Output amplifiers

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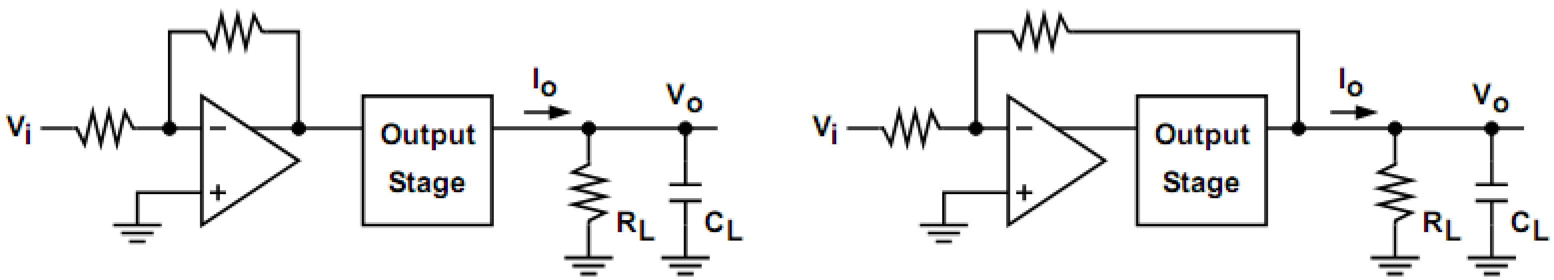
Output amplifier



- Deliver large output current to low-impedance loads (resistive and/or capacitive).
- Usually is a voltage buffer, i.e., low voltage gain, high Z_{in}, and low Z_o.
- High Z_{in} is to maintain voltage gain and bandwidth of previous stage.
- Wide bandwidth if in the feedback loop,
- May need protection against load shorts.

- Design considerations
  - Frequency response, Output impedance, Output current, Output voltage range, Power efficiency and Distortion

Common-source output stage

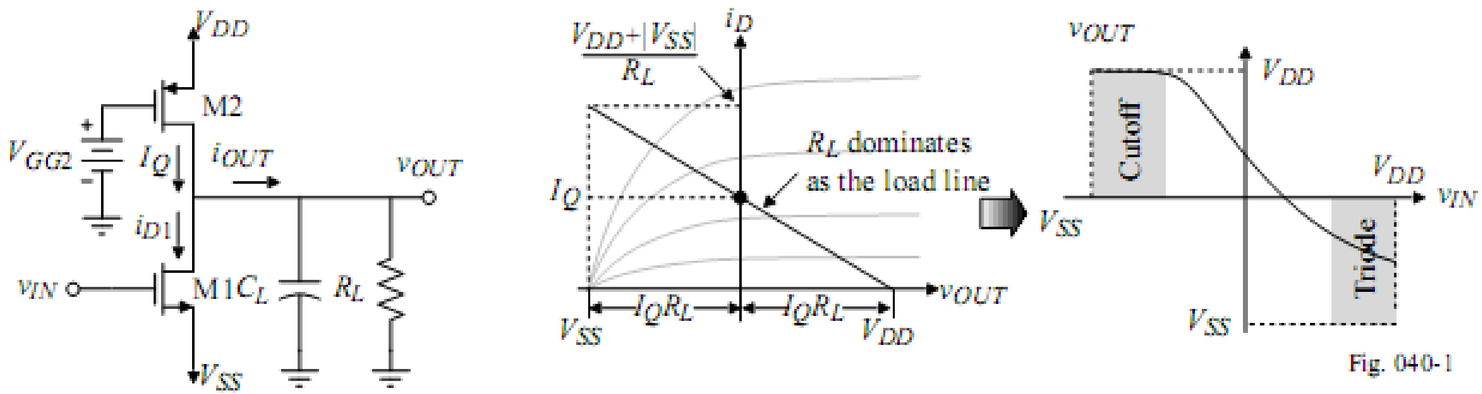


Fig. 040-1

A Class A circuit has current flow in the MOSFETs during the entire period of a sinusoidal signal.

Characteristics of Class A amplifiers:

- Unsymmetrical sinking and sourcing
- Linear
- Poor efficiency

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

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

Common-source output stage

Output resistance:

$$r_{out} = \frac{1}{g_{ds1} + g_{ds2}} = \frac{1}{(\lambda_1 + \lambda_2) I_D}$$

Current:

- Maximum sinking current is,

$$\bar{I}_{OUT} = \frac{K'_1 W_1}{2L_1}(V_{DD} - V_{SS} - V_{T1})^2 - I_Q$$

- Maximum sourcing current is,

$$\overset{+}{I}_{OUT} = \frac{K'_2 W_2}{2L_2}(V_{DD} - V_{GG2} - |V_{T2}|)^2 \leq I_Q$$

Requirements:

- Want $r_{out} << R_L$
- $|I_{OUT}| > C_L \cdot SR$
- $|I_{OUT}| > \frac{v_{OUT}(\text{peak})}{R_L}$

The maximum current will be determined by **both** the current required to provide the necessary slew rate (C_L) and the current required to provide a voltage across the load resistor (R_L).

Source follower output stage

N-Channel Source Follower
with current sink bias:

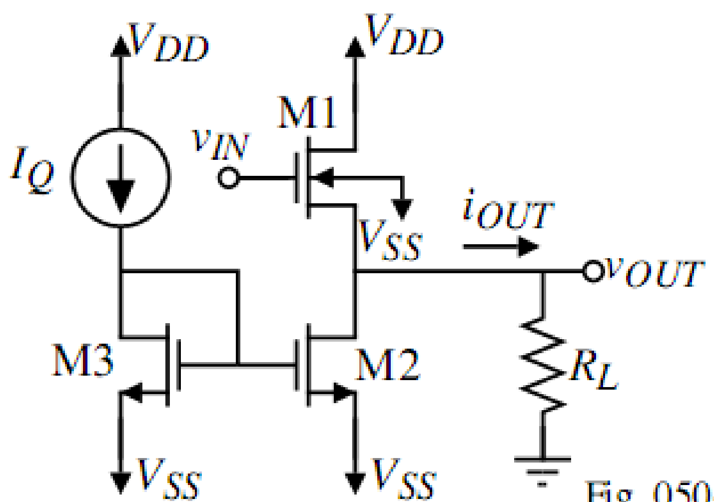


Fig. 050-01

Voltage transfer curve:

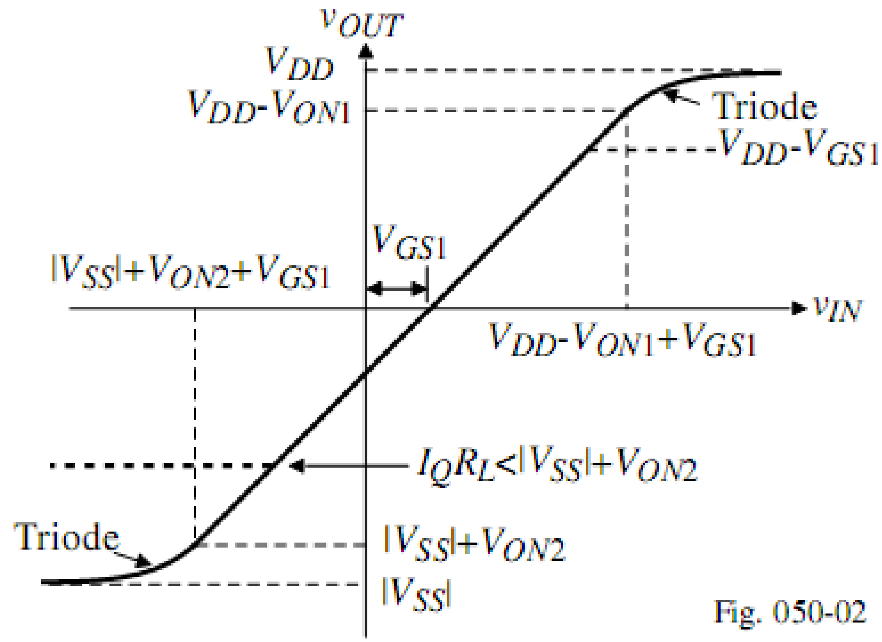


Fig. 050-02

Maximum output voltage swings:

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

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

Source follower output stage

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

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

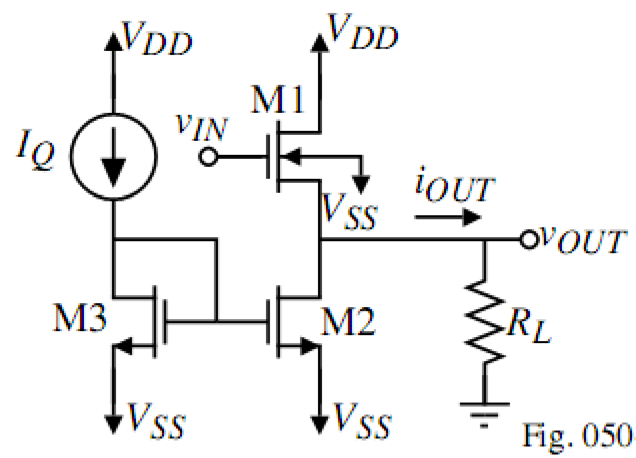


Fig. 050-01

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:

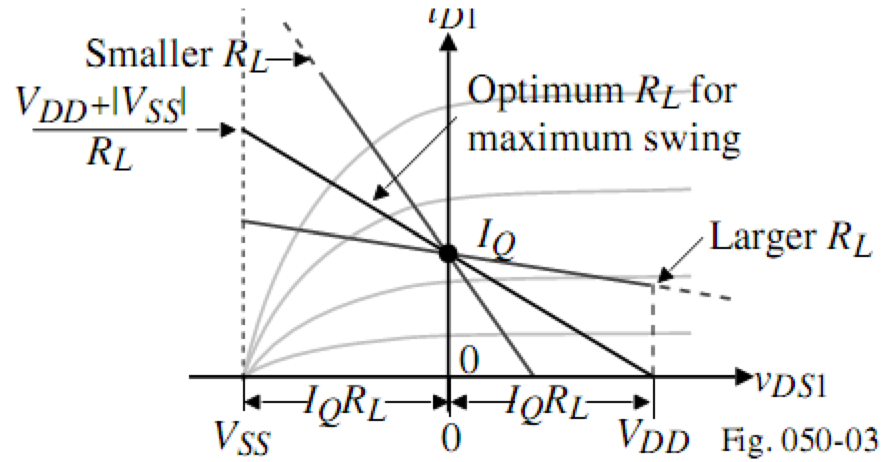


Fig. 050-03

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

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

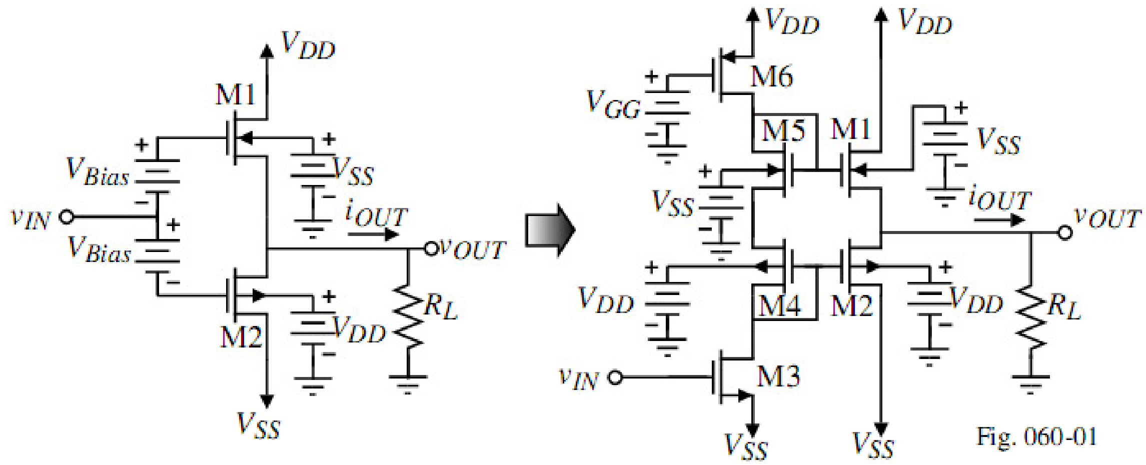
Comments:

- 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.

Push-pull source follower

Push-Pull Source Follower

Can both sink and source current and provide a slightly lower output resistance.



Efficiency:

Depends on how the transistors are biased.

- Class B - one transistor has current flow for only 180° of the sinusoid (half period)

$$\therefore \text{ Efficiency} = \frac{P_{RL}}{P_{VDD}} = \frac{\dfrac{v_{OUT}(\text{peak})^2}{2R_L}}{(V_{DD} - V_{SS})\left(\dfrac{1}{2}\right)\left(\dfrac{2v_{OUT}(\text{peak})}{\pi R_L}\right)} = \frac{\pi}{2}\,\frac{v_{OUT}(\text{peak})}{V_{DD} - V_{SS}}$$

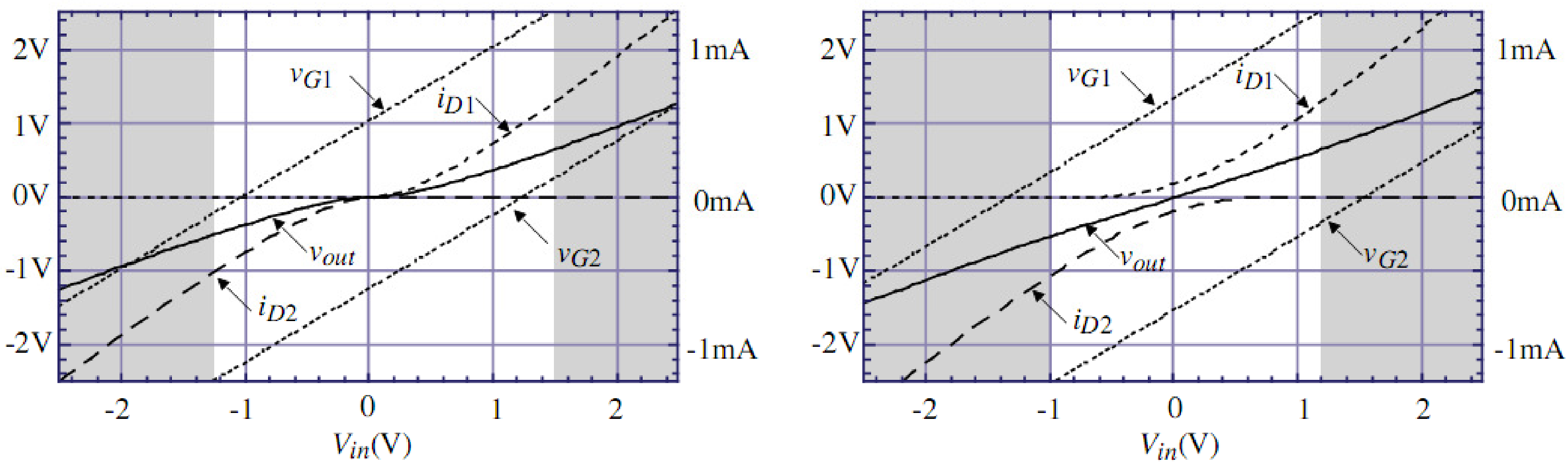
Maximum efficiency occurs when $v_{OUT}(\text{peak}) = V_{DD}$ and is 78.5%

- Class AB - each transistor has current flow for more than 180° of the sinusoid.

Maximum efficiency is between 25% and 78.5%

Class-B and class-AB source followers

Output current and voltage characteristics of the push-pull, source follower (R_L = 1kΩ):



Class B, push-pull, source follower   Class AB, push-pull, source follower   Fig. 060-0

Comments:

- Note that v_{OUT} cannot reach the extreme values of V_{DD} and V_{SS}
- I_{OUT}^{+}(max) and I_{OUT}^{-}(max) is always less than V_{DD}/R_L or V_{SS}/R_L
- For v_{OUT} = 0V, there is quiescent current flowing in M1 and M2 for Class AB
- Note that there is significant distortion at v_{IN} =0V for the Class B push-pull follower

Small-signal analysis of push-pull source follower

$$\frac{v_{out}}{v_{in}} = \frac{g_{m1} + g_{m2}}{g_{ds1}+g_{ds2}+g_{m1}+g_{mbs1}+g_{m2}+g_{mbs2}+G_L}$$

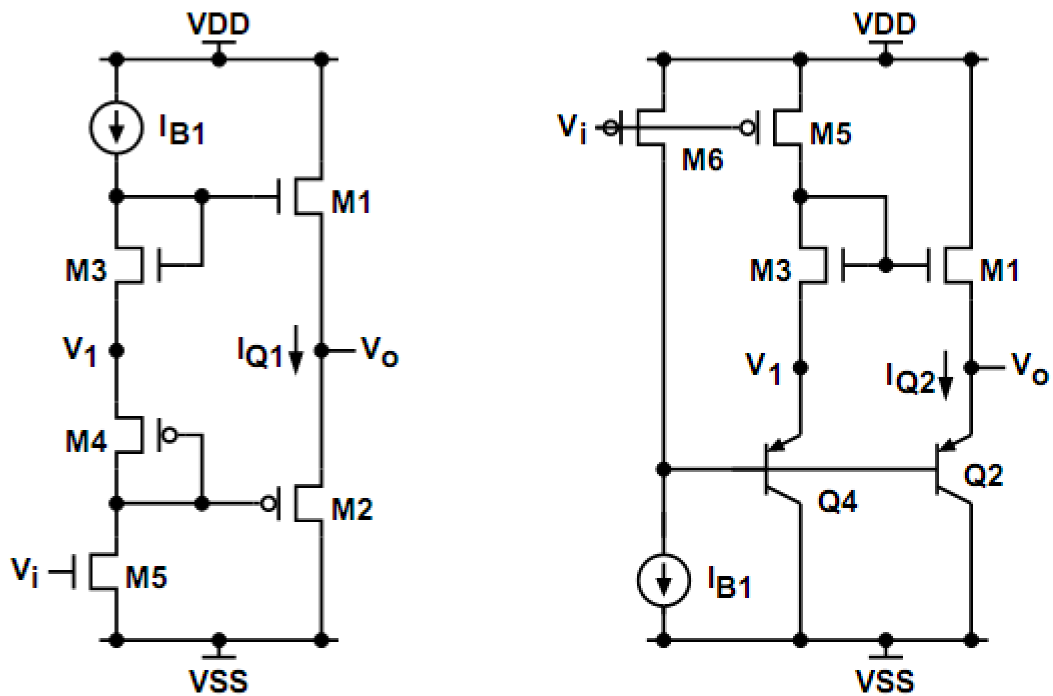
$$R_{out} = \frac{1}{g_{ds1}+g_{ds2}+g_{m1}+g_{mbs1}+g_{m2}+g_{mbs2}} \quad \text{(does not include } R_L\text{)}$$

A zero and pole are located at

$$z = \frac{-(g_{m1}+g_{m2})}{C_1} \qquad p = \frac{-(g_{ds1}+g_{ds2}+g_{m1}+g_{mbs1}+g_{m2}+g_{mbs2}+G_L)}{C_1+C_2}.$$

These roots will be high-frequency because the associated resistances are small.

Push-pull source follower



$$V_{GS1} + |V_{GS2}| = V_{GS3} + |V_{GS4}| \quad \Rightarrow \quad I_{Q1} = I_{B1}\left(\frac{1/\sqrt{k_n'(W/L)_3} + 1/\sqrt{k_p'(W/L)_4}}{1/\sqrt{k_n'(W/L)_1} + 1/\sqrt{k_p'(W/L)_2}}\right)^2$$

Push-pull common-source amplifier

Similar to the class A but can operate as class B providing higher efficiency.

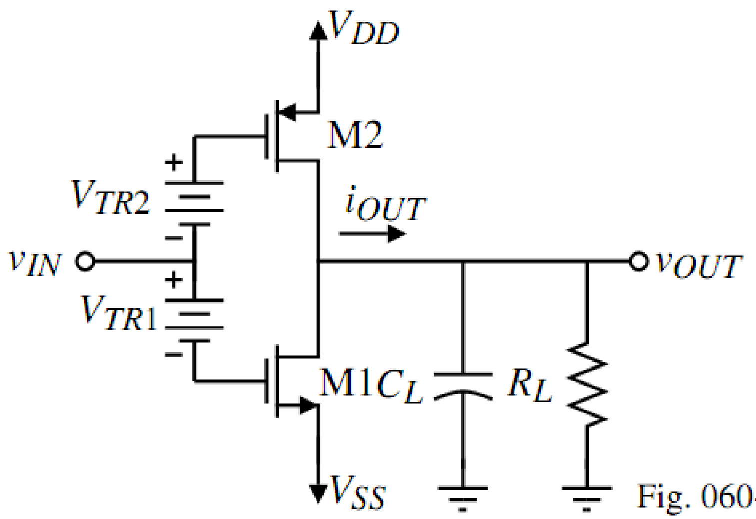


Fig. 060-04

Comments:

- The batteries V_{TR1} and V_{TR2} are necessary to control the bias current in M1 and M2.
- The efficiency is the same as the push-pull, source follower.

Push-pull common-source amplifier

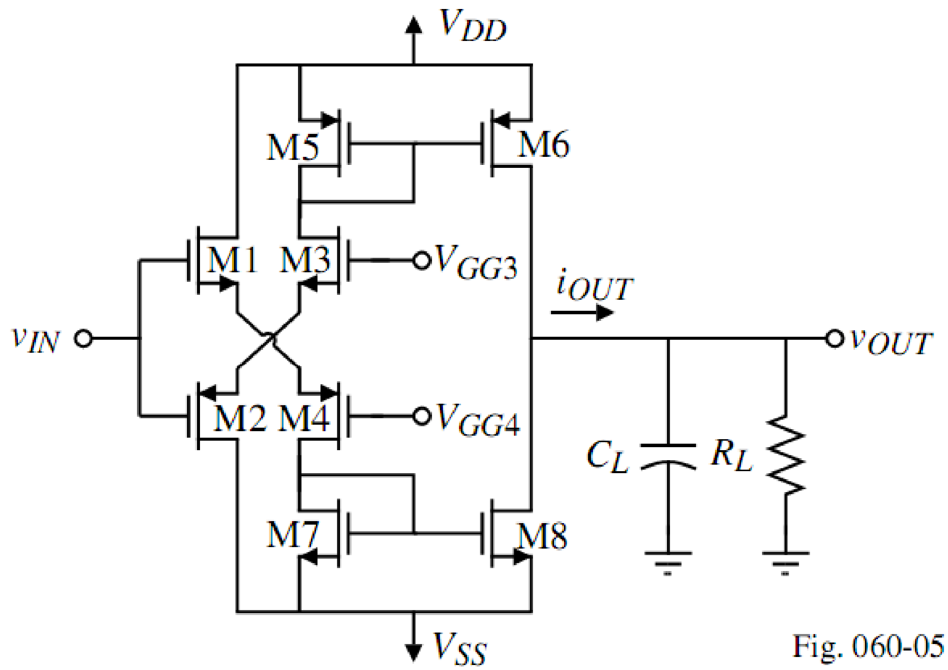
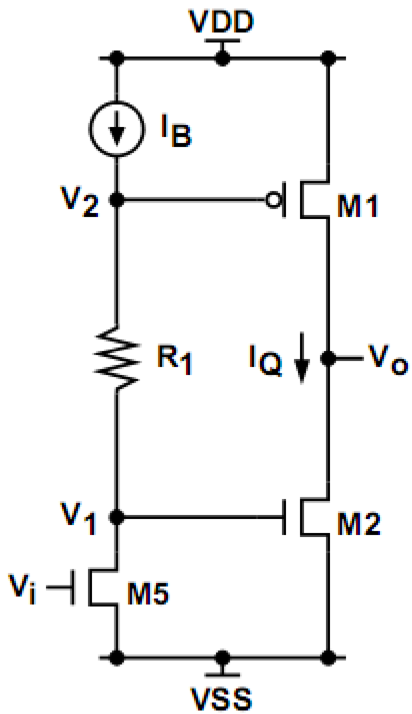


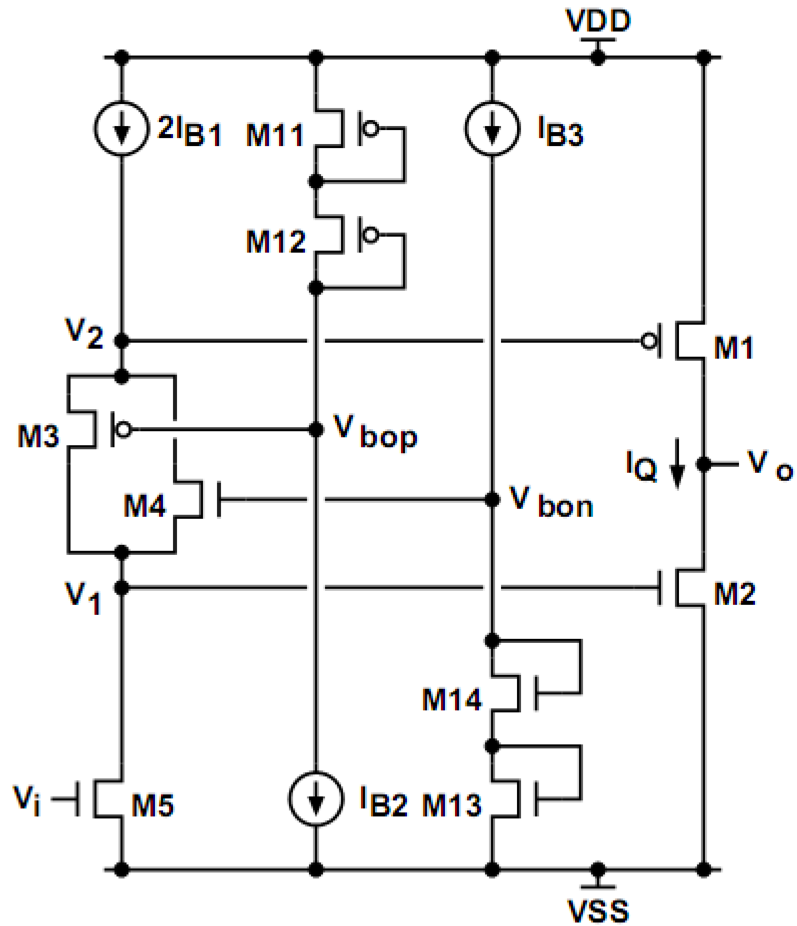
Fig. 060-05

V_{GG3} and V_{GG4} can be used to bias this amplifier in class AB or class B operation.

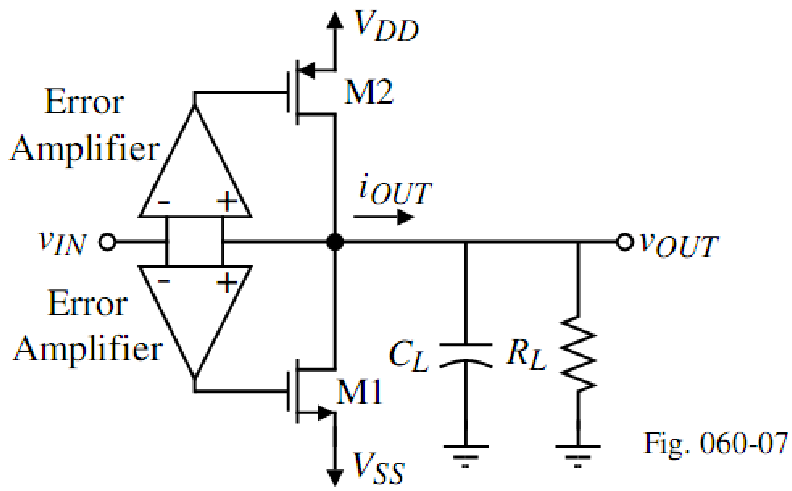
Note, that the bias current in M6 and M8 is not dependent upon V_{DD} or V_{SS} (assuming V_{GG3} and V_{GG4} are not dependent on V_{DD} and V_{SS}).

Push-pull common-source amplifier





Using shunt feedback to reduce output resistance



$$R_{out} = \frac{r_{ds1} || r_{ds2}}{1+\text{Loop Gain}}$$

Comments:

- Can achieve output resistances as low as 10Ω.
- If the error amplifiers are not balanced, it is difficult to control the quiescent current in M1 and M2
- Great linearity because of the strong feedback
- Can be efficient if operated in class B or class AB

A simple example

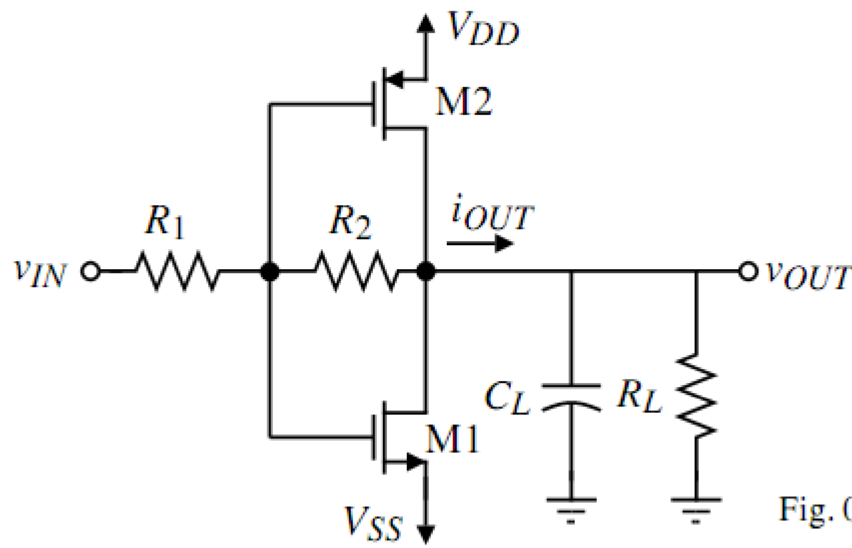


Fig. 06

$$\text{Loop gain} \approx \left(\frac{R_1}{R_1+R_2}\right)\left(\frac{g_{m1}+g_{m2}}{g_{ds1}+g_{ds2}+G_L}\right)$$

$$R_{out} = \frac{r_{ds1} \| r_{ds2}}{1+\left(\frac{R_1}{R_1+R_2}\right)\left(\frac{g_{m1}+g_{m2}}{g_{ds1}+g_{ds2}+G_L}\right)}$$