Understanding the High-Frequency Cutoff in a JFET Common-Source Amplifier

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Objective

To deeply understand the cause of the $-3\,\mathrm{dB}$ cutoff frequency in a JFET amplifier by examining the role of inter-electrode capacitances (from datasheet), the Miller effect, and the resulting low-pass behavior.

1. Background: The JFET Amplifier

The J310 JFET was used in a common-source amplifier configuration:

- Gate: receives the input signal
- Drain: connected to a load resistor, produces the output
- Source: grounded or bypassed

This configuration is **inverting**, meaning:

> If the input voltage increases, the output voltage decreases, and vice versa.

2. Datasheet Parameters Relevant to Cutoff

From the J310 datasheet (ON Semiconductor):

- Gate–Drain Capacitance C_{gd}: $1.8\,\mathrm{pF}$ (typical), $2.5\,\mathrm{pF}$ (max)
- Gate–Source Capacitance C_{gs}: $4.3\,\mathrm{pF}$ (typical), $5.0\,\mathrm{pF}$ (max)

These are internal capacitances between the transistor terminals and are not shown explicitly in the schematic, but they significantly affect circuit performance at high frequencies.

3. Miller Effect: Why Capacitance Appears to Grow

3.1 Voltage Swing Across C_{gd}

In the LTspice simulation, the input signal amplitude was 0.1 V. Assuming an amplifier voltage gain of $A_v = -11$, the corresponding output swing would be approximately -1.1 V.

So the voltage across C_{gd} changes by:

$$V_{gd} = V_g - V_d = (+0.1) - (-1.1) = 1.2\,\text{V}$$

This significant voltage swing across a small internal capacitance creates a large displacement current, making the capacitor pass more current than expected. This causes it to **behave like a much larger capacitor**.

3.2 Effective Capacitance

The Miller effect makes C_{gd} look larger from the input side:

$$C_{gd,\text{eff}} = C_{gd} \cdot (1 + |A_v|)$$

If $C_{gd} = 2.5\,\text{pF}$ and $A_v = -11$:

$$C_{gd,\text{eff}} = 2.5 \cdot (1 + 11) = 30\,\text{pF}$$

Adding C_{gs} gives the total input capacitance:

$$C_{in} = C_{gs} + C_{gd}(1 + |A_v|) \approx 5 + 30 = 35\,\text{pF}$$

This increased effective input capacitance is responsible for the **lowering of the cutoff frequency**, meaning the amplifier cannot respond to high-frequency signals beyond a certain point.

4. RC Low-Pass Filter and Cutoff Frequency

4.1 What is a Low-Pass Filter?

A low-pass filter is a circuit that allows low-frequency signals to pass through while attenuating (blocking) high-frequency signals. It is typically formed by a resistor (R) and a capacitor (C). In the JFET amplifier, the input gate forms a low-pass filter with:

- R_g: the gate resistor (e.g., $100\,\text{k}\Omega$)
- C_{in}: the effective capacitance due to C_{gs} and the Miller-multiplied C_{gd}

4.2 Why This Causes Cutoff

At low frequencies, the capacitor blocks current, so the signal goes to the gate and gets amplified. At high frequencies, the capacitor conducts current and "shorts" the signal to ground, preventing it from reaching the gate. This leads to a drop in gain.

4.3 Cutoff Frequency Calculation

The cutoff frequency (where gain drops by 3 dB) is given by:

$$f_c = \frac{1}{2\pi RC}$$

In this case:

$$R = 100\,\mathrm{k}\Omega, \quad C = C_{gs} + C_{gd}(1 + |A_v|) \approx 35\,\mathrm{pF}$$

$$f_c = \frac{1}{2\pi \cdot 100{,}000 \cdot 35 \cdot 10^{-12}} \approx 45.5\,\mathrm{MHz}$$

This formula does not use C_{gd} directly as a standalone value because its effect is embedded within the Miller-multiplied term. So although C_{gd} is internal and not shown in the schematic, it is indirectly included in the calculation via the Miller effect.

5. Why Gain Drops at High Frequency

- At low frequencies: capacitor blocks changes, so signal reaches the gate → amplifier works fully.
- At high frequencies: capacitor conducts more → signal leaks through capacitor instead of reaching the gate → less input → less output gain.

This is how the **gain drops** beyond the cutoff frequency.

6. What Affects Cutoff Frequency?

- $\mathbf{C_{gd}}$ — higher C_{gd} = lower cutoff frequency (due to stronger Miller effect)
- **Gain** — higher gain = larger $C_{gd,eff}$ = lower cutoff
- **Gate resistance (R)** — higher R = lower cutoff
- **Bypass/coupling capacitors** — can introduce additional poles

7. Visual Summary (Conceptual)

> *"Think of the gate as drinking signal through a straw. C_{gd} is like a leaky hole in the straw that grows bigger as gain increases. At high frequencies, most of the signal leaks out before it reaches the amplifier — that's why gain drops."*

8. Reference Datasheet

The J310 datasheet referenced for capacitance values and electrical characteristics is available from ON Semiconductor (now part of onsemi):

- **J310 Datasheet (onsemi)**: `https://www.onsemi.com/pdf/datasheet/j310-d.pdf`