Lecture 31:

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Context

We are looking at more examples of single transistor active circuits and typical design problems, and starting multi-stage amplifiers

Lecture Outline

- Example: Voltage regulator
- Transimpedance Amplifier
- Source Follower
- Current Mirror
- Push-Pull Amplifier
- Multistage Amplifiers

Reading

- We are starting on chapter 9, multi-stage amplifiers

Homework:
Make sure you do problem P8.18, not example E8.18
One problem that often arises is that of taking an imperfect power supply and creating a regulated power supply. For example, Electrically programmable memories are often very sensitive to voltage.

There are two basic solutions to the voltage regulation problem:

- Series regulators
- Shunt regulators

And there are Analog and Switched solutions

Series regulators

In a series regulator, a higher voltage unregulated supply is reduced and regulated by putting a device in series with the source.

\[ V_{\text{unregulated}} - V_{\text{regulated}} \]

In this shunt regulator, we need the unregulated voltage to be sufficiently higher than the regulation point so that the device works properly, and the power \( I_{\text{load}}(V_{\text{unregulated}} - V_{\text{regulated}}) \) is lost.

Shunt regulators

In a shunt regulator, a higher voltage unregulated supply which has some source resistance is shunted to ground by a parallel device in order to keep the regulated voltage from going too high.

\[ V_{\text{unregulated}} - V_{\text{regulated}} \]

In a shunt regulator, the controlling device can even be turned off, so that the power lost can be reduced to zero in the case where power is most critical, but the power lost can be high if the unregulated voltage goes up, or if the source impedance is low. The power \( (I_{\text{source}} - I_{\text{load}})(V_{\text{unregulated}}) \) is lost.

Uses

For a battery powered device, you would want to use a series regulator to avoid draining the battery.

If the source of power can't be depleted, you might want to use a shunt regulator so that losses only occur when you are trying to throw away power anyway!

- Solar powered device or array
- Passive RFID tags
- Wind or Small hydroelectric

(What does an automobile use?)
**Series regulators**

- Here is a linear series regulator using a common gate connected transistor. Since the drain current is relatively independent of the drain voltage when the transistor is in saturation, regulation can be good as long as sufficient drop is available.

\[ V_{\text{unregulated}} - V_{\text{regulated}} = \text{drop} \]

In this series regulator, we need the unregulated voltage to be sufficiently higher than the regulation point so that the transistor will be in forward saturation (or the regulation will be poor). The power \( I_{\text{load}}(V_{\text{unregulated}} - V_{\text{regulated}}) \) is lost. For large currents, with devices that need approximately a volt drop across them, this is a large loss.

**Shunt regulators**

- In this shunt regulator, a common source device is used as an active load configuration to pull down excessive voltage at the load.

\[ V_S - V_{\text{DD}} = \text{drop} \]

**Load line diagram**

- In order to find the operating point for the regulator at a given supply voltage, we draw a load line for the resistor, and the current available from the resistor as a function of \( V_{\text{DD}} \).

**Regulation**

- Two questions that we can ask about regulation:
  - If the supply voltage varies, how much does the output voltage vary?
  - If the load current varies, how much does the output voltage vary?

- If the load current is held constant, the change in the output voltages is given by the variation in the supply voltage divided down by a resistive divider.

Since the drain current is a relatively insensitive function of the drain voltage, we get that the change in the drain current is just:

\[ I_D = I_{\text{source}} \frac{1}{R_{\text{source}}} \]

So the FET in small signal looks like a resistor with a resistance:

\[ R_s = \left( \frac{1}{R_{\text{source}}} \right) \]
shunt regulator

- So we have
\[
\frac{\Delta V_{DD}}{\Delta V_s} = \frac{V_{ss}}{V_{ss} + R} = \frac{1}{g_m + 1}
\]

- Let's hold VDD constant and vary the load current by a small amount. In small signal, this looks like a current being divided between two resistors to SS ground:
\[
R \quad \frac{I_L}{+} \quad \left( \frac{1}{g_m} \right)
\]
So a small change in the output current sees a source impedance:
\[
Z_s = \frac{1}{g_m} R = \frac{1}{g_m + \frac{V}{R}} = \frac{R}{g_m + 1}
\]
In both cases, the regulation is poor because \( g_m \) is relatively small.

Add Voltage gain: common gate stage

- If we add gain in the small signal voltage at the gate of the FET, we can improve regulation
\[
\begin{align*}
\Delta V_{DD} & = \frac{1}{1 + g_m RA} \\
\Delta V_s & = \frac{1}{1 + g_m R^2}
\end{align*}
\]
As VDD goes up, the current through the PMOS transistor goes up: \( \Delta I_v = V_{DD} R g_m \) so the small signal voltage
\[
\frac{\Delta V_{DD}}{\Delta V_s} = 1 + g_m R A
\]

Transimpedance Amplifier

- The transimpedance is:
\[
A_I = \frac{V_{in}}{I_{in}} = \frac{i_g}{i_i} = \frac{W_{L1}}{g_m W_1 L_1}
\]
Source Follower

- Gain:
  \[ A_i = \frac{V_{out}}{V_{in}} = \frac{1}{g_{m1}} = \frac{1}{1 + \frac{g_{m1}}{g_{m2}}} = \frac{1}{1 + \frac{W_L}{W_D}} \]

Current Mirror

- Since \( V_{gs1} = V_{gs2} \)
  \[ \frac{I_{D1}}{I_{D2}} = \frac{W_1}{W_2} \]

Using a Current Source as a Load

- Gain is given by:
  \[ A_i = \frac{g_{m1}}{g_{m2}} = \frac{-\sqrt{2R}}{(\lambda_1 + \lambda_2) \sqrt{I_D}} \]
- Notice that the gain can be adjusted by changing the bias current

Push-Pull Amplifier

- Gain:
  \[ A_i = \frac{V_{out}}{V_{in}} = \frac{-\lambda_i (g_{m1} + g_{m2})}{\lambda_j (g_{m1} + g_{m2})} \]
Multistage Amplifiers

Typically needed to meet specifications for any of the 4 types of amplifiers, single transistor solutions won’t be enough.

We have 2 flavors (NMOS, PMOS) of CS, CG, and CD and the npn versions of CE, CB, and CC (for a BiCMOS process)

What are the intra-stage constraints?

1. Input/output resistance matching
2. DC coupling (no passive elements to block the signal)

Summary of Cascaded Amplifiers

General goals:

1. Boost the gain (except for buffers)
2. Improve frequency response
3. Optimize the input and output resistances:

<table>
<thead>
<tr>
<th>Type</th>
<th>(R_{in})</th>
<th>(R_{out})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage</td>
<td>(\infty)</td>
<td>0</td>
</tr>
<tr>
<td>Current</td>
<td>0</td>
<td>(\infty)</td>
</tr>
<tr>
<td>Transconductance</td>
<td>(\infty)</td>
<td>(\infty)</td>
</tr>
<tr>
<td>Transresistance</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Start: Two-Stage Voltage Amplifier

- Use two-port models to explore whether the combination "works"

\[
A_v = -G_{m1} \left( R_{in} \parallel R_{out} \right) \times \left( -G_{m2} R_{out} \right)
\]

\[
A_c = G_{m1} G_{m2} \left( R_{in} \parallel R_{out} \right) \left( R_{out} \right)
\]

Cascading stages

Input resistance: \(\infty\)

Voltage gain (2-port parameter):

\[
A_v = -g_{m1} \left( r_{in} \parallel r_{m1} \right) \times g_{m2} \left( -r_{m2} \parallel r_{m2} \right)
\]

Output resistance:

\[
R_{out} = \frac{1}{g_{m} + g_{ab}}
\]
Multistage Current Buffers

Are two cascaded common-base stages better than one?

\[ R_{in} = R_{in1} \]

Common-Gate 2nd Stage

Two-Port Models

Second Design Issue: DC Coupling

Constraint: large inductors and capacitors are not available
Output of one stage is directly connected to the input of the next stage \( \rightarrow \) must consider DC levels

\[ R_{out} = R_{out2} \approx r_{o2} \left( 1 + g_m r_{x2} \| R_{S2} \right) \| r_{oc2} \]

\[ R_{out} \approx r_{o2} \left( g_m r_{x2} \right) \| r_{oc2} = \left( \beta r_{o2} \right) \| r_{oc2} \]
Alternative CG-CC Cascade

Use a PMOS CD Stage: DC level shifts upward

CG Cascade: Sharing a Supply

First stage has no current supply of its own → its output resistance is modified

CG Cascade: DC Biasing

Two stages can have different supply currents

Extreme case: \( I_{\text{BIAS}} = 0 \, \text{A} \)

The Cascode Configuration

Common source / common gate cascade is one version of a cascode (all have shared supplies)