(7) Differential Amplifier with Active Load

Reference: Neamen, Chapter 11

1

Learning Outcome

Able to:

- Describe active loads.
- Design a diff-amp with an active load to yield a specified differential-mode voltage gain.

2

7.0) Active Loads

- **Active loads** are essentially **transistor current sources used in place of the resistive loads** in the diff-amp circuits **to increase differential-mode gain.**
- BJTs {**MOSFETs**} in the active load circuit are biased at Q-point in forward-active {**saturation**} mode.
- Diff-pair induces a change in I_C {I_D}, which in turn, produces a change in V_{EC} {V_{SD}}.

➔ Refer to **Figure 11.27** for BJT.

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7.0) Active Loads (Cont)

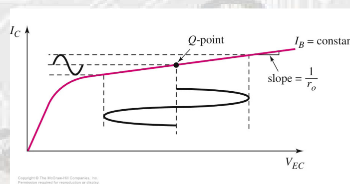

Figure 11.27: Current-voltage characteristics of active load device using BJT.

- ΔV_{EC} {ΔV_{SD}} **is proportional to** r_o (small-signal output resistance) of the transistor.
- Value of r_o **is much larger than resistive loads**, so the small-signal **voltage gain will be larger** with the active load.

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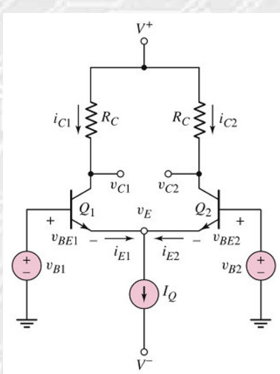
5.2) Basic BJT Differential Pair



- **Figure 11.2** shows the basic BJT differential-pair configuration using npn transistors.

REMEMBER…

Figure 11.2: Basic BJT differential-pair **using npn transistors**.

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7.1) BJT Diff-Amp with Active Load

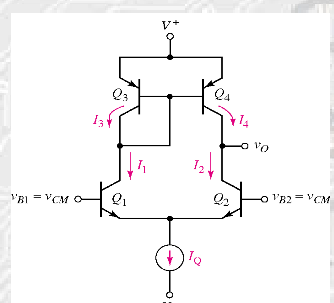

Figure 11.28: BJT diff-amp with active load.

- **Figure 11.28** shows a diff-amp with active load.

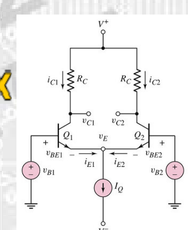

Figure 11.2

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7.1) BJT Diff-Amp with Active Load (Cont)

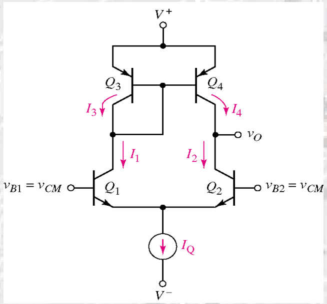

Figure 11.28: BJT diff-amp with active load.

- Q_1 and Q_2 are diff pair biased with a constant current I_Q, and **Q_3 and Q_4 form the load circuit**.
- From the collectors of Q_2 and Q_4, obtain a **one-sided output v_O.**

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7.1) BJT Diff-Amp with Active Load (Cont)

IDEAL CASE:

- All Qs are matched:
  - → $v_{B1} = v_{B2} = v_{CM}$
  - → I_Q splits evenly between Q_1 and Q_2
- Neglecting base currents:
  - → $I_4 = I_3$ [through current-source circuit]
  - → $I_1 = I_2 = I_3 = I_4 = I_Q/2$ with no load connected at output.

ACTUAL CASE:

- Base currents are non-zero.
- A second amplifier stage is connected at the diff-amp output.

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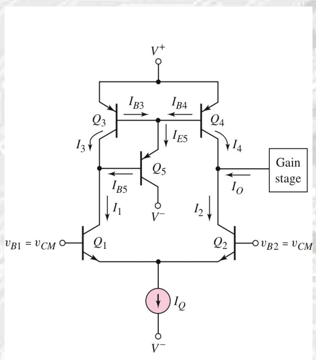
7.1) BJT Diff-Amp with Active Load (Cont)



- **Figure 11.29** shows a diff-amp with **an active load, corresponding to a 3-transistor current source**, as well as a second amplifying stage (**gain stage**).

Figure 11.29: BJT diff amp with 3-transistor active load and second stage gain.

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7.1) BJT Diff-Amp with Active Load (Cont)

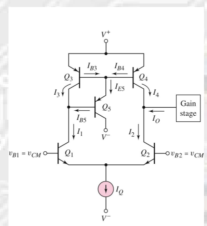

Figure 11.29: BJT diff amp with 3-transistor active load and second stage gain.

- For simplicity, assume all Qs current gain (β) are equal.
- Current I_O is the dc bias current from the gain stage.
- Assuming all Qs are matched and $v_{B1} = v_{B2} = v_{CM}$, current I_Q splits evenly and $I_1 = I_2$
- To ensure that Q_2 and Q_4 are biased in forward-active mode, **dc currents must be balanced, or $I_3 = I_4$**

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7.1) BJT Diff-Amp with Active Load (Cont)

- From **Figure 11.29**

$$I_{E5} = I_{B3} + I_{B4} = \frac{I_3}{\beta} + \frac{I_4}{\beta} \quad (11.93)$$

Then

$$I_{B5} = \frac{I_{E5}}{1+\beta} = \frac{I_3 + I_4}{\beta(1+\beta)} \quad (11.94)$$

If base currents and I_O are small, then

$$I_3 + I_4 \cong I_Q$$

Therefore,

$$I_{B5} \cong \frac{I_Q}{\beta(1+\beta)} \quad (11.96)$$

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7.1) BJT Diff-Amp with Active Load (Cont)

- For the **circuit to be balanced**, i.e. for $I_1 = I_2$ and $I_3 = I_4$, must have

$$I_O = I_{B5} = \frac{I_Q}{\beta(1+\beta)} \quad (11.97)$$

Equation (11.97) implies that 2nd amplifying stage must be **designed and biased such that the direction of the dc bias current** is as shown in **Figure 11.29** and its value is equal to the result of Equation (11.97).

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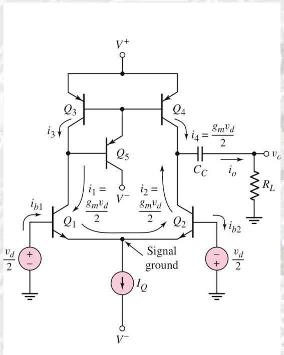
7.2) Small-Signal Analysis of BJT Active Load



• **Figure 11.30** shows a differential amplifier with a 3-transistor active load circuit.

Figure 11.30: BJT diff-amplifier with 3-transistor active load, showing the signal currents.

7.2) Small-Signal Analysis of BJT Active Load (Cont)

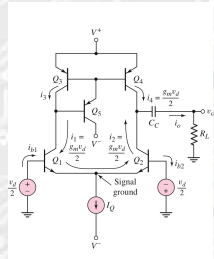


Figure 11.30: BJT diff amp with 3-transistor active load, showing the signal currents.

• The resistance R_L represents small-signal input resistance of the gain stage.

• A pure diff-mode input voltage is applied as indicated.

• Signal voltage at base of Q_1 produces a signal collector current

$$i_1 = (g_m v_d) / 2$$

where g_m is transconductance for both Q_1 and Q_2

7.2) Small-Signal Analysis of BJT Active Load (Cont)

• Assume the **base currents are negligible**, a signal current $i_3 = i_1$ is induced in Q_3, and the current mirror produces a signal current i_4 equal to i_3.

• Signal voltage at the base of Q_2 produces a signal collector current $i_2 = (g_m v_d) / 2$, with direction shown.

7.2) Small-Signal Analysis of BJT Active Load (Cont)

• The two signal currents' transistors are biased at the same quiescent current, i_2 and i_4, add to produce a signal current in the load resistance R_L.

• The discussion is a first-order evaluation of circuit operation → know the induced currents in Q_2 and Q_4
➔ **To more accurately determine the output voltage,** need to consider equivalent small-signal collector-emitter output circuit of the 2 transistors.

7.2) Small-Signal Analysis of BJT Active Load (Cont)

• **Figure 11.31(a)** shows the small-signal equivalent circuit at collector nodes of Q_2 and Q_4. The circuit can be rearranged to combine signal grounds at a common point, as in Figure 11.31(b).

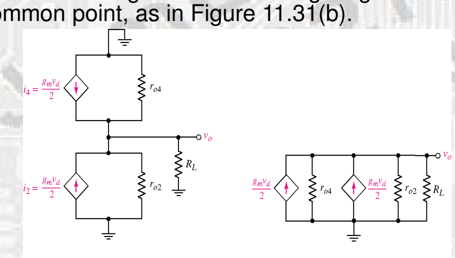


Figure 11.31: (a) Small-signal equivalent circuit BJT diff amp with active load and (b) rearrangement of small-signal equivalent circuit.

7.2) Small-Signal Analysis of BJT Active Load (Cont)

• From **Figure 11.31(b),** the Output Voltage is

$$v_o = 2\left(\frac{g_m v_d}{2}\right)\left(r_{o2} \| r_{o4} \| R_L\right) \quad (11.98)$$

and the small-signal diff-mode voltage gain is

$$A_d = \frac{v_o}{v_d} = g_m\left(r_{o2} \| r_{o4} \| R_L\right) \quad (11.99)$$

Equation (**11.99**) can be rewritten in the form

$$A_d = \frac{g_m}{\frac{1}{r_{o2}} + \frac{1}{r_{o4}} + \frac{1}{R_L}} = \frac{g_m}{g_{o2} + g_{o4} + G_L} \quad (11.100)$$

7.2) Small-Signal Analysis of BJT Active Load (Cont)

• Recall that

$$g_m = I_Q / 2V_T, r_{o2} = V_{A2} / I_2, r_{o4} = V_{A4} / I_4$$

The parameters g_{02}, g_{04}, and G_L are the corresponding conductances. Assuming

$$I_2 = I_4 = I_Q / 2$$

Equation (**11.100**) can be rewritten in the form

$$A_d = \frac{\frac{I_Q}{2V_T}}{\frac{I_Q}{2V_{A2}} + \frac{I_Q}{2V_{A4}} + \frac{1}{R_L}} \qquad (11.101)$$

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7.2) Small-Signal Analysis of BJT Active Load (Cont)

• The **Output Resistance** looking back into the common collector node is

$$R_o = r_{o2} \| r_{o4}$$

• To minimize loading effects, need $R_L > R_o$.

• However, since R_o is generally large for active loads, this condition may not be able to be satisfied.

• The severity of the loading effect can be determined by comparing R_L and R_o.

Next

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7.2) Small-Signal Analysis of BJT Active Load (Cont)

Example 11.10

Objective:
Determine the differential-mode gain of a diff-amp with an active load, taking loading effects into account.

Consider the diff-amp in **Figure 11.30**, biased with I_Q**= 0.20 mA**. Assume an Early voltage of V_A **= 100 V** for all transistors.

Determine the open-circuit ($R_L = \infty$) differential-mode voltage gain, as well as the differential-mode voltage gain when $R_L = 100\ \text{k}\Omega$.

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7.2) Small-Signal Analysis of BJT Active Load (Cont)

Example 11.10 (Cont)

Solution:

From Equation (11.101), the open-circuit voltage gain becomes

$$A_d = \frac{\frac{I_Q}{2V_T}}{\frac{I_Q}{2V_{A2}} + \frac{I_Q}{2V_{A4}}} = \frac{\frac{0.2\text{m}}{2(0.026)}}{\frac{0.2\text{m}}{2(100)} + \frac{0.2\text{m}}{2(100)}} = 1923$$

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7.2) Small-Signal Analysis of BJT Active Load (Cont)

Example 11.10 (Cont)

Solution: (Cont)

When $R_L = 100\ \text{k}\Omega$, the voltage gain is

$$A_d = \frac{\frac{I_Q}{2V_T}}{\frac{I_Q}{2V_{A2}} + \frac{I_Q}{2V_{A4}} + \frac{1}{R_L}}$$

$$A_d = \frac{\frac{0.2\text{m}}{2(0.026)}}{\frac{0.2\text{m}}{2(100)} + \frac{0.2\text{m}}{2(100)} + \frac{1}{100\text{k}}} = 321$$

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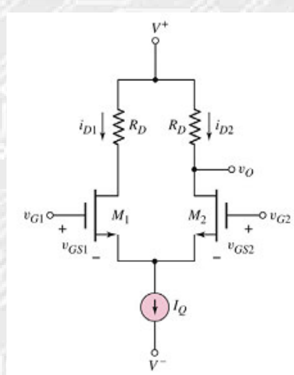
6.1) Basic MOSFET Differential Pair



• **Figure 11.19** shows the basic MOSFET diff-pair configuration using N-MOSFET.

REMEMBER…

Figure 11.19: Basic MOSFET differential-pair configuration.

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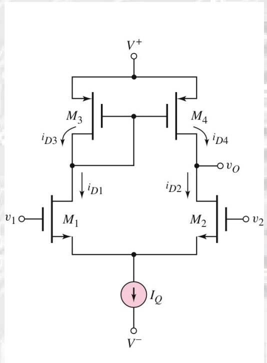
7.3) MOSFET Diff-Amp with Active Load



- **Figure 11.32** shows a MOSFET diff-amp with an active load.

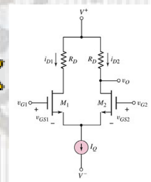


Figure 11.32: MOSFET diff-amp with active load.

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7.3) MOSFET Diff-Amp with Active Load (Cont)

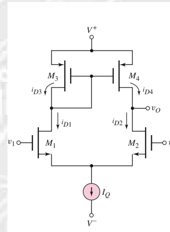

Figure 11.32: MOSFET diff amp with active load.

- M_1 **and** M_2 are n-channel devices and form the **diff pair biased with** I_Q.
- **The load circuit consists of** M_3 **and** M_4, both p-channel devices, connected in a current-mirror configuration.
- A one-sided output v_O is taken from the common drains of M_2 and M_4.

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7.3) MOSFET Diff-Amp with Active Load (Cont)

- When a common-mode voltage

$$v_1 = v_2 = v_{CM}$$

is applied:
→ the current I_Q splits evenly between transistors M_1 and M_2,
→ and $i_{D1} = i_{D2} = I_Q / 2$.

- There are no gate currents, therefore $i_{D3} = i_{D1}$ and $i_{D4} = i_{D2}$

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7.3) MOSFET Diff-Amp with Active Load (Cont)

- If a small diff-mode input voltage $v_d = v_1 - v_2$ is applied, then from (11.66) and (11.67):

$$i_{D1} = (I_Q / 2) + i_d \quad (11.102(a))$$
$$i_{D2} = (I_Q / 2) - i_d \quad (11.102(b))$$

where i_d is the signal current.

- For small values of v_d,

$$i_d = (g_m v_d) / 2$$

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7.3) MOSFET Diff-Amp with Active Load (Cont)

- Since M_1 and M_2 are in series, can be seen that

$$i_{D3} = i_{D1} = (I_Q / 2) + i_d \quad (11.103)$$

- Finally, the current mirror consisting of M_3 and M_4 produces

$$i_{D4} = i_{D3} = (I_Q / 2) + i_d \quad (11.104)$$

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7.4) Small-Signal Analysis of MOSFET Active Load

- **Figure 11.33** is ac equivalent circuit of the diff-amp with active load circuit, showing the signal currents.

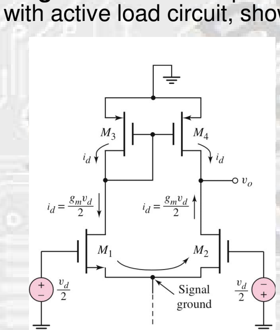

Figure 11.33: The ac equivalent circuit, MOSFET diff amp with active load.

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7.4) Small-Signal Analysis of MOSFET Active Load (Cont)

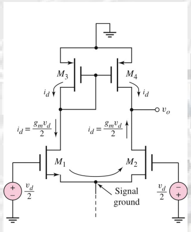

Figure 11.33: The ac equivalent circuit, MOSFET diff amp with active load.

- The negative sign for i_{D2} in (11.102(b)) shows up as a change in current direction in M_2, as indicated in the figure.
- **Figure 11.34(a)** shows the small-signal equivalent circuit at drain nodes of M_2 and M_4.
- By connecting the output to gate of **another MOSFET** (i.e. equivalent to ∞ **impedance** at low frequency), output terminal is effectively an open circuit.

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7.4) Small-Signal Analysis of MOSFET Active Load (Cont)

- Therefore, the circuit can be rearranged by combining the signal grounds at a common point, as shown in **Figure 11.34(b)**.

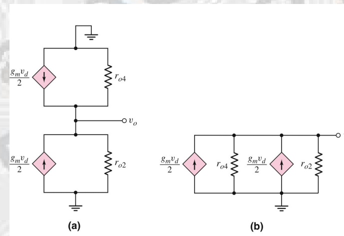

Figure 11.34: (a) Small-signal equivalent circuit, MOSFET diff amp with active load and (b) rearranged small-signal equivalent circuit.

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7.4) Small-Signal Analysis of MOSFET Active Load (Cont)

- From **Figure 11.34(b),** the **Output Voltage** is

$$v_o = 2\left(\frac{g_m v_d}{2}\right)\left(r_{o2} \| r_{o4}\right) \qquad (11.105)$$

and the **small-signal diff-mode voltage gain** is

$$A_d = \frac{v_o}{v_d} = g_m\left(r_{o2} \| r_{o4}\right) \qquad (11.106)$$

Equation (11.106) can be rewritten in the form

$$A_d = \frac{g_m}{\frac{1}{r_{o2}} + \frac{1}{r_{o4}}} = \frac{g_m}{g_{o2} + g_{o4}} \qquad (11.107)$$

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7.4) Small-Signal Analysis of MOSFET Active Load (Cont)

- Recall that

$$g_m = 2\sqrt{K_n I_D} = \sqrt{2K_n I_Q}$$

$$g_{o2} = \lambda_2 I_{DQ2} = (\lambda_2 I_Q)/2$$

$$g_{o4} = \lambda_4 I_{DQ4} = (\lambda_4 I_Q)/2$$

then Equation (**11.107**) becomes

$$A_d = \frac{2\sqrt{2K_n I_Q}}{I_Q(\lambda_2 + \lambda_4)} = 2\sqrt{\frac{2K_n}{I_Q}} \cdot \frac{1}{\lambda_2 + \lambda_4} \qquad (11.108)$$

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7.5) MOSFET Diff-Amp with Cascode Active Load

- The differential-mode voltage gain is proportional to the output resistance (R_o) looking into the active load transistor.

➔The voltage gain can be increased, therefore, if R_o can be increased.

- An increase in R_o can be achieved by using, for example, **a cascode active load**.

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7.5) MOSFET Diff-Amp with Cascode Active Load (Cont)

- **Figure 11.36** shows a MOSFET differential amplifier with cascode active load.

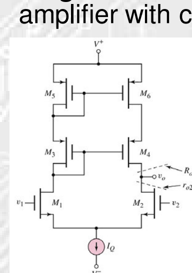

Figure 11.36: MOSFET diff amp with cascode active load.

- R_o for the circuit, **as discussed in the cascode current source**, is given by

$$R_o = r_{o4} + r_{o6}(1 + g_m r_{o4})$$

$$\rightarrow \quad R_o \approx g_m r_{o4} r_{o6} \qquad (11.109)$$

- Therefore, the small-signal diff-mode voltage gain is

$$A_d = v_o / v_d$$

$$\rightarrow \quad A_d = g_m (r_{o2} \| R_o) \qquad (11.110)$$

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7.5) MOSFET Diff-Amp with Cascode Active Load (Cont)

Example 11.12

Objective:
Calculate the differential-mode gain of a MOSFET diff-amp with a cascode active load.

Consider the diff-amp in **Figure 11.36.**
Assume that NMOS devices are available with the following parameters: V_{TN} **= 0.5 V,** k'_n **= 80 µA/V²,** λ_n**= 0.02 V⁻¹**, and **(W/L)**$_n$ **= 10**.
Assume that PMOS devices are available with the following parameters: V_{TP} **= -1.0 V,** k'_p **= 40 µA/V²,** and λ_p **= 0.02 V⁻¹**.

Choose supply voltages of 5 V and choose a bias current of approximately I_Q **= 200 µA**.

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7.5) MOSFET Diff-Amp with Cascode Active Load (Cont)

Example 11.12 (Cont)

Solution:

The transistor transconductance is

$$g_m = 2\sqrt{K_n I_{DQ}} = 2\sqrt{\left(\frac{80\mu}{2}\right)(10)(\frac{200\mu}{2})} = 0.40\text{mA/V}$$

The output resistance of individual transistor is

$$r_o = \frac{1}{\lambda I_{DQ}} = \frac{1}{(0.02)(\frac{200\mu}{2})} = 500\text{k}\Omega$$

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7.5) MOSFET Diff-Amp with Cascode Active Load (Cont)

Example 11.12 (Cont)

Solution: (Cont)

The output resistance of the cascode active load is then

$$R_o = r_{o4} + r_{o6}(1 + g_m r_{o4})$$
$$R_o = 500\text{k} + 500\text{k}[1 + (0.40\text{m})(500\text{k})] = 101\text{M}\Omega$$

The differential-mode voltage gain is then found to be

$$A_d = g_m\left(r_{o2} \| R_o\right) = (0.40\text{m})(500\text{k} \| 101\text{M}) = 200$$

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7.5) MOSFET Diff-Amp with Cascode Active Load (Cont)

Ex 11.12

Do! Help yourself.

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7.5) MOSFET Diff-Amp with Cascode Active Load (Cont)

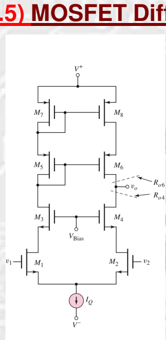

Figure 11.37: A MOSFET cascode diff amp with a cascode active load.

- The diff-mode voltage gain can be further increased by using a cascode configuration in the differential pair as well as in the active load, **Figure 11.37**.
  → M_3 and M_4 are the cascode for the differential pair M_1 and M_2
- Diff-mode voltage gain is now
  $A_d = v_o / v_d = g_m (R_{o4} \| R_{o6})$

  where $R_{o4} \approx g_m r_{o2} r_{o4}$
  and $R_{o6} \approx g_m r_{o6} r_{o8}$
- The small-signal A_d of this type of amplifier can be in the order of 10,000.

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Larger circuits

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7.1) BJT Diff-Amp with Active Load

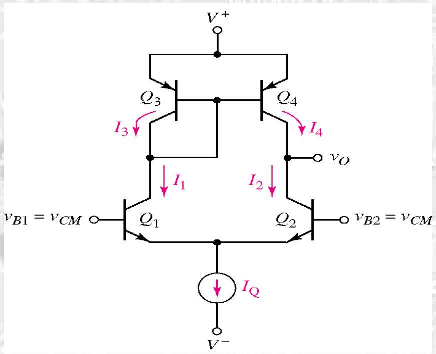

Figure 11.28: BJT diff amp with active load.

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7.1) BJT Diff-Amp with Active Load (Cont)

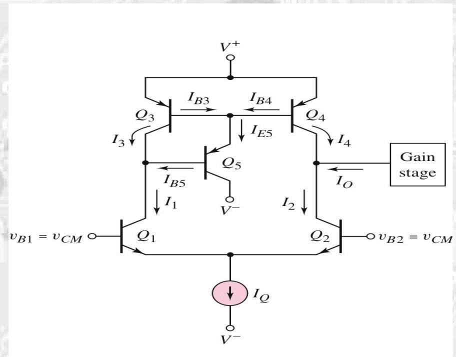

Figure 11.29: BJT diff amp with 3-transistor active load and second stage gain

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7.2) Small-Signal Analysis of BJT Active Load

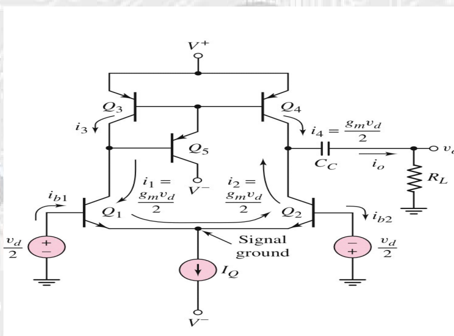

Figure 11.30: BJT diff amp with 3-transistor active load, showing the signal currents.

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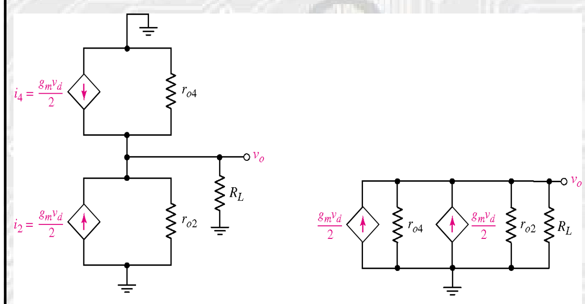
7.2) Small-Signal Analysis of BJT Active Load (Cont)



(a) (b)

Figure 11.31: (a) Small-signal equivalent circuit BJT diff amp with active load and (b) rearrangement of small-signal equivalent circuit.

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7.3) MOSFET Diff-Amp with Active Load

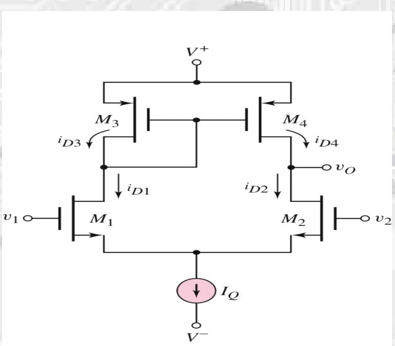

Figure 11.32: MOSFET diff-amp with active load.

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7.4) Small-Signal Analysis of MOSFET Active Load

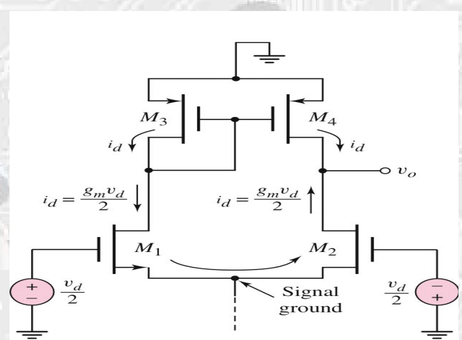

Figure 11.33: The ac equivalent circuit, MOSFET diff amp with active load.

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7.4) Small-Signal Analysis of MOSFET Active Load (Cont)

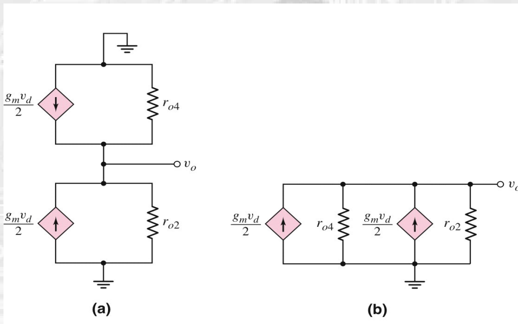

Figure 11.34: (a) Small-signal equivalent circuit, MOSFET diff amp with active load and (b) rearranged small-signal equivalent circuit.

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7.5) MOSFET Diff-Amp with Cascode Active Load (Cont)

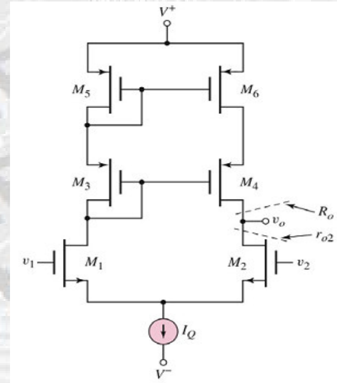

Figure 11.36: MOSFET diff amp with cascode active load.