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

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

\[
\text{Efficiency} = \frac{P_{RL}}{P_{\text{Supply}}} = \frac{v_{OUT}(\text{peak})^2}{2RL} \times \frac{1}{(V_{DD}-V_{SS})I_Q} = \frac{v_{OUT}(\text{peak})^2}{2RL} \left(\frac{(V_{DD}-V_{SS})}{2RL} \right) = \left(\frac{v_{OUT}(\text{peak})}{V_{DD}-V_{SS}}\right)^2
\]

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

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

- Maximum sourcing current is,

\[ I_{OUT}^+ = \frac{K'_2 W_2}{2L_2} (V_{DD} - V_{GG2} - |V_{T2}|)^2 \leq I_Q \]

Requirements:

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

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:

Voltage transfer curve:

Maximum output voltage swings:

\[ v_{OUT}(\text{min}) \approx V_{SS} - V_{ON2} \text{ (if } R_L \text{ is large)} \]

\[ v_{OUT}(\text{max}) = V_{DD} - V_{ON1} \text{ (if } v_{IN} > V_{DD} \) \]

or

\[ v_{OUT}(\text{min}) \approx -I_{Q}R_{L} \text{ (if } R_L \text{ is small)} \]

or

\[ v_{OUT}(\text{max}) \approx V_{DD} - V_{GS1} \]
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

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

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

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

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:

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

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)
  \[ v_{OUT}(\text{peak})^2 \]
  \[ P_{RL} \]

\[ \therefore \text{Efficiency} = \frac{P_{RL}}{P_{VDD}} = \frac{2v_{OUT}(\text{peak})^2}{(V_{DD} - V_{SS})(\frac{1}{2}) 2v_{OUT}(\text{peak})} = \frac{\pi}{2} \frac{v_{OUT}(\text{peak})}{V_{DD} - V_{SS}} \]

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 ($R_L = 1k\Omega$):

Comments:
- Note that $v_{\text{OUT}}$ cannot reach the extreme values of $V_{DD}$ and $V_{SS}$
- $I_{\text{OUT}}^{+}(\text{max})$ and $I_{\text{OUT}}^{-}(\text{max})$ is always less than $V_{DD}/R_L$ or $V_{SS}/R_L$
- For $v_{\text{OUT}} = 0V$, 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

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

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

A zero and pole are located at

\[
z = \frac{-(g_{m1} + g_{m2})}{C_1}
\]

\[
p = \frac{-(g_{ds1} + g_{ds2} + g_{m1} + g_{mbs1} + g_{m2} + g_{mbs2} + G_L)}{C_1 + C_2}
\]

These roots will be high-frequency because the associated resistances are small.
Push-pull source follower

\[ V_{GS1} + |V_{GS2}| = V_{GS3} + |V_{GS4}| \Rightarrow I_{Q1} = I_{B1} \left( \frac{1}{\sqrt{k'_n(W/L)_3}} + \frac{1}{\sqrt{k'_p(W/L)_4}} \right)^2 \left( \frac{1}{\sqrt{k'_n(W/L)_1}} + \frac{1}{\sqrt{k'_p(W/L)_2}} \right)^2 \]
Push-pull common-source amplifier

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

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

$V_{GG3}$ 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

\[ R_{out} = \frac{r_{ds1} \parallel r_{ds2}}{1 + \text{Loop Gain}} \]

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

![Circuit Diagram](image)

**Loop gain**

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

**\(R_{out}\)**

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