

# Output Amplifier

## Output stage generalities

- Efficiently drive signals into an output load. The output load may consist of a resistor or a capacitor, or both. In general, the output resistor will be small (50-1000 $\Omega$ ) and the output capacitor will be large, in the range of 5-1000 pF. The output amplifier should be capable of providing sufficient output signal (voltage, current or power).
- Requirements:
  - 1)to drive a low-load resistor, it has to have a small-signal output resistance that is equal to or smaller than the load resistor.
  - 2)to drive a large capacitance it has to output a large sink or source current. (An amplifier driving a large capacitance does not need to have a low output resistance).

## Specific Requirements of the output stages

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, overtemperature, etc.)

The 2<sup>nd</sup> requirement results from the fact that the signal swings are large and that nonlinearities normally non encountered in small-signal amplifiers will become important.

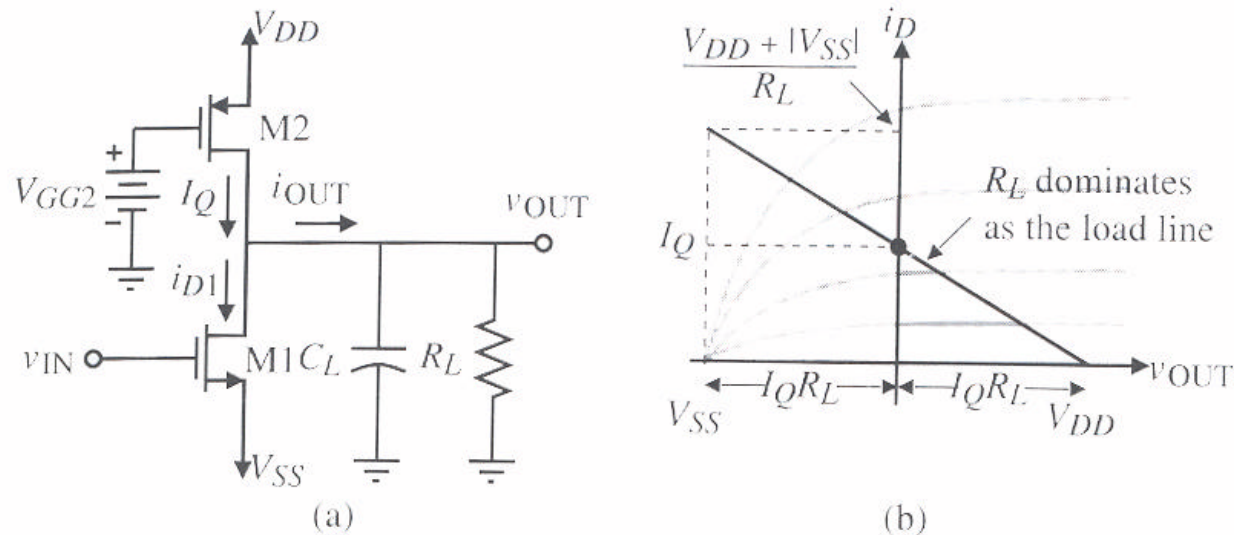
The 3<sup>rd</sup> is born out of the need to minimize power dissipation in the driver transistors themselves compared with that dissipated in the load.

The 4<sup>th</sup> requirement is normally met with CMOS output stage since MOS devices are, by nature, thermally self-limiting.

Output amplifier here considered are: Class A, source followers, push-pull amplifier, the use of the substrate bipolar junction transistor (BJT), the use of a negative feedback.

# Class A Amplifiers

- In order to reduce the output resistance and increase the current driving capability, a straightforward approach is simply to increase the bias current in the output stage.



(a) Class A amplifier. (b) Load line for the amplifier of (a).

## Performances of the output stage

There are several way to specify the performance of the output amplifier.

- 1) To specify the ac output resistance of the amplifier, which is in the case of the figure:

$$r_{out} = \frac{1}{g_{ds1} + g_{ds2}} = \frac{1}{(I_1 + I_2)I_D}$$

- 2) To specify the output swing  $V_p$  for a given  $R_L$ . In this case, the maximum current to be sourced or sunk is equal to  $V_p/R_L$ . The maximum sinking current for the simple output stage in figure is:

$$I_{out}^- = \frac{K'_1 W_1}{2L_1} (V_{DD} - V_{SS} - V_{T1})^2 - I_Q \quad \text{where it has been assumed } v_{IN} = V_{DD}$$

The maximum sourcing current is:  $I_{out}^+ = \frac{K'_2 W_2}{2L_2} (V_{DD} - V_{GG2} - |V_{T2}|)^2 \leq I_Q$

Where  $I_Q$  is the dc current provided by the current source, M2.

## The maximum sinking and sourcing current

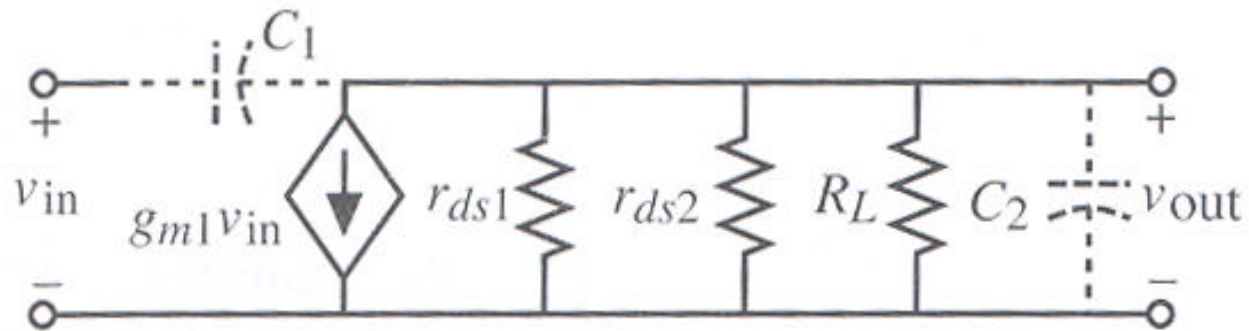
- Generally  $I_{out}^- > I_{out}^+$  because  $v_{IN}$  can be taken to  $V_{DD}$  strongly turning M1 on and  $I_Q$  is a fixed current that is normally a constant.
- The capacitor  $C_L$  also places a requirement on the output current through the slew-rate specification.

This limit can be expressed as:

$$|I_{out}| \cong C_L \left( \frac{dv_{out}}{dt} \right) = C_L (SR)$$

This approximation becomes poor when the load resistance shunting  $C_L$  is low enough to divert a significant portion of  $I_{OUT}$ , making it unavailable as charging current. For such cases the familiar exponential relationship describing the voltage across  $C_L$  is needed for accuracy. Therefore, when designing an output stage, it is necessary to consider the effects of both  $R_L$  and  $C_L$ .

## The small signal performances of the Class A



$$\frac{v_{out}}{v_{in}} = \frac{-g_{m1}}{g_{ds1} + g_{ds2} + G_L} \quad r_{out} = \frac{1}{g_{ds1} + g_{ds2}} = \frac{1}{(I_1 + I_2)I_D}$$

$$z = \frac{g_{m1}}{C_{gd1}} \quad p = \frac{-(g_{ds1} + g_{ds2} + G_L)}{C_{gd1} + C_{gd2} + C_{bd1} + C_{bd2} + C_L}$$

## Efficiency

- *Efficiency* is defined as the ratio of the power dissipated in  $R_L$  to the power required from the power supplies.

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

- The maximum efficiency of the Class A output stage occurs when  $v_{OUT}(peak)$  is  $0.5*(V_{DD}-V_{SS})$ , which is 25%.

## Harmonic Distortion (HD)

- An amplifier's distortion can be characterized by the influence of the amplifier upon a pure sinusoidal signal. Distortion is caused by the nonlinearity of the transfer curve of the amplifier. If a pure sinusoid given as:

$$V_{in}(\omega) = V_p \sin(\omega t)$$

is applied to the input, the output of an amplifier with distortion will be

$$V_{out}(\omega) = a_1 V_p \sin(\omega t) + a_2 V_p \sin(2\omega t) + \dots + a_n V_p \sin(n\omega t)$$

Harmonic distortion (HD) for the  $i$ th harmonic can be defined as the ratio of the magnitude of the  $i$ th harmonic to the magnitude of the fundamental.

For example:  $HD_2 = a_2/a_1$

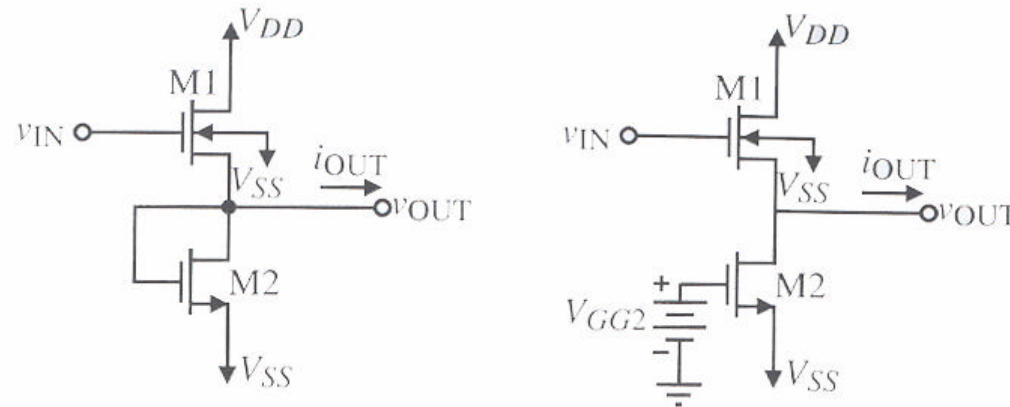
Total harmonic distortion (THD) is defined as the square root of the ratio of the sum of all of the second and higher harmonics to the magnitude of the first or fundamental harmonic.

$$THD = \frac{[a_2^2 + a_3^2 + \dots + a_n^2]^{1/2}}{a_1}$$

## Source follower

- A second approach to implementing an output amplifier is to use the common-drain or source-follower.
- This configuration has both large current gain and low output resistance.
- Unfortunately since the source is the output node, the MOS device becomes dependent on the body effect. The body effect causes the threshold voltage  $V_T$  to increase as the output voltage is increased, creating a situation where the maximum output is substantially lower than  $V_{DD}$ .

## Large-signal consideration



- $V_{OUT(\min)}$  can be essentially  $V_{SS}$  because when  $v_{IN}$  approaches  $V_{SS}$ , the current through M2 goes to zero, allowing the output voltage to go to zero. This result assumes that no current is required by the external load.
- If the source follower must sink external load current, then  $V_{OUT(\min)}$  will be greater than  $V_{SS}$ .
- The maximum value of  $V_{OUT}$  is:

$$V_{OUT(\max)} = V_{DD} - V_{T1} - V_{ON1} \approx V_{DD} - V_{T1}$$

assuming that  $v_{IN}$  can be taken to  $V_{DD}$  and no output current is flowing.

- $V_{T1}$  is a function of  $v_{OUT}$

$$V_{T1} \cong V_{TO} + g \sqrt{v_{SB}} = V_{TO1} + g_1 \sqrt{v_{out}(\max) - V_{SS}}$$

- solving for  $v_{OUT}$

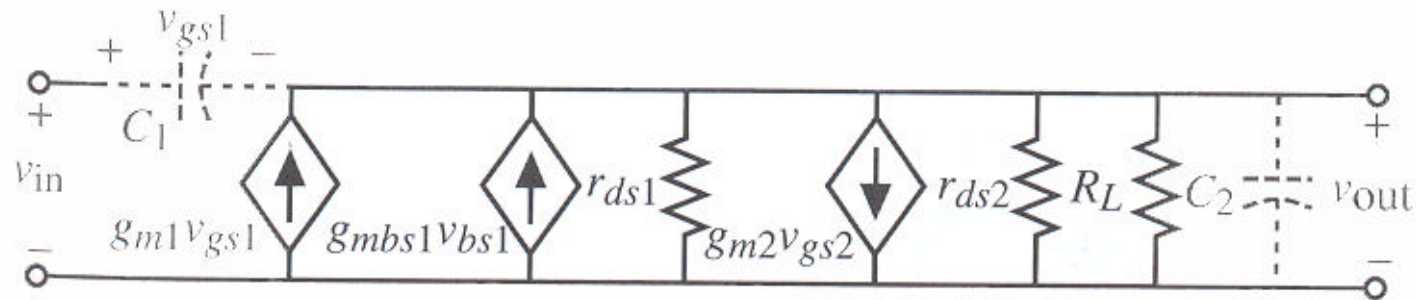
$$v_{OUT}(\max) = V_{DD} + \frac{g_1^2}{2} - V_{TO1} \sqrt{g_1^2 + 4(V_{DD} - V_{SS} - V_{TO1})}$$

- Maximum current sink

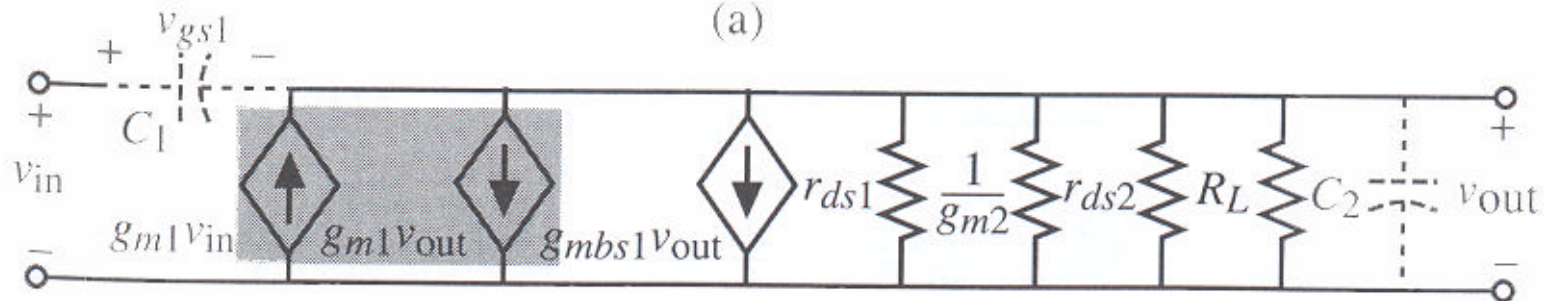
$$I_{OUT}^+ = \frac{K'_1 W_1}{2L_1} [V_{DD} - V_{SS} - V_{T1}]^2 - I_{D2}$$

- The efficiency is similar to the Class A.
- The distortion will be better because of the inherent negative feedback

## Small-signal analysis



(a)



(b)

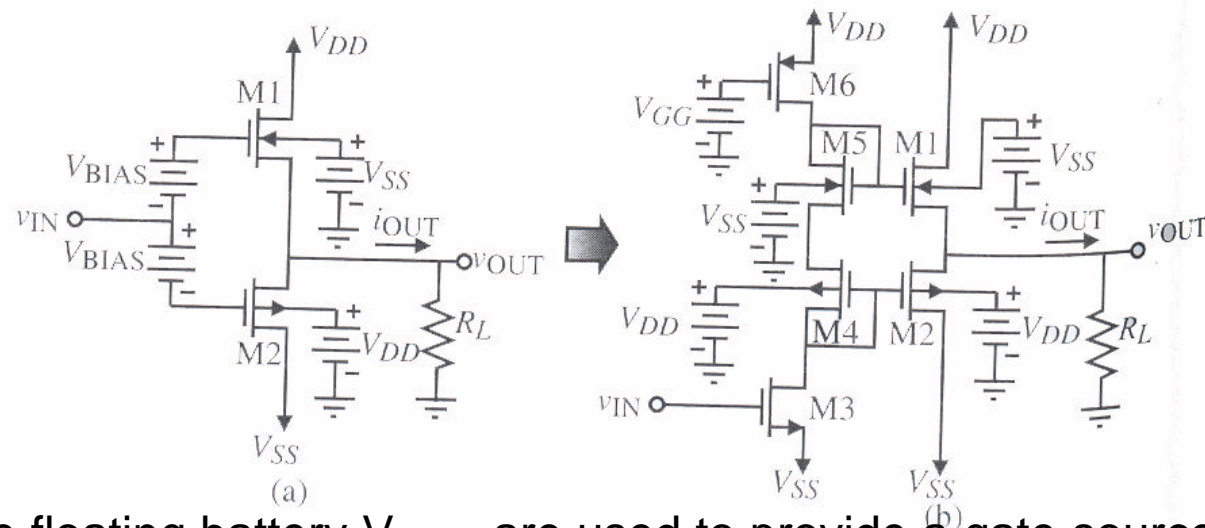
$$\frac{v_{out}}{v_{in}} = \frac{g_{m1}}{G_L + g_{ds1} + g_{ds2} + g_{m1} + g_{mbs1} + g_{m2}} \cong \frac{g_{m1}}{G_L + g_{m1} + g_{mbs1} + g_{m2}}$$

$$R_{out} = \frac{1}{g_{ds1} + g_{ds2} + g_{m1} + g_{mbs1} + g_{m2}}$$

$$\frac{V_{out}(s)}{V_{in}(s)} = \frac{g_{m1} + sC_1}{G_L + g_{ds1} + g_{ds2} + g_{m1} + g_{mbs1} + g_{m2} + s(C_1 + C_2)}$$

## Push pull

- It is of interest to consider a push-pull version of the source follower:

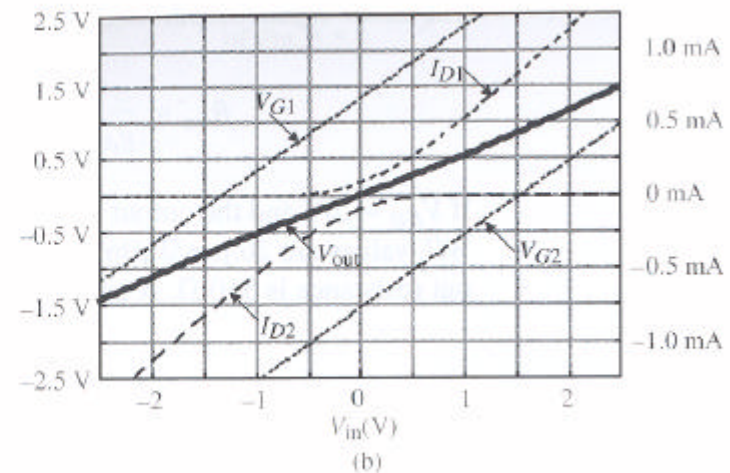
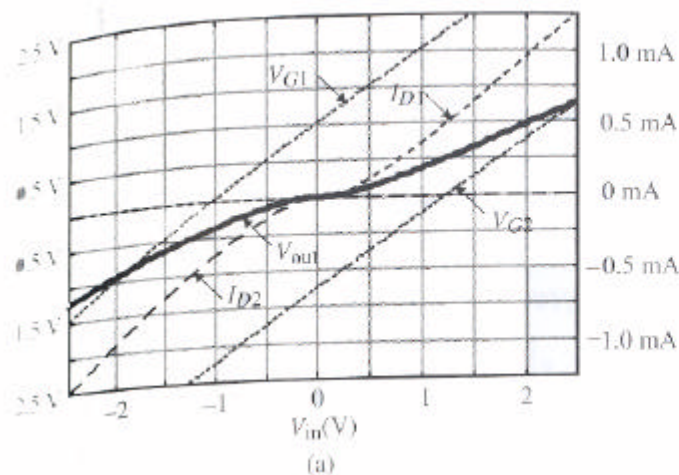


- The floating battery  $V_{BIAS}$ , are used to provide a gate-source bias to M1 and M2 in order to define the quiescent current in M1 and M2. An advantage of this circuit is that the currents are actively sourced and sunk.
- A disadvantage is that the output swing are at best limited to a threshold drop below the upper and above the power-supply voltages. This threshold are increased due to the bulk effect and severely limit the output swing.

- The efficiency of the push-pull type amplifier can be much greater than the efficiency of the class A amplifier.
- Push-pull type amplifier are called Class B or Class AB because the current in the output transistors is not flowing for the entire period of a sinusoidal output voltage.

## Output voltage and current characteristics vs input voltage

- Push-pull amplifiers are called Class B or Class AB because the current in the output transistors is not flowing for the entire period of a sinusoidal output voltage. For a Class B, the current only flows in one transistor for 180° of the 360° period and for Class AB, the current only flows between 180° and 360° of the period.



Output voltage and current characteristics for (a) Class B and (b) Class AB operation

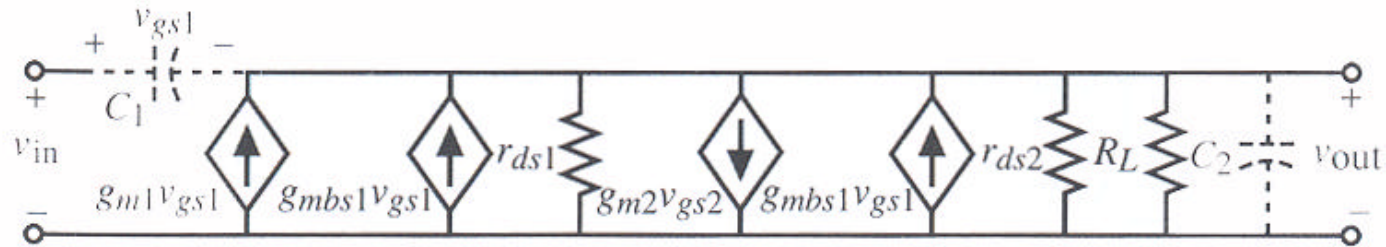
## Efficiency of a Class B amplifier

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

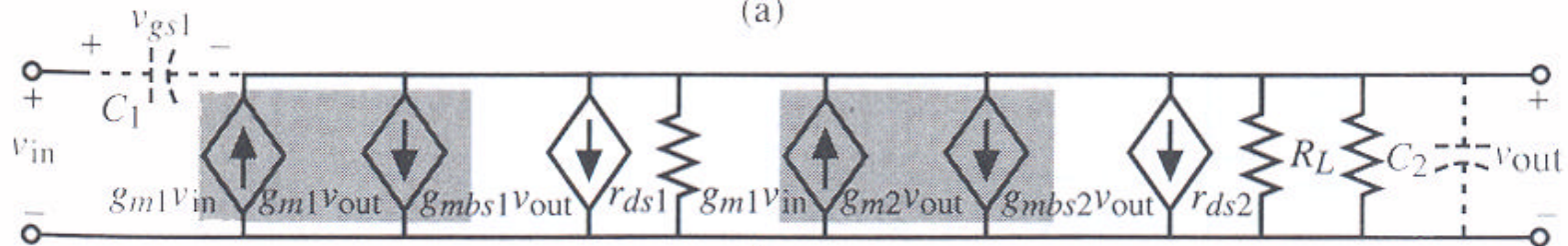
The term  $v_{OUT}(peak)/\pi R_L$  in the denominator of the middle expression represents the average current flow for half-wave rectified sinusoid. The maximum efficiency occurs when  $v_{OUT}(peak)$  is the largest, i.e.  $0.5(V_{DD}-V_{SS})$ , and it is 78.5%.

The Class AB amplifier will have efficiency between the Class A and B depending on the biasing.

## Small-signal performances of the push-pull



(a)



(b)

$$\frac{v_{out}}{v_{in}} = \frac{g_{m1} + g_{m2}}{G_L + g_{ds1} + g_{ds2} + g_{m1} + g_{mbs1} + g_{m2} + g_{mbs2}} \quad R_{out} = \frac{1}{g_{ds1} + g_{ds2} + g_{m1} + g_{mbs1} + g_{m2} + g_{mbs2} + G_L}$$

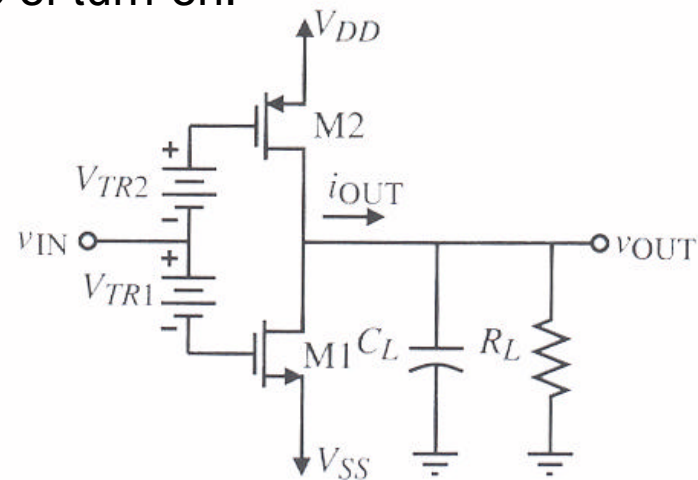
$$z = \frac{g_{m1} + g_{m2}}{C_1} \quad p = \frac{-1}{(C_1 + C_2)(g_{ds1} + g_{ds2} + g_{m1} + g_{mbs1} + g_{m2} + g_{mbs2} + G_L)}$$

## Push-pull common-source amplifier

- Class B has a maximum efficiency of 78%, which means that less quiescent current is needed to meet the output-current demands of the amplifier.
- Smaller quiescent current imply smaller values  $W/L$  and smaller area requirements.
- The class A configuration could be a push pull amplifier if the gate of M2 is simply connected to  $v_{IN}$ . This configuration has the disadvantage that large quiescent current flows when operated in the high-gain region (I.e. Class AB operation).

- If voltage sources,  $V_{TR1}$  and  $V_{TR2}$  are inserted between the gates as shown by considering the case when  $v_{IN}$  is precisely at the threshold of the n-channel device and  $V_{TR1}$  and  $V_{TR2}$  are such that the p-channel device is also operating at the verge of turn-on.

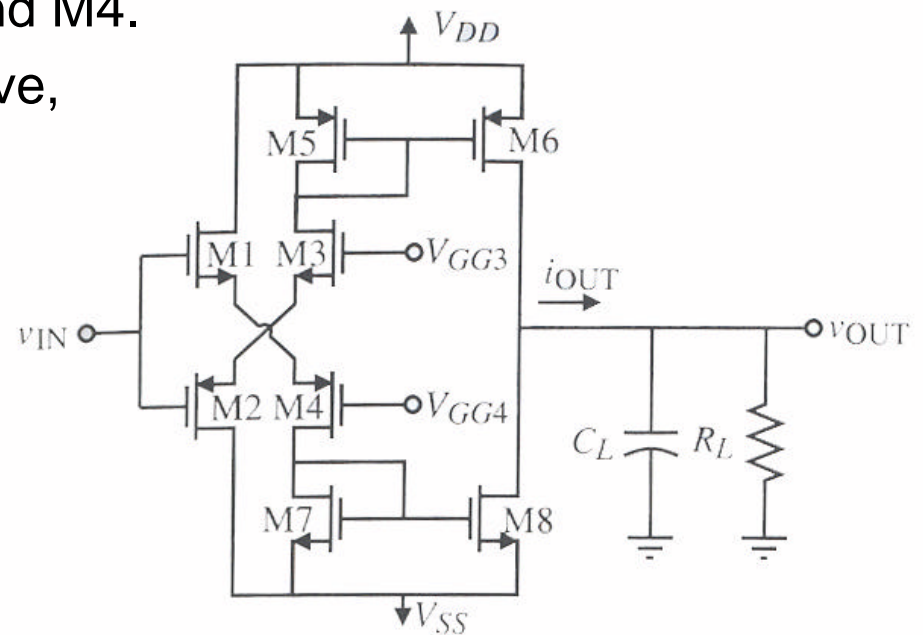
- If  $v_{IN}$  is perturbed in the positive direction, then the p-channel device turns off and all of the current in the n-channel sink the load current.



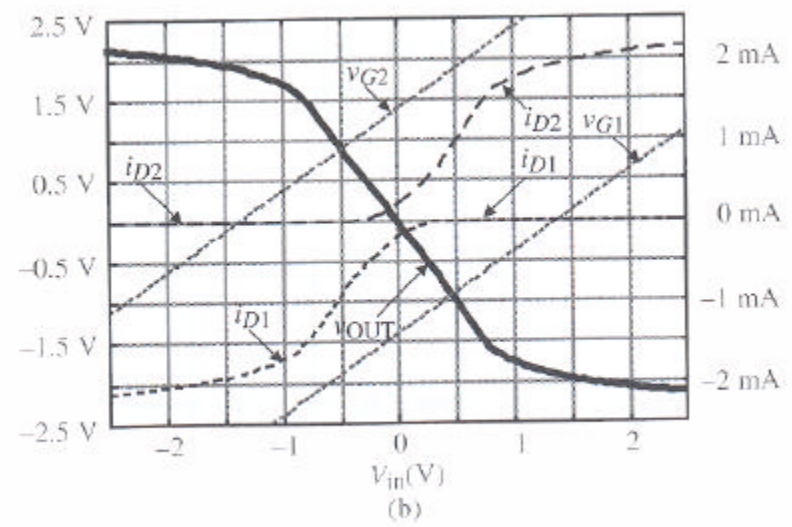
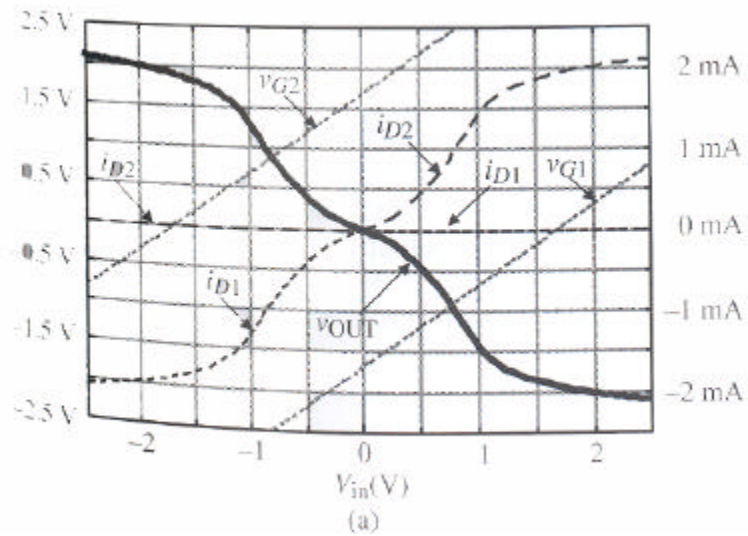
similar action occurs when  $v_{IN}$  is perturbed negatively, with the result that all of the load current is sourced by the p-channel device

## Practical Implementation

- The operation (Class B or AB) can be determined by the voltages at the gates of M3 and M4.
- When the input is taken positive, the current in M1 increases, it is mirrored as an increasing current in M3, which provides the sinking capability for the output current. When  $v_{IN}$  decreased, M6 can source output current.



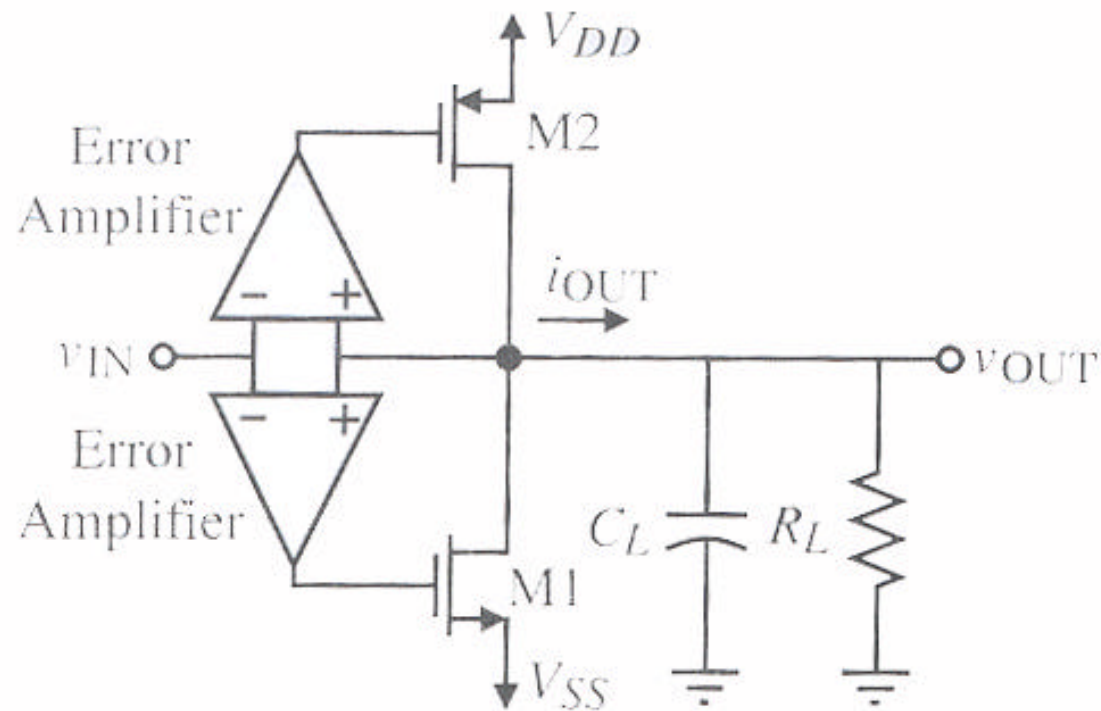
# Output voltage and current for the class B and AB



## Using BJT to reduce output resistance

- In order to reduce the output resistance and decrease the area of output stages, the substrate bipolar junction transistor available in the standard CMOS process has been used.
- The advantage of using the BJT is that the output resistance is approximately  $1/g_m$ , which for a BJT can be less than  $100\Omega$ .
- The disadvantages of the BJT is that the positive and negative parts of the voltage transfer curve are not symmetrical and therefore large distortion is encountered.
- Another disadvantage of the BJT is that as it begins to source more current, more base current is required. It is difficult for the driver to provide this base current when the base is approaching  $V_{DD}$ .

## Use of negative feedback to reduce the output resistance



## Use of negative feedback to reduce the output resistance (2)

- If the push-pull amplifier has sufficient gain, the error amplifiers can be replaced by a resistive feedback network. The resistor could be polysilicon or could be MOS transistors.
- If the resistors were equal, the output resistance would be divided by approximately  $g_{m1} R_L/2$

