LECTURE 050 – FOLLOWERS
(READING: GHLM – 344-362, AH – 221-226)

Objective

The objective of this presentation is:

Show how to design stages that

1.) Provide sufficient output power in the form of voltage or current.
2.) Avoid signal distortion.
3.) Be efficient
4.) Provide protection from abnormal conditions (short circuit, over temperature, etc.)

Outline

- Source follower
- Emitter follower
- Common source stage
- Common emitter stage
- Push-Pull MOS (Class B)
- Push-Pull BJT (Class B)
- Summary

SOURCE FOLLOWERS

Maximum and Minimum Output Voltage of the Source Follower

N-Channel Source Follower with current sink bias:

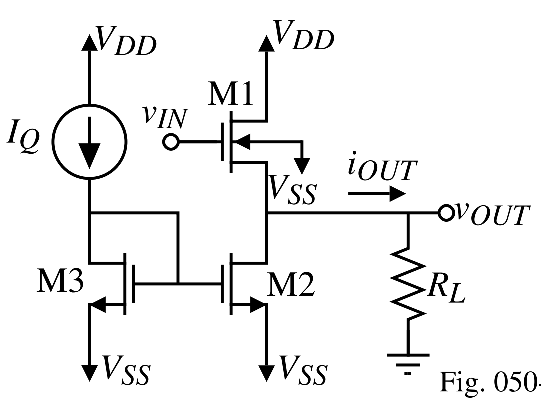

Fig. 050-01

Voltage transfer curve:

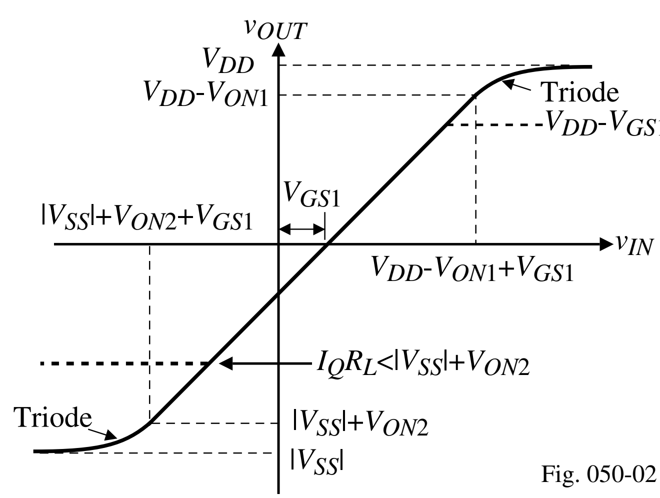

Fig. 050-02

Maximum output voltage swings:

$v_{OUT}(\min) \approx V_{SS} - V_{ON2}$ (if R_L is large) or $v_{OUT}(\min) \approx -I_Q R_L$ (if R_L is small)

$v_{OUT}(\max) = V_{DD} - V_{ON1}$ (if $v_{IN} > V_{DD}$) or $v_{OUT}(\max) \approx V_{DD} - V_{GS1}$

Output Voltage Swing of the Follower - Continued

The previous results do not include the bulk effect on V_{T1} of V_{GS1}.

Therefore,

$$V_{T1} = V_{T01} + \gamma[\sqrt{2|\phi_F| - v_{BS}} - \sqrt{2|\phi_F|}] \approx V_{T01} + \gamma\sqrt{v_{SB}} = V_{T01} + \gamma_1\sqrt{v_{OUT}(\max) - V_{SS}}$$

$$\therefore \quad v_{OUT}(\max) - V_{SS} \approx V_{DD} - V_{SS} - V_{ON1} - V_{T1} = V_{DD} - V_{SS} - V_{ON1} - V_{T01} - \gamma_1\sqrt{v_{OUT}(\max) - V_{SS}}$$

Define $v_{OUT}(\max) - V_{SS} = v_{OUT}'(\max)$

which gives the quadratic,

$$v_{OUT}'(\max) + \gamma_1\sqrt{v_{OUT}'(\max)} - (V_{DD} - V_{SS} - V_{ON1} - V_{T01}) = 0$$

Solving the quadratic gives,

$$v_{OUT}'(\max) \approx \frac{\gamma_1^2}{4} - \frac{\gamma_1}{2}\sqrt{\gamma_1^2 + 4(V_{DD} - V_{SS} - V_{ON1} - V_{T01})} + \frac{\gamma_1^2 + 4(V_{DD} - V_{SS} - V_{ON1} - V_{T01})}{4}$$

If $V_{DD} = 2.5\text{V}$, $\gamma_N = 0.4\text{V}^{1/2}$, $V_{TN1} = 0.7\text{V}$, and $V_{ON1} = 0.2\text{V}$, then $v_{OUT}'(\max) = 3.661\text{V}$ and

$$v_{OUT}(\max) = 3.661 - 2.5 = 0.8661\text{V}$$

Maximum Sourcing and Sinking Currents for the Source Follower

Maximum Sourcing Current (into a short circuit):

We assume that the transistors are in saturation and $V_{DD} = -V_{SS} = 2.5\text{V}$, thus

$$I_{OUT}(\text{sourcing}) = \frac{K'_1 W_1}{2L_1}[V_{DD} - v_{OUT} - V_{T1}]^2 - I_Q$$

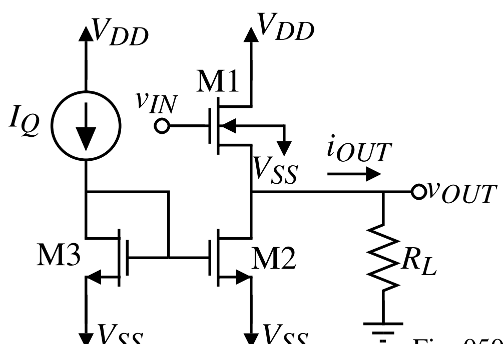

Fig. 050-01

where v_{IN} is assumed to be equal to V_{DD}.

If $W_1/L_1 = 10$ and if $v_{OUT} = 0\text{V}$, then

$V_{T1} = 1.08\text{V} \Rightarrow I_{OUT}$ equal to 1.11 mA.

However, as v_{OUT} increases above 0V, the current rapidly decreases.

Maximum Sinking Current:

For the current sink load, the sinking current is whatever the sink is biased to provide.

$I_{OUT}(\text{sinking}) = I_Q$

Efficiency of the Source Follower

Assume that the source follower can swing to power supply:

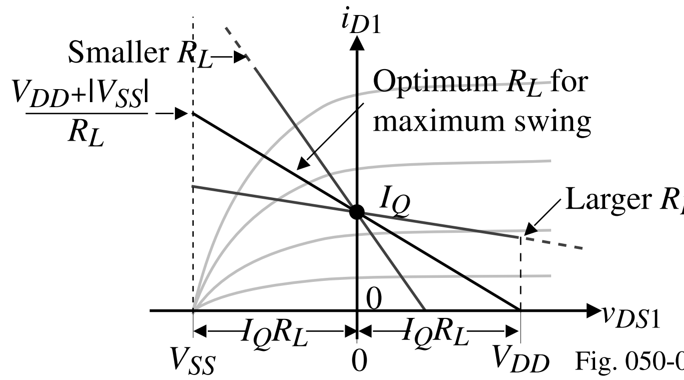

Fig. 050-03

$$\text{Efficiency} = \frac{P_{RL}}{P_{Supply}} = \frac{\frac{v_{OUT}(\text{peak})^2}{2R_L}}{(V_{DD}-V_{SS})I_Q} = \frac{\frac{v_{OUT}(\text{peak})^2}{2R_L}}{(V_{DD}-V_{SS})\left(\frac{(V_{DD}-V_{SS})}{2R_L}\right)} = \left(\frac{v_{OUT}(\text{peak})}{V_{DD}-V_{SS}}\right)^2$$

Maximum efficiency occurs when $v_{OUT}(\text{peak}) = V_{DD} = |V_{SS}|$ which gives 25%.

Comments:

- Maximum efficiency occurs for the optimum value of R_L which gives maximum swing.
- Other values of R_L result in less efficiency (and smaller signal swings before clipping)
- We have ignored the fact that the dynamic Q point cannot travel along the full length of the load line because of minimum and maximum voltage limits.

Small Signal Performance of the Source Follower

Small-signal model:

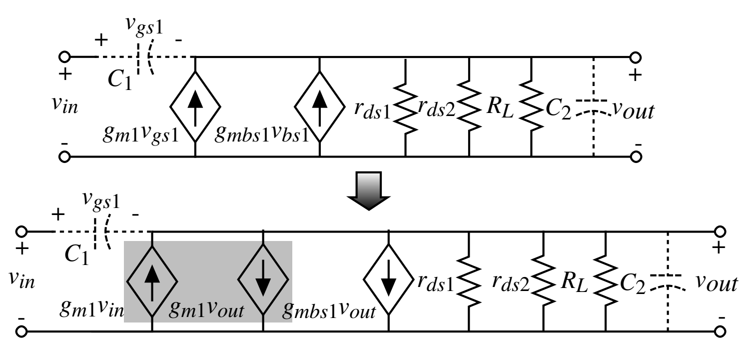

Fig. 050-04

$$\frac{V_{out}}{V_{in}} = \frac{g_{m1}}{g_{ds1} + g_{ds2} + g_{m1} + g_{mbs1} + G_L} \cong \frac{g_{m1}}{g_{m1} + g_{mbs1} + G_L} \cong \frac{g_{m1}R_L}{1 + g_{m1}R_L}$$

If $V_{DD} = -V_{SS} = 2.5$V, $V_{out} = 0$V, $W_1/L_1 = 10\mu$m/1 μm, $W_2/L_2 = 1\mu$m/1 μm, and $I_D = 500$ μA, then

For the current sink load follower ($R_L = \infty$):

$$\frac{V_{out}}{V_{in}} = 0.869\text{V/V, if the bulk effect were ignored, then } \frac{V_{out}}{V_{in}} = 0.963\text{V/V}$$

For a finite load, $R_L = 1000\Omega$:

$$\frac{V_{out}}{V_{in}} = 0.512\text{V/V}$$

Small Signal Performance of the Source Follower - Continued

The output resistance is:

$$R_{out} = \frac{1}{g_{m1} + g_{mbs1} + g_{ds1} + g_{ds2} + G_L}$$

For the current sink load follower:

$$R_{out} = 830\Omega$$

The frequency response of the source follower:

$$\frac{V_{out}(s)}{V_{in}(s)} = \frac{(g_{m1} + sC_1)}{g_{ds1} + g_{ds2} + g_{m1} + g_{mbs1} + G_L + s(C_1 + C_2)}$$

where

C_1 = capacitances connected between the input and output ≈ C_{GS1}

$C_2 = C_{bs1} + C_{bd2} + C_{gd2}(\text{or } C_{gs2}) + C_L$

$z = -\frac{g_{m1}}{C_1}$ and $p \approx -\frac{g_{m1}+G_L}{C_1+C_2}$

The presence of a LHP zero leads to the possibility that in most cases the pole and zero will provide some degree of cancellation leading to a broadband response.

EMITTER FOLLOWER

Voltage Transfer Characteristic

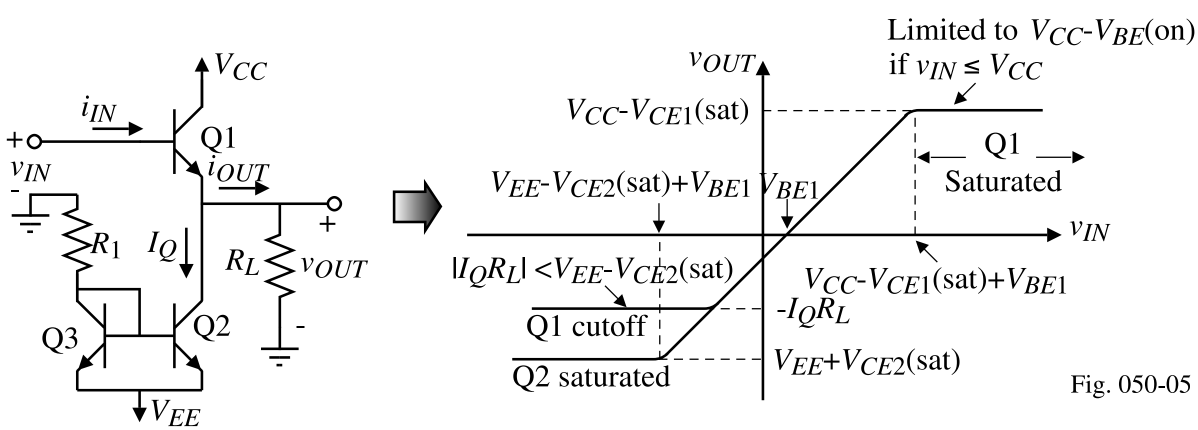

Fig. 050-05

Maximum signal swings:

- $v_{OUT}(\max) = V_{CC}-V_{CE1}(\text{sat})$ or $V_{CC}-V_{BE1}$ if $v_{IN}(\max) \leq V_{CC}$

  (The circuit driving the emitter follower must provide a current of $\frac{V_{CC}-V_{CE1}(\text{sat})}{\beta_F R_L}$)

- $v_{OUT}(\min) = V_{EE}+V_{CE2}(\text{sat})$ or $v_{OUT}(\min) = -I_Q R_L$ (if $|I_Q R_L| < V_{EE}+V_{CE2}(\text{sat})$
- $i_{OUT}(\text{source}) = \beta_F i_{IN}$
- $i_{OUT}(\text{sink}) = I_Q$

Efficiency of the Emitter Follower

Assume that the emitter follower can swing to power supply:

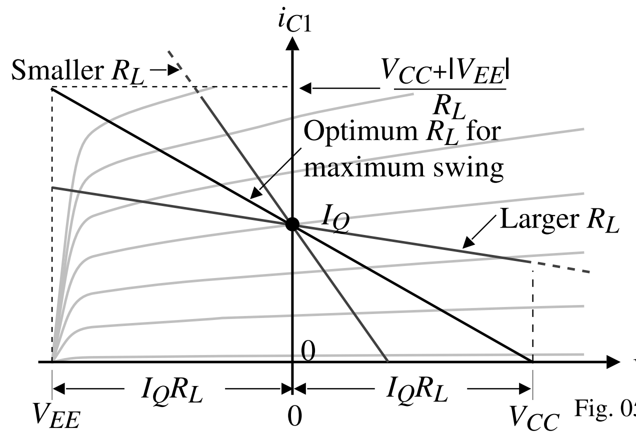

Fig. 050-06

$$\text{Efficiency} = \frac{P_{RL}}{P_{Supply}} = \frac{\frac{v_{OUT}(\text{peak})^2}{2R_L}}{(V_{CC}-V_{EE})I_Q} = \frac{\frac{v_{OUT}(\text{peak})^2}{2R_L}}{(V_{CC}-V_{EE})\left(\frac{(V_{CC}-V_{EE})}{2R_L}\right)} = \left(\frac{v_{OUT}(\text{peak})}{V_{CC}-V_{EE}}\right)^2$$

Maximum efficiency occurs when $v_{OUT}(\text{peak}) = V_{CC} = |V_{EE}|$ which gives 25%.

Comments:

- Maximum efficiency occurs for the optimum value of R_L which gives maximum swing.
- Other values of R_L will result in less efficiency (smaller signal swings before clipping)

Power Considerations of the Emitter Follower

Waveforms of the transistor variables for maximum efficiency ($V_{CC} = -V_{EE}$).

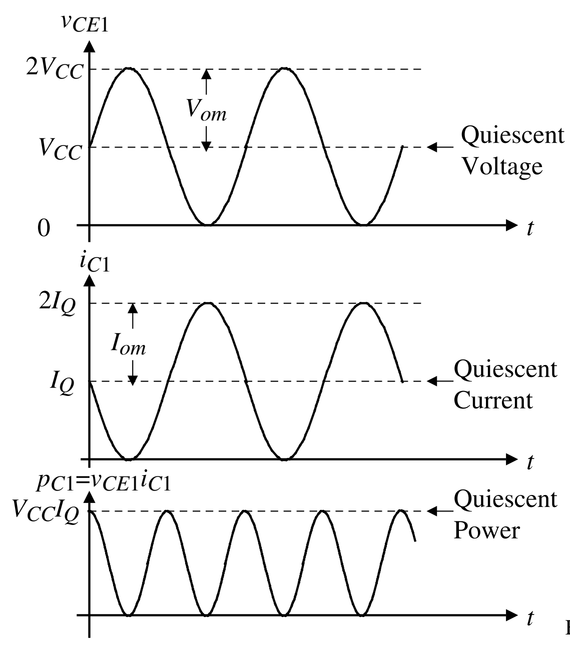

Fig. 050-07

$$p_{C1} = v_{CE1}i_{C1} = [V_{CC}(1+\sin\omega t)][I_Q[1-\sin\omega t)] = V_{CC}\,I_Q(1-\sin^2\omega t) = \frac{V_{CC}I_Q}{2}(1+\cos 2\omega t)$$

Power Considerations of the Emitter Follower - Continued

Parabolas of constant power:

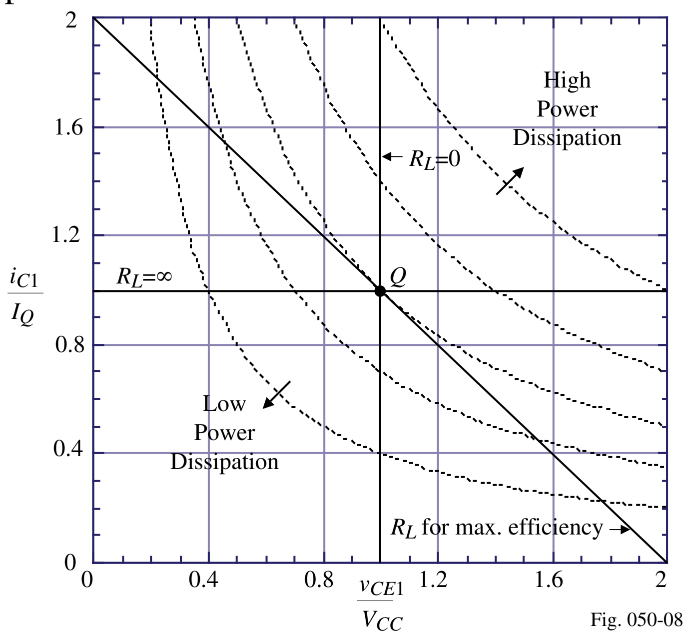

Fig. 050-08

Comments:

- Maximum power dissipation occurs at the Q point for the optimum R_L corresponding to maximum efficiency.
- For smaller values of R_L the power dissipation can become very large.

Example - Design of an Emitter Follower for Maximum Efficiency

The emitter follower shown has V_{CC} = -V_{EE} = 5V, R_1 = 2.15kΩ, and V_{CE}(sat) = 0.2V. Find the optimum value of R_L for maximum efficiency and find the value of this efficiency.

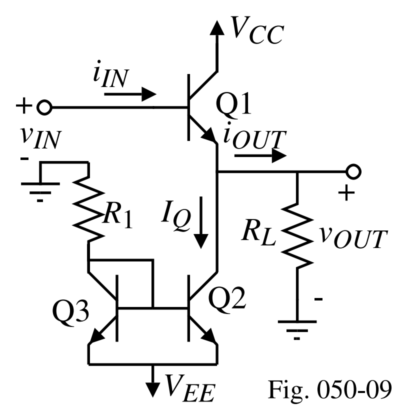

Fig. 050-09

Solution

The optimum R_L for maximum efficiency is found as,

$$R_L = \frac{V_{CC}\text{-}V_{CE}(\text{sat})}{I_Q}$$

$$I_Q = \frac{-V_{EE}\text{-}V_{BE}}{R_1} = \frac{5\text{-}0.7}{2.15\text{k}\Omega} = 2\text{mA}$$

$$\therefore \quad R_L = \frac{5\text{-}0.2}{2\text{mA}} = 2.4\text{k}\Omega$$

The efficiency can be found by calculating the power to the load and from the sources.

$$P_L(\text{max}) = \left(\frac{V_{CC}\text{-}V_{CE}(\text{sat})}{\sqrt{2}}\right)\left(\frac{I_Q}{\sqrt{2}}\right) = 0.5(4.8\text{V})(2\text{mA}) = 4.8\text{mW}$$

$$P_{supply} = 2V_{CC}I_Q = 2(5)(2\text{mA}) = 20\text{mW}$$

$$\therefore \quad \eta = \frac{P_L(\text{max})}{P_{supply}} = \frac{4.8}{20} = 0.24 \text{ or } 24\% \text{ which is close to the theoretical maximum.}$$

Emitter Follower - Small Signal Performance

The small signal model of the emitter follower is:

$R_{in} = R_S + r_\pi + (1+\beta_F)R_L$

$R_{out} \approx 1/g_m$ (excluding R_L)

$v_{out} = (g_m + g_\pi)v_1 R_L = (g_m + g_\pi)(i_{in} r_\pi)R_L$

$= (g_m + g_\pi)\, r_\pi R_L \left(\frac{v_{in}}{R_{in}}\right)$

$$\therefore \quad \frac{v_{out}}{v_{in}} = \frac{(g_m + g_\pi)\, r_\pi R_L}{R_S + r_\pi + (1+\beta_F)R_L} \approx \frac{R_L}{R_L + \frac{1}{g_m} + \frac{R_S}{\beta_F}}$$

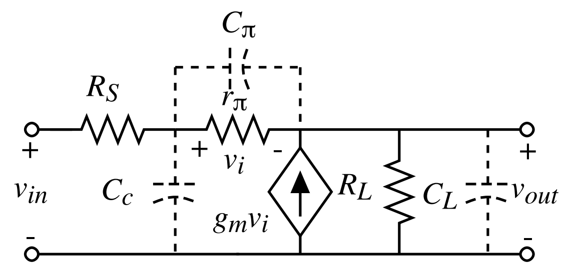

Fig. 050-10

If $\beta_F = 100$, $g_m = 20$mA/V, $R_L = R_S = 1$kΩ, $C_\pi = 5$pF and $C_L = 10$pF, we get

$$R_{in} = 1\text{k}\Omega + 5\text{k}\Omega + 101\text{k}\Omega = 107\text{k}\Omega,\ R_{out} = 50\Omega,\ \frac{v_{out}}{v_{in}} = \frac{1\text{k}\Omega}{1\text{k}\Omega + 50\Omega + 9.9\Omega} = 0.943\text{V/V}$$

The transfer function assuming $R_S = 0$, is given as,

$$\frac{V_{out}}{V_{in}} = \frac{g_m + g_\pi + sC_\pi}{g_m + g_\pi + G_L + sC_\pi + sC_L} \quad \Rightarrow \quad \text{Zero} \approx -\frac{g_m}{C_\pi} \quad \text{and} \quad \text{Pole} \approx -\frac{g_m + G_L}{C_\pi + C_L}$$

Zero = -4x10^9 rads./sec. and Pole = -1.4x10^9 rads./sec.

SUMMARY

Requirements of Output Stages

- The objectives are to provide output power in form of voltage and/or current.
- In addition, the output amplifier should be linear and be efficient.
- Low output resistance is required to provide power efficiently to a small load resistance.
- High source/sink currents are required to provide sufficient output voltage rate due to large load capacitances.
- Types of output stages considered:
  Source and emitter follower (Class A)
- Did not consider the distortion analysis of GHLM, Sec. 5.3.2