\text{(min)}} = V_{EE} + V_{CE5\text{(sat)}} + V_{BE1}$
- $V_{out\text{(max)}} = V_{CC} - V_{CE6\text{(sat)}}$
- $V_{out\text{(min)}} = V_{EE} + V_{CE7\text{(sat)}}$

Notice that the output stage is class A ⇒ $I_{sink} = I_7$ 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,

\[ v_{out} = g_{m1}v_{in} + g_{m2}v_{in} + g_{m3}v_{1} + g_{m4}v_{2} + g_{m5}v_{2} + g_{m6}v_{2} \]

where,

\[ R_1 = \frac{1}{g_m^3} || r_{\pi 3} || r_{\pi 4} || r_{\pi 3} = \frac{1}{g_m^3} \]

\[ R_2 = r_{\pi 6} || r_{\pi 2} || r_{\pi 4} = r_{\pi 6} \]

\[ R_3 = r_{\pi 6} || r_{\pi 7} \]

\[ C_1 = C_{\pi 3} + C_{\pi 4} + C_{cs1} + C_{cs3} \]

\[ C_2 = C_{\pi 6} + C_{cs2} + C_{cs4} \]

\[ C_3 = C_L + C_{cs6} + C_{cs7} \]

Note that we have ignored the base-collector capacitors, \( C_\mu \), 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

\[ A_o = g_{m1}g_{m2}R_1R_2 = g_{m1}g_{m6}r_{\pi 6}r_{\pi 6}r_{\pi 6} \]

\[ R_{out} = r_{\pi 6} || r_{\pi 7} \]

\[ R_{in} = 2r_{\pi 1} \]

Roots:

Zero = \( \frac{g_{m1}}{C_c} = \frac{g_{m6}}{C_c} \)

Poles at

\[ p_1 = -\frac{g_{m1}R_1R_2C_c}{g_{m6}r_{\pi 6}r_{\pi 6}r_{\pi 6}} \]

\[ p_2 = -\frac{g_{m1}}{C_{\pi 6}} C_{\pi 6} = -\frac{g_{m6}}{C_{\pi 6}} C_{\pi 6} \]

Assume that \( \beta_F =100 \), \( g_{m1} =1mS \), \( g_{m6} =10mS \), \( r_{\pi 6} = r_{\pi 7} = 0.5M\Omega \), \( C_c =5pF \) and \( C_L =10pF \):

\[ A_o=(1mS)(100)(250k\Omega)=25,000V/V, \quad R_{in} 2(\beta_F/g_{m1})2(100k\Omega)=200k\Omega, \quad R_{out}=250k\Omega \]

\[ Zero = \frac{10mS}{5pF} = 2 \times 10^9 \text{ rads/sec} \]

or 318.3MHz,

\[ p_1 = \frac{-1mS}{(25,000)5pF} = 2 \times 10^8 \]

\[ = -8000 \text{ rads/sec or } 1273Hz, \]

and \( p_2 = -10mS/10pF = -10^9 \text{ rads/sec or } 159.15MHz \)
**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

\[ I_{lim} = C \frac{dv_C}{dt} \]

where \( v_C \) is the voltage across the capacitor \( C \).

![Positive Slew Rate](image1)

\[ SR^+ = \min \left\{ \frac{I_5}{C}, \frac{I_6-I_5-I_7}{C_L} \right\} = \frac{I_5}{C_c} \] because \( I_6 \gg I_5 \)

\[ SR^- = \min \left\{ \frac{I_5}{C_c}, \frac{I_7-I_5}{C_L} \right\} = \frac{I_5}{C_c} \] if \( I_7 \gg I_5 \).

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

![Folded-Cascode BJT Op Amp Circuit](image2)

DC Conditions:

\[ I_3 = I_{bias}, \quad I_1 = I_2 = 0.5I_5 = 0.5I_{bias}, \quad I_4 = I_5 = kI_{bias}, \quad I_{10} = I_{11} = kI_{bias} - 0.5I_{bias} \quad (k>1) \]

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

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

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:

\[ i_{10} = \frac{-g_{m1}v_{in}}{2(r_{\pi6}+R_A)} = \frac{-g_{m1}v_{in}}{2} \]

\[ i_7 = \frac{g_{m2}r_{\pi7}v_{in}}{2(r_{\pi7}+r_{\pi7}+0.5r_{\pi7})} = \frac{g_{m2}v_{in}}{3} \]

\[ v_{out} = (i_7-i_{10})R_{out}v_{in} = 5 \left( \frac{g_{m1}R_{out}}{v_{in}} \right) \quad \text{if} \quad g_{m1} = g_{m2} \Rightarrow \frac{v_{out}}{v_{in}} = \frac{5}{6} \left( \frac{g_{m1}R_{out}}{v_{in}} \right) \]

\[ R_{out} = \beta_{p11} || \left[ \beta_N (r_{o5} || r_{o2}) \right] \quad \text{and} \quad \frac{R_{in}}{2} = r_{\pi1} \]

Assume that \( \beta_{FN} = 100, \beta_{FP} = 50, \; g_{m1} = g_{m2} = 1 \text{mS}, \; r_{oN} = 1 \text{M\Omega}, \; \text{and} \; r_{oP} = 0.5 \text{M\Omega}: \]

\[ \frac{v_{out}}{v_{in}} = 14,285 \text{V/V} \quad \frac{R_{out}}{R_{in}} = 14.285 \text{ M\Omega} \quad \text{and} \; R_{in} = 100 \text{k\Omega} \]

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 \( C_L = 25 \text{pF}, \) then \( |p_1| = 2800 \text{ rads/sec.} \; \text{or} \; 446 \text{Hz} \Rightarrow \; GB = 6.371 \text{ MHz} \)

Checking some of the nondominant poles gives:

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

\[ \text{(the capacitance to ac ground at the emitter of Q6)} \]

\[ |p_B| = \frac{1}{R_B C_B} = \frac{2}{r_{\pi7} C_B} \Rightarrow 6.37 \text{MHz} \; \text{if} \; C_B = 1 \text{pf} \]

\[ \text{(the capacitance to ac ground at the emitter of Q7)} \]

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

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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 \( I_S/C_c \)
- 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