Lecture 32: Multi-Transistor High Frequency

- Announcements:
  - HW#10 online soon and due Friday Nov. 16 via Gradescope
  - Lab#5 due Tuesday, Nov. 6, 5 p.m.
  - Midterm coming up
    - Friday this week, Nov. 9, @ 5 p.m., in 277 Cory (just like last time)
    - Midterm Info Sheet online
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- Lecture Topics:
  - Multi-Transistor Example (Inspection Analysis)
    - Input/Output Resistances
    - Gain
    - High Frequency
  - MOS Inspection Analysis

- Last Time:
  - Got the gain of the amplifier
  - Now, get the high frequency cut-off

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Example. Multi-Transistor Amplifier, Inspection Analysis

(C.E. w/ Degeneration, C.C. Cascade)

Find $R_s, R_o, g_m = \frac{g_m}{R_o}$ and $f_h$.

First, find the DC operating pt:

- Good Design: $I_{BAS1} > 10I_B1$
- $V_{B1} = \frac{R_2}{R_1 + R_2} V_{CC} \rightarrow V_{E1} = V_{B1} - V_{BE(on)} \approx 0.7V$
- $I_{d1} \approx I_{E1} = \frac{V_{E1}}{R_{E1} + R_{E1}} = \frac{V_{B1} - V_{BE(on)}}{R_{E1} + R_{E1}}$
- $V_{Q1}, V_{CC} = I_{d1} R_{E1} = V_{R2} \rightarrow V_{G2} = V_{B2} - V_{BE(on)}$
\[ I_{E2} = I_{E1} = \frac{V_E}{R_E} \]

Remarks:
1. Look for the \( V_{BEQ} \)'s \( \rightarrow \) well-defined voltages.
2. Current usually be determined by \( \frac{V_E}{R_E} \)'s.

For Bias Stability:
\[ I_{BQ1} > 10I_B \quad \text{also} \quad I_{Q1} > I_{BDQ2} = 10I_B \]

Midband Small-Signal Analysis for Gain, \( R_i \), and \( R_o \):

\[ R_i = R_{BB} \frac{r_n + (\beta + 1) R_E}{R_E} \]
\[ R_o = R_{E2} \frac{R_{E2} + R_{E1}(1 + \frac{g_m R_E}{r_{n+1}})}{(\beta + 1)} \]

Get gain \( \frac{V_o}{V_i} \) (gain from 0 to 7):

\[ \frac{V_o}{V_i} = \frac{R_o}{R_i} = \frac{R_{E2} + (\beta + 1) R_E}{R_1 + R_E} \]

\[ \frac{V_o}{V_i} = -\frac{g_m R_E}{1 + g_m R_E} \]

\[ \frac{V_o}{V_i} = \frac{g_m R_E}{1 + \frac{g_m R_E}{R_{E2} + (\beta + 1) R_E}} \]

\[ \frac{V_o}{V_i} \approx 1 \]
Procedure for Midband Gain Inspection Analysis:

- Identify and label all signal path nodes
- Get stage gain from node to node
  - For each stage, be sure to account for loading by the next stage, specifically load resistance to ground
  - For transistor terminal-to-terminal gains, will likely need to determine output node resistance to ground
    - including loading by the next stage, and
    - even the influence of loading by the previous stage, e.g., when determining $R_c$
- Take the product of all node-to-node gains to get the total gain
- Can do all of this by inspection if
  - There is no feedback
  - You know all the terminal-to-terminal gain equations or can “see” or “derive” them quickly
  - You know all the equations for resistances looking into the transistor terminals (to ground) or can “see” or “derive” them quickly
  - “See” or “derive” quickly can often be done by following the currents

Procedure for High Frequency Inspection Analysis:

- Identify and label all signal path nodes
- Draw in the small transistor capacitors
- Use the Miller transform to turn the base-to-collector or gate-to-drain capacitor into shunt capacitors to ground
- For the base-to-emitter or gate-to-source capacitor you will need to know the equation for driving point resistance, i.e., resistance in parallel
- Get the time constant for each node by
  - Determining the total capacitance $C_{node}$ from that node to ground
  - Determining the total resistance $R_{node}$ from that node to ground
  - Time constant = $R_{node} * C_{node}$
- Handle each feedback capacitor separately using knowledge of its driving point $R$ equation (or derive the equation from scratch using the hybrid-$\pi$ model)
- Add up all the time constants and take the reciprocal to get the $\omega_H$
Using OCTA Analysis:

\[ \omega_H = \frac{1}{C_R + C_{m2} + C_{m3} + C_{m4} + C_{m5} R_{m1} + C_{m6} R_{m2}} \]

Total Shunt

\[ C_{m1}(1-\frac{1}{\omega_H}) : C_H(1+\frac{C_{m1} R_{m2}}{\omega_H}) \]

\[ \frac{1}{\omega_H} + \frac{C_{m1} R_{m2}}{\omega_H} \]

\[ C_{m1} \]

Total Shunt R

\[ C_E \]

\[ \text{node } \Theta \]

\[ \text{node } \Theta \]

\[ \text{yet to need to determine the } R_{m1} \text{'s} \]

Do it for the general case:

\[ K_C I_x = \frac{N_x}{R_{m1}} + \frac{N_x + N_{x'}}{R_E} = \frac{N_x}{R_R} + \frac{N_x}{R_R} + \frac{N_x}{R_R} \]

\[ V_C = R_E \left( \frac{N_x}{R_R} - I_x + g_m V_x \right) \]

\[ I_x = \frac{V_x}{R_{m2}} + \frac{N_x}{R_E} \left( \frac{N_x}{R_R} - I_x + g_m V_x \right) \]

\[ I_x(1 + \frac{R_E}{R_{m2}}) = \frac{V_x}{R_R} \left( \frac{1}{R_R} R_E + \frac{1}{R_E} + g_m R_E \right) \]

\[ R_{m1} = \frac{N_x}{I_x} = \frac{1}{(R_{m1} + R_E)} + \frac{1}{g_m R_E} \]

\[ R_{m2} = \frac{N_x}{I_x} = \frac{1}{(R_{m2} + R_E)} + \frac{1}{g_m R_E} \]

\[ R_{m1} = \frac{R_E + R_{m1}}{g_m R_E} = R_{m2} \]
\[ R_{TH} = \frac{R_{RE}}{1 + g_m R_E} \]

\[ R_E = 100 \Omega \]

\[ R_N || \frac{1}{g_m} \text{ small \rightarrow can be neglected} \]

\[ N_2/N_1 = \frac{R_E}{g_m + R_E} \]

\[ 25 \Omega \]

\[ N_1 = 0 \rightarrow C_{IT} \text{ not large!} \]

\[ V_i \rightarrow \frac{V_o}{N_0} = \frac{R_E}{g_m R_E} \]

Now get the Cs to get useful:

\[ C_2 = C_{su} \left( 1 + g_m R_2 \right) \]

\[ \approx C_{su} \left( 1 + g_m R_2 \right) \frac{R_2 || R_{oi} \left( 1 + g_m R_E \right) \left( 1 + \frac{R_2 || R_{oi}}{g_m} \right) \left( 1 + \frac{R_{oi} || R_E}{g_m} \right)}{\beta + 1} \]

\[ \approx C_{su} \left( 1 + g_m R_2 \right) \frac{R_2 || R_{oi} \left( 1 + g_m R_E \right) \left( 1 + \frac{R_2 || R_{oi}}{g_m} \right)}{\beta + 1} \]

\[ C_0 = C_{su} \left( 1 + g_m R_2 \right) \]

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\[ L_0 = C_{su} \left( 1 + g_m R_2 \right) \]

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