Advanced Current Mirrors and Opamps

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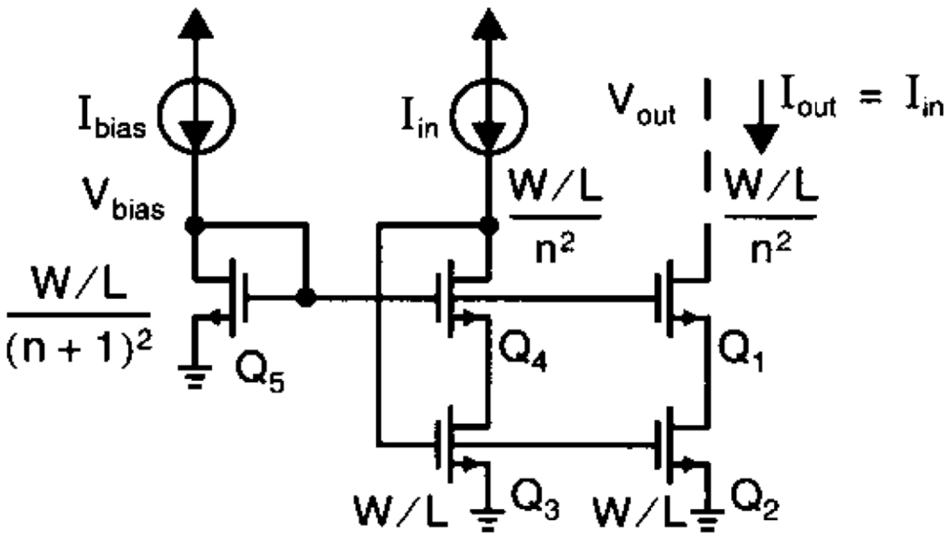
Wide-Swing Current Mirrors



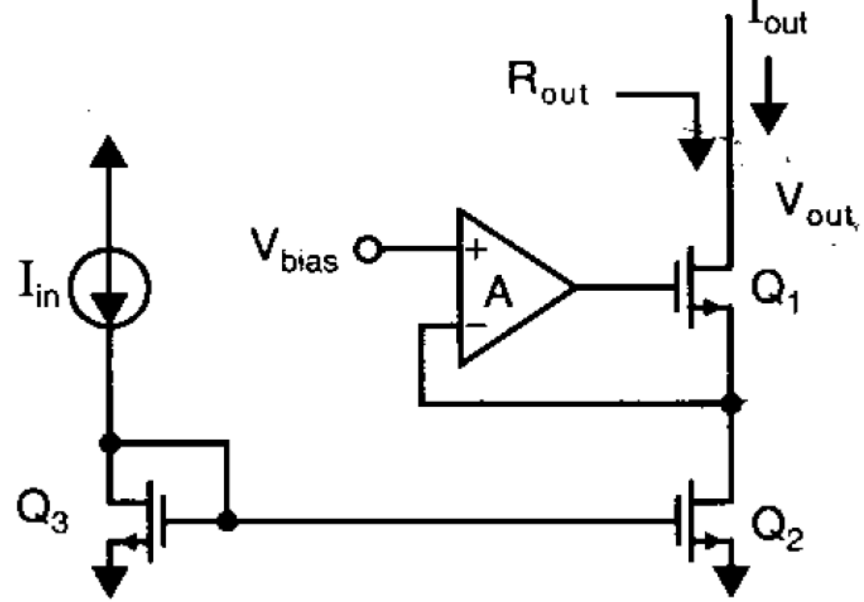
It is proven that if both of the following conditions are satisfied, then all transistors will be biased in the saturation region.

$$\begin{cases} V_{out} \geq (n+1)V_{eff} \\ V_{tn} \geq nV_{eff} \end{cases}$$

Typically n is chosen identical to 1. So the output swing will be:

$$V_{out} \geq 2V_{eff}$$

Enhanced Output-Impedance Current Mirrors

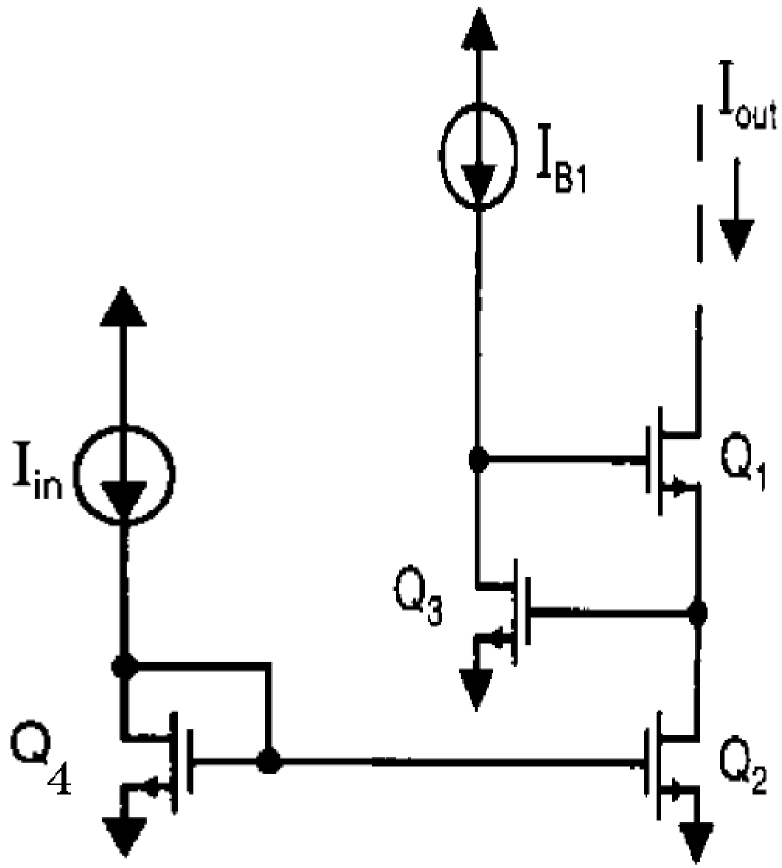


$$R_{out} \cong g_{m1} r_{ds1} r_{ds2} (1 + A)$$

Implementation of Enhanced Output-Impedance Current Mirror

$$R_{out} \cong g_{m1} r_{ds1} r_{ds2} g_{m3} \frac{r_{ds3}}{2}$$

$$V_{out} \geq V_{tn} + V_{eff\,3} + V_{eff\,1}$$



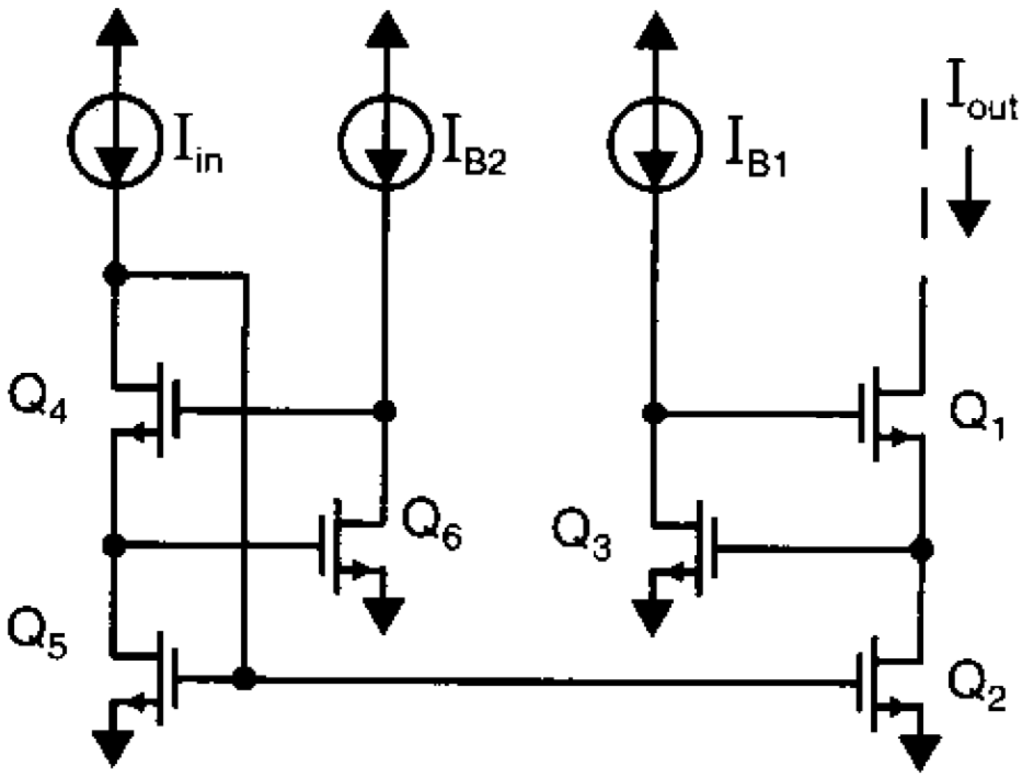
Advantage:
- High Output-Impedance

Disadvantages:
- Low Output-Swing
- Imprecise Current Mirror

Implementation of Enhanced Output-Impedance Current Mirror

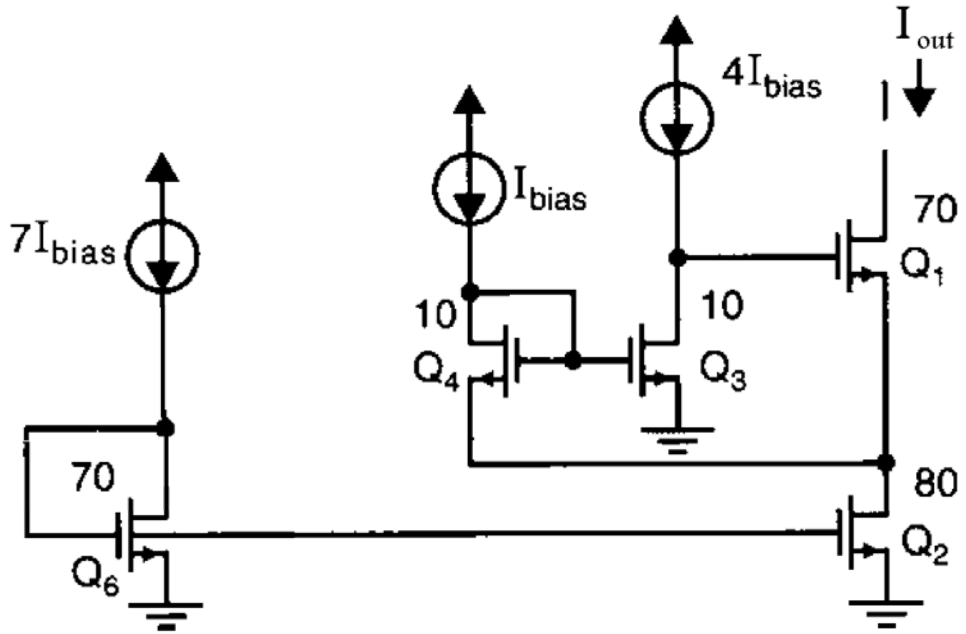
$$R_{out} \cong g_{m1} r_{ds1} r_{ds2} g_{m3} \frac{r_{ds3}}{2}$$

$$V_{out} \geq V_{tn} + V_{eff\,3} + V_{eff\,1}$$



Advantages:
•High Output-Impedance
•Precise Current Mirror
Disadvantage:
•Low Output-Swing

Implementation of Enhanced Output-Impedance Current Mirror



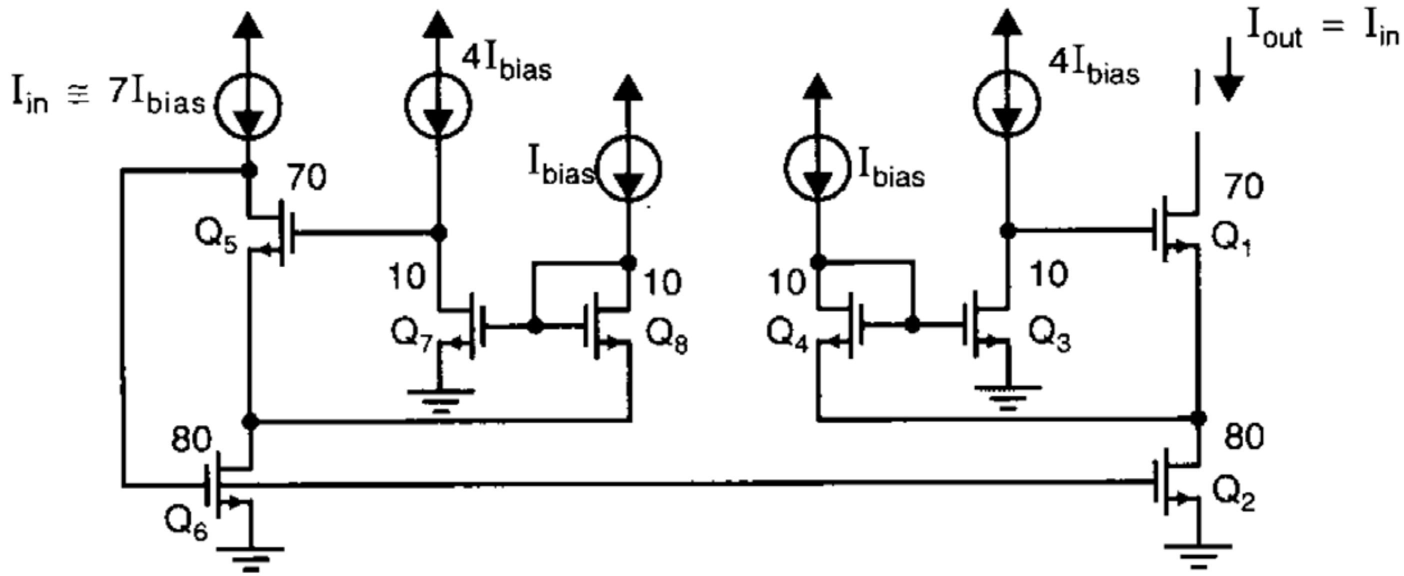
$$R_{out} \cong g_{m1} r_{ds1} r_{ds2} g_{m3} \frac{r_{ds3}}{2}$$

$$V_{out} \geq 2V_{eff1}$$

Advantages:
- High Output-Impedance
- High Output-Swing

Disadvantage:
- Imprecise Current Mirror

Wide-Swing Current Mirror with Enhanced Output-Impedance



$$R_{out} \cong g_{m1} r_{ds1} r_{ds2} g_{m3} \frac{r_{ds3}}{2} \qquad V_{out} \geq 2V_{eff1}$$

Advantages:

•High Output-Impedance

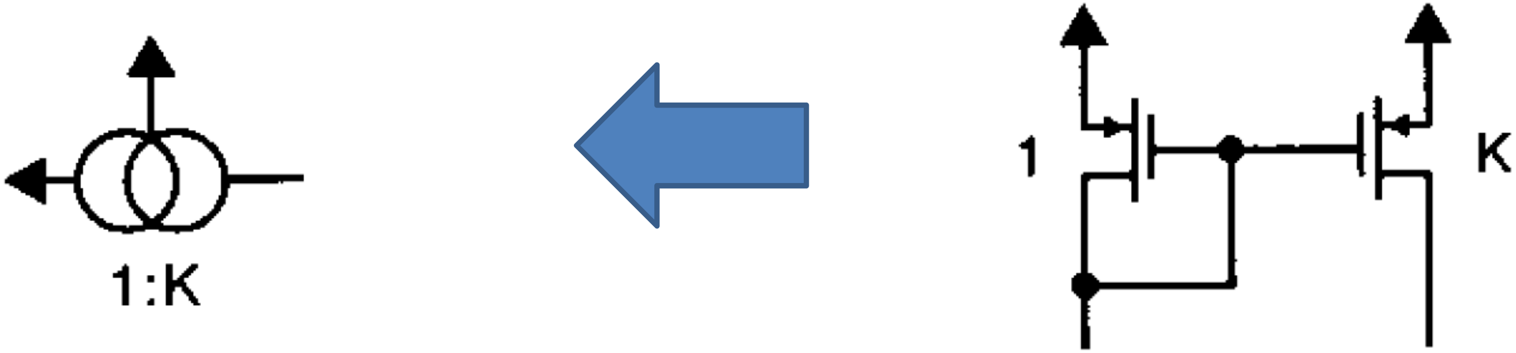
•Precise Current Mirror

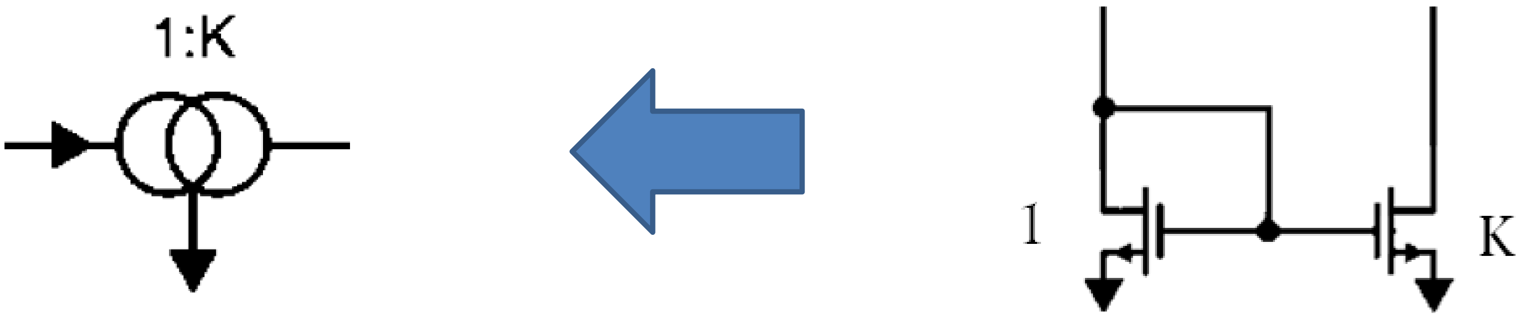
•High Output-Swing

Disadvantage:

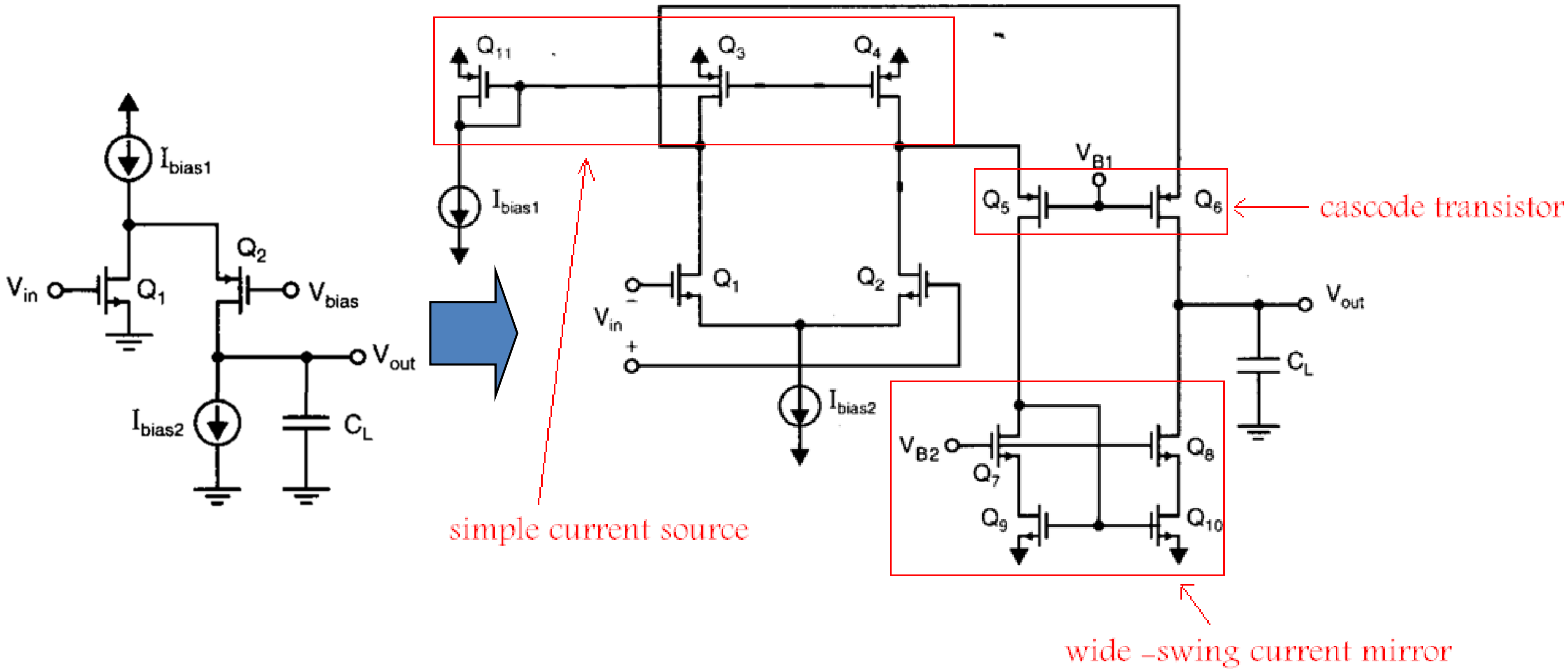
•High Power Consumption

Current Mirror Symbol



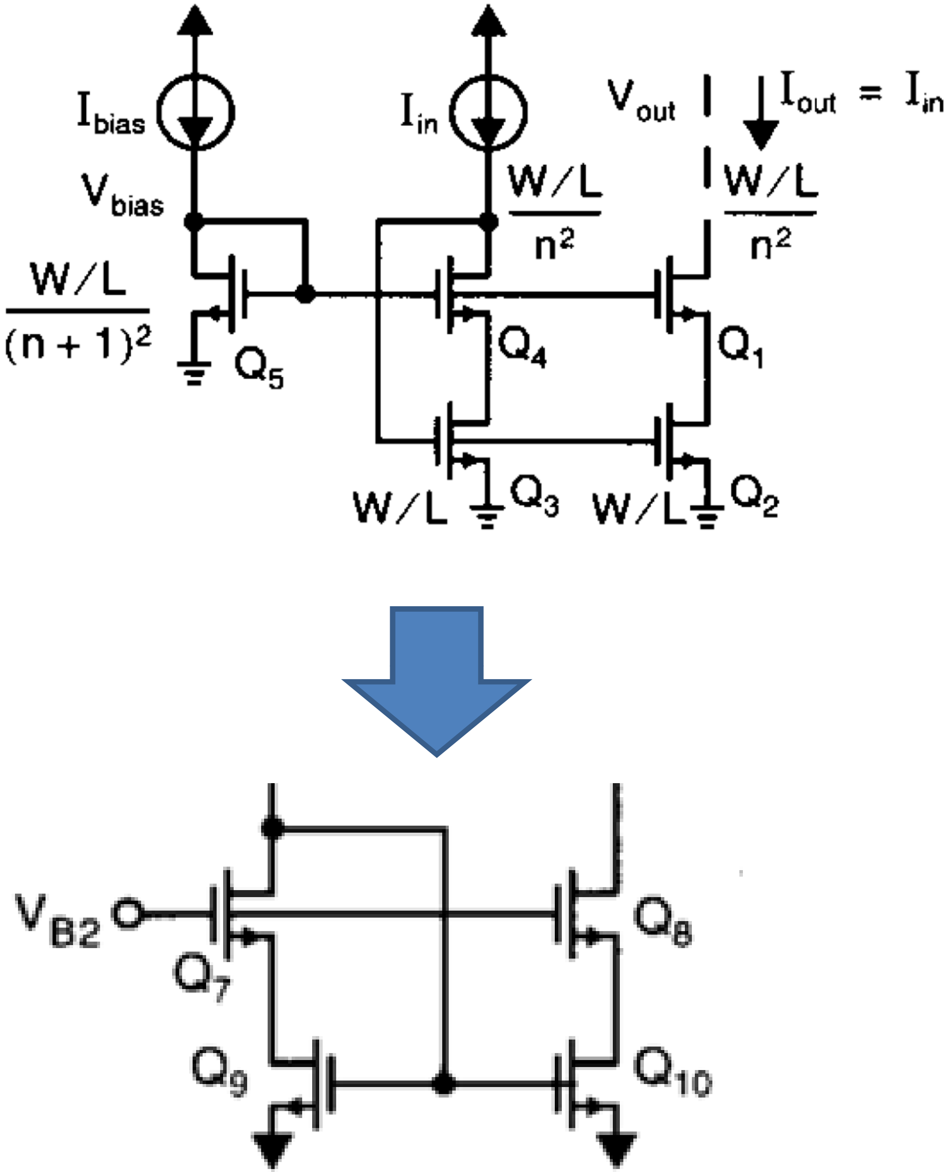


Folded-Cascode Opamp

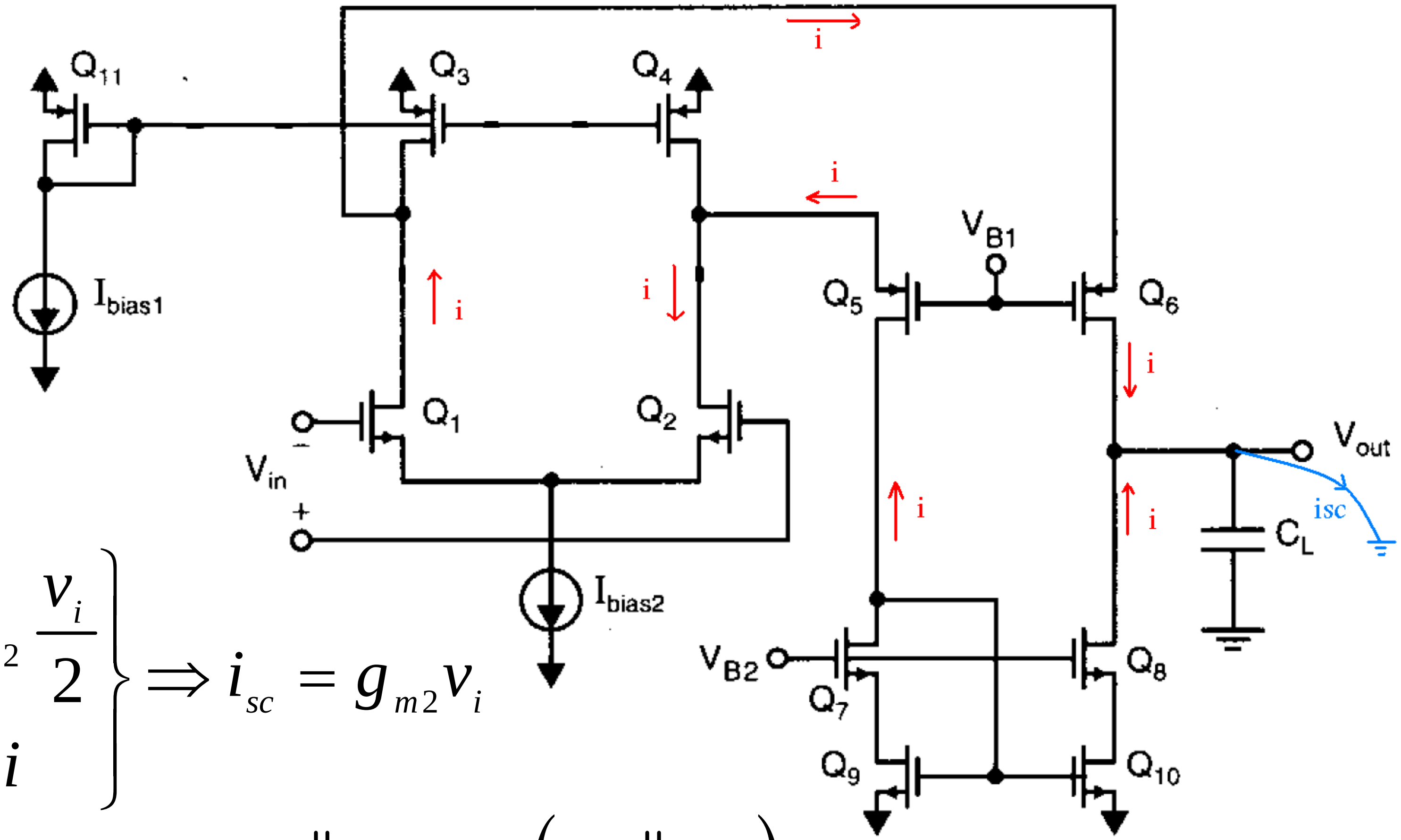


- This opamp is useful when we want to drive capacitive loads.
- One of the most important parameters of this modern opamp is its transconductance value.
- Therefore, some designers refer to this modern opamp as <u>Operational Transconductance Amplifier</u> (OTA).

Remember the wide-swing current mirror



Opamp Gain



$$\left.\begin{aligned} i &= g_{m2}\frac{v_i}{2} \\ i_{sc} &= 2i \end{aligned}\right\} \Rightarrow i_{sc} = g_{m2}v_i$$

$$r_{out} \cong g_{m8}r_{ds8}r_{ds10} \| g_{m6}r_{ds6}\left(r_{ds3} \| r_{ds1}\right)$$

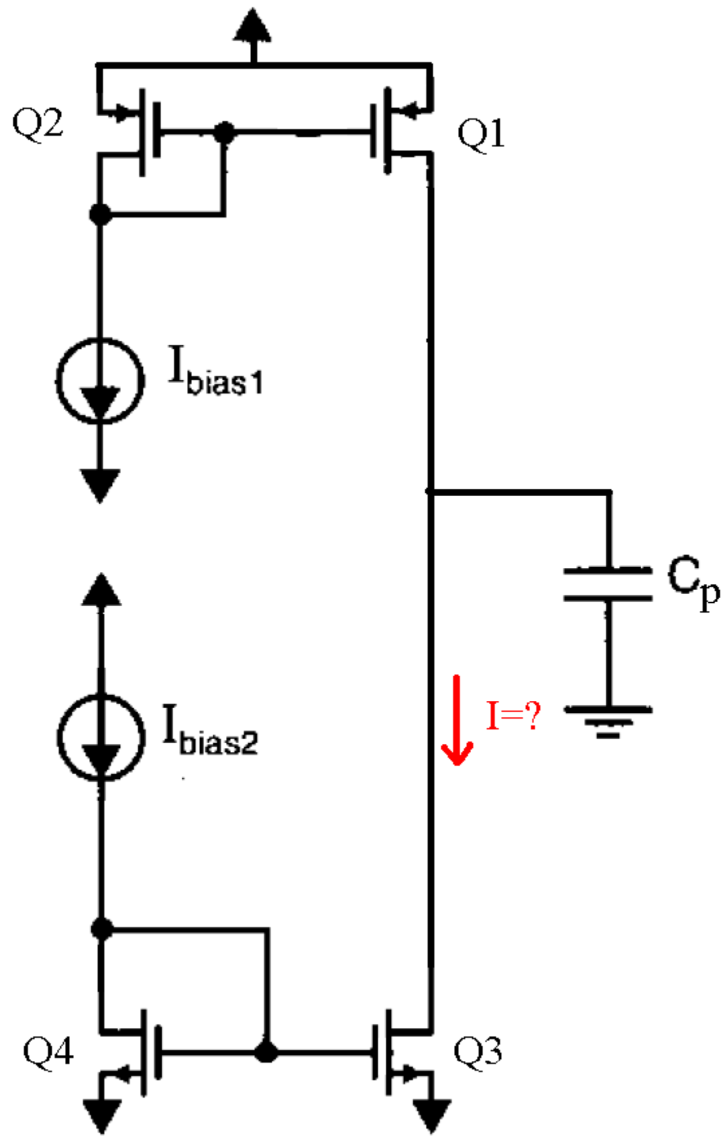
$$v_o = r_{out}i_{sc} \Rightarrow A_V = g_{m1}r_{out}$$

Competition between Two Current Sources

Assume that:

$$\left(\frac{W}{L}\right)_1 = \left(\frac{W}{L}\right)_2$$

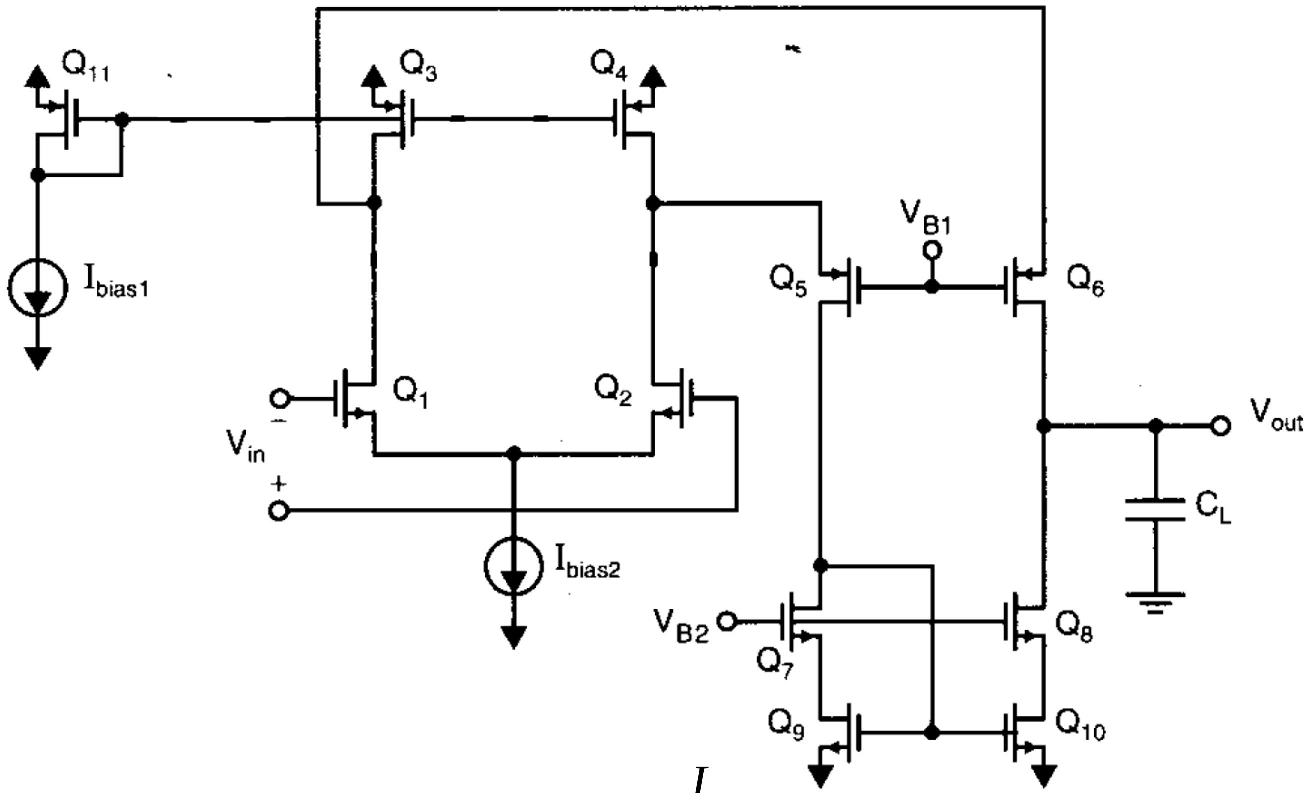
$$\left(\frac{W}{L}\right)_3 = \left(\frac{W}{L}\right)_4$$



If Ibias1>Ibias2 ➔ Q1:Triode Q3:Active I=Ibias2

If Ibias2>Ibias1 ➔ Q1:Active Q3:Triode I=Ibias1

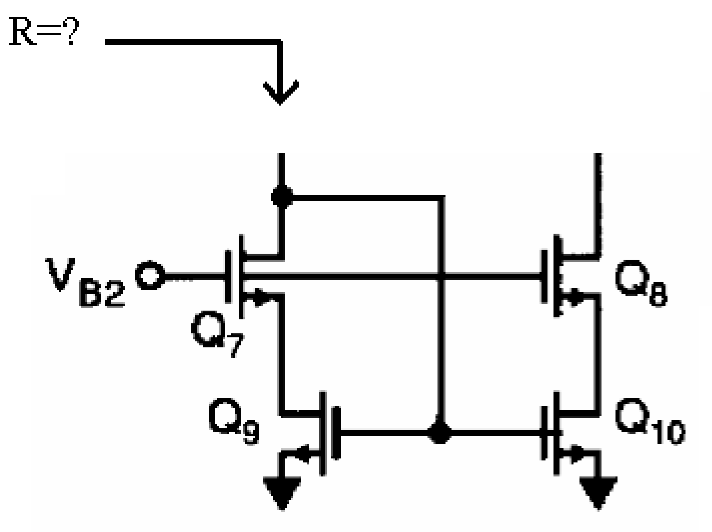
Slew Rate



Assuming $I_{bias2}>I_{D4}$ and $V_{in+}>>V_{in-}$ ➔ $SR^{+}=\frac{I_{D4}}{C_L}$

Assuming $I_{bias2}>I_{D4}$ and $V_{in-}>>V_{in-}$ ➔ $SR^{-}=\frac{I_{D4}}{C_L}$

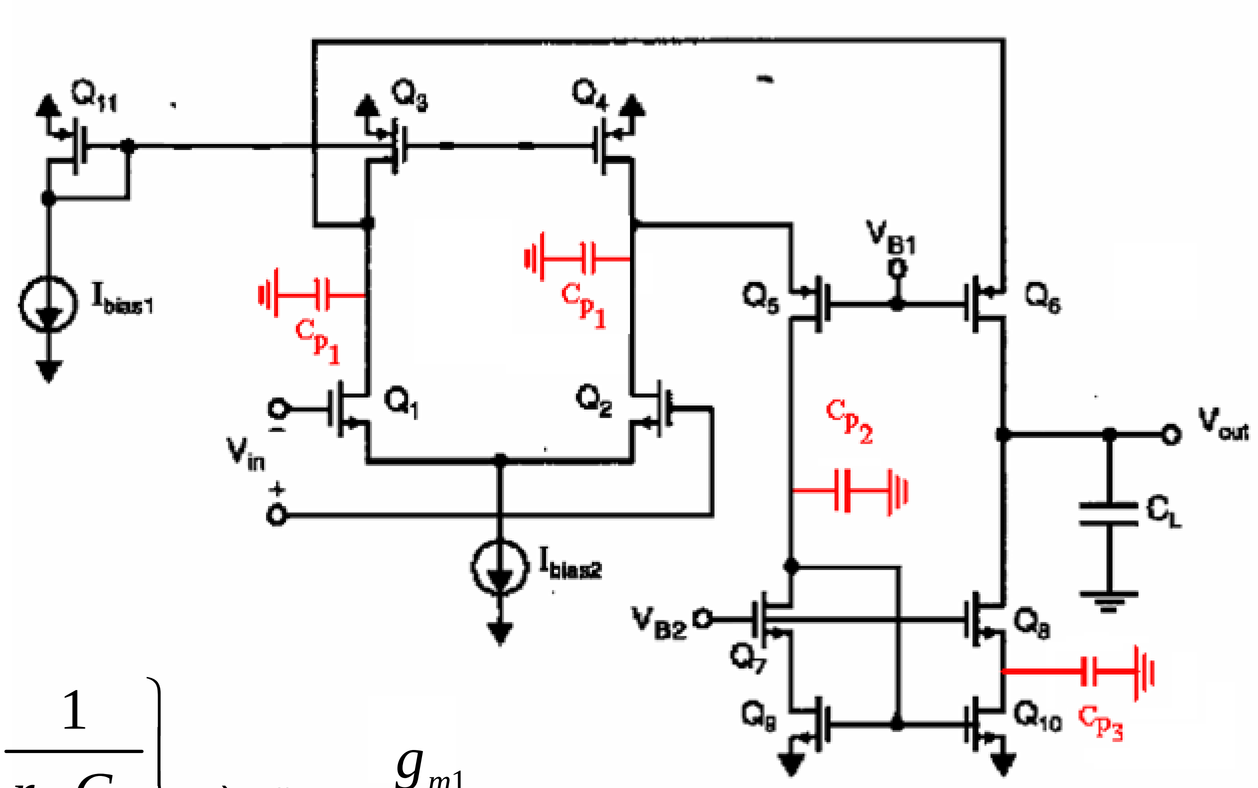
Lemma



Wide-swing current mirror

$$R \cong \frac{1}{g_{m9}}$$

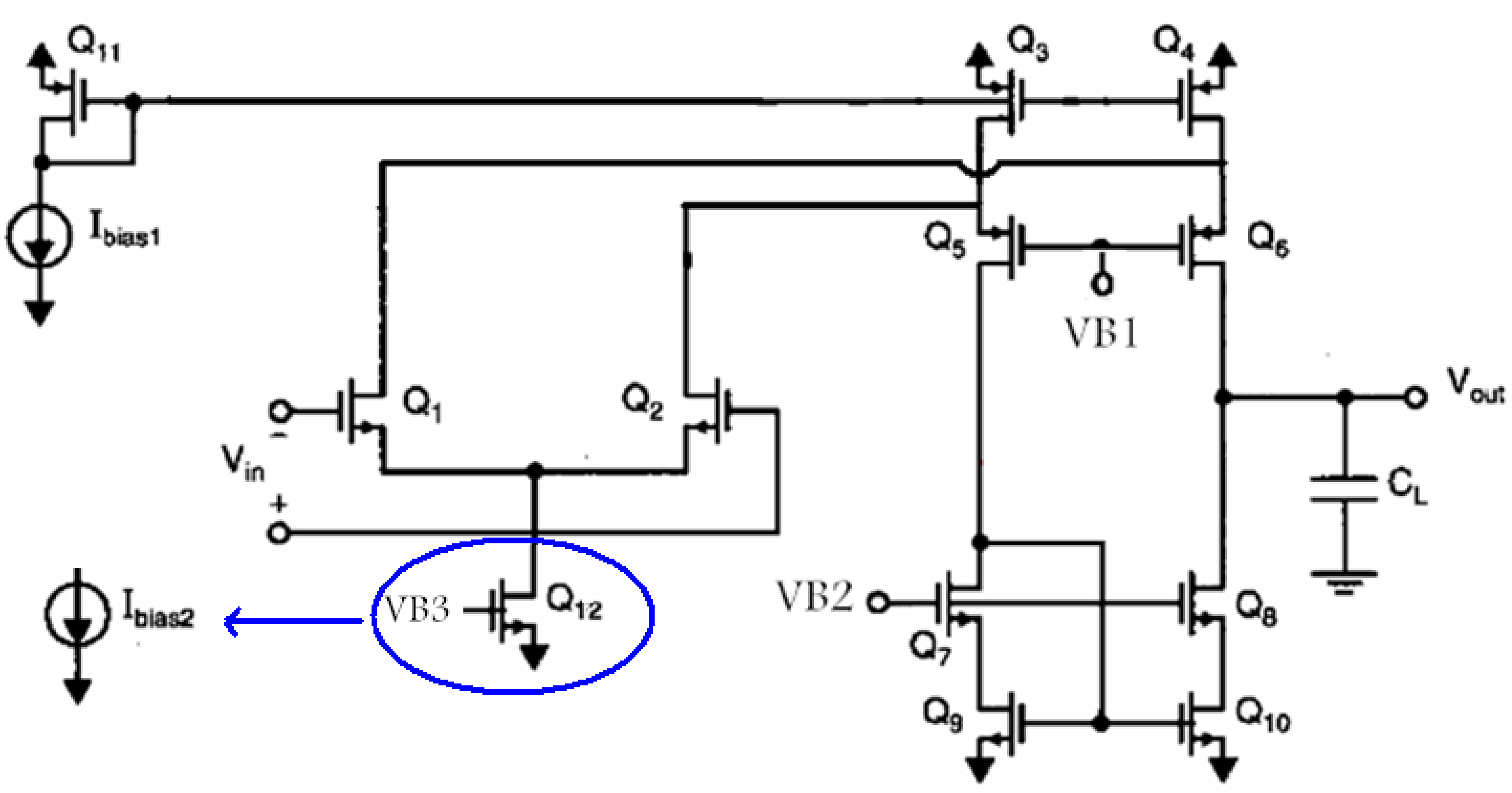
Frequency Response



$$\left.\begin{aligned}\omega_{p1} &\cong \frac{1}{r_{out}C_L}\\ A_0 &= g_{m1}r_{out}\end{aligned}\right\} \Rightarrow \omega_{ta} = \frac{g_{m1}}{C_L}$$

$$\omega_{p2} \cong \frac{1}{\frac{1}{g_{m5}}C_{p1} + \frac{1}{g_{m9}}C_{p2} + \frac{1}{g_{m8}}C_{p3}}$$

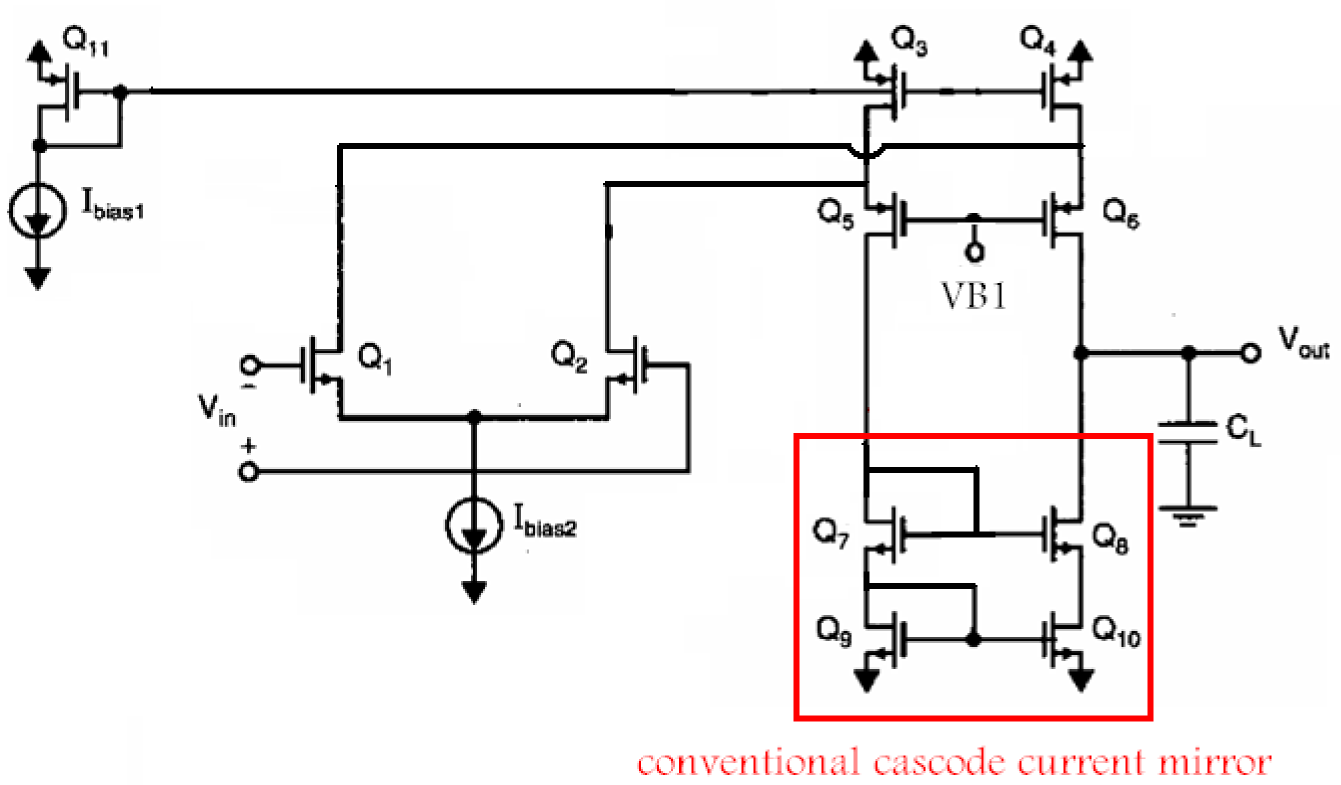
Another Schematic for Folded-Cascode Opamp



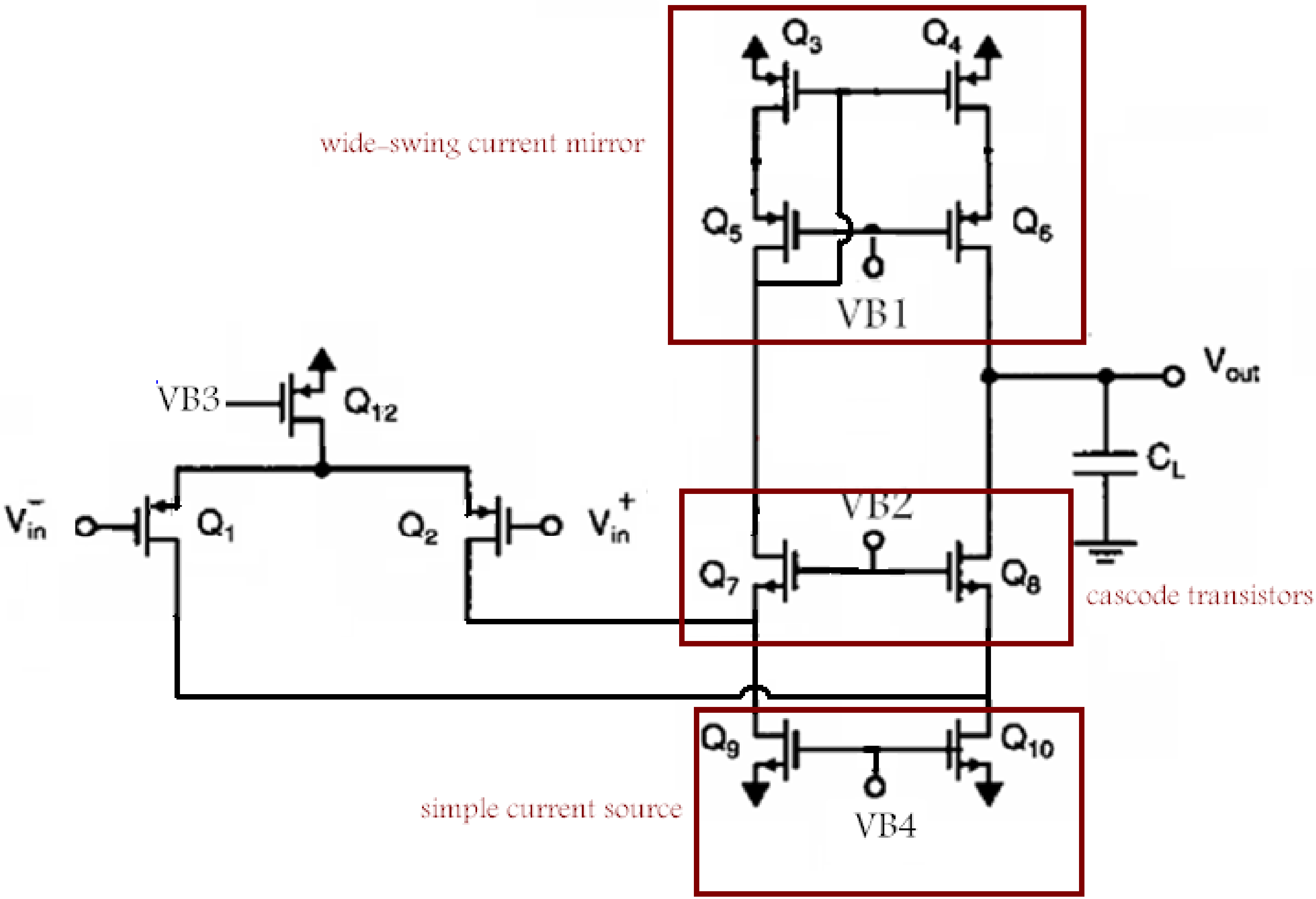
Output swing: $V_{B2} - V_{tn} \leq V_{out} \leq V_{B1} + |V_{tp}|$

Input common-mode range: $V_{tn} + V_{eff1} + V_{eff12} \leq V_{cmi} \leq V_{B1} + |V_{tp}| + |V_{eff6}| + V_{tn}$

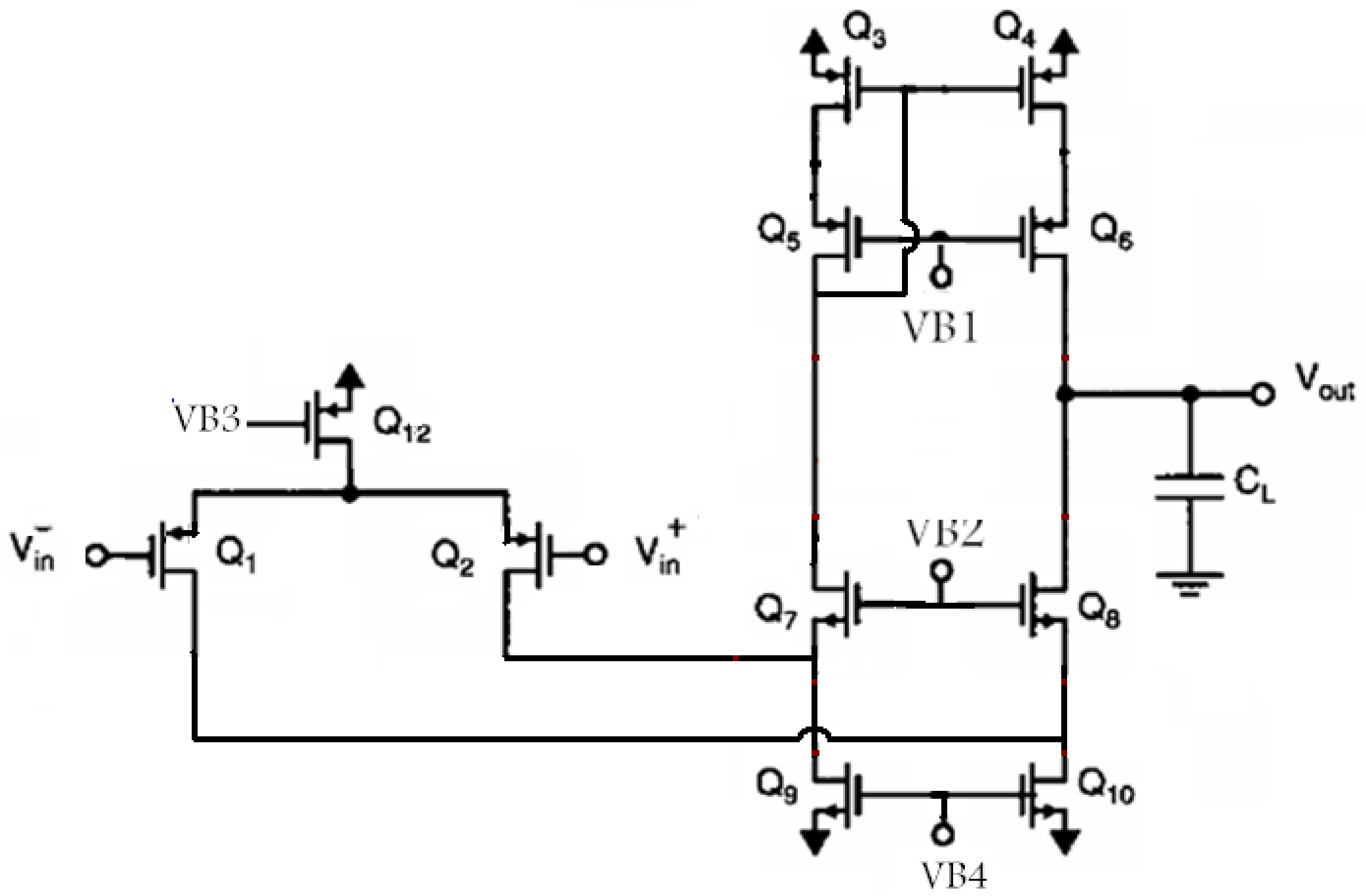
Folded-Cascode Opamp without wide-swing current source



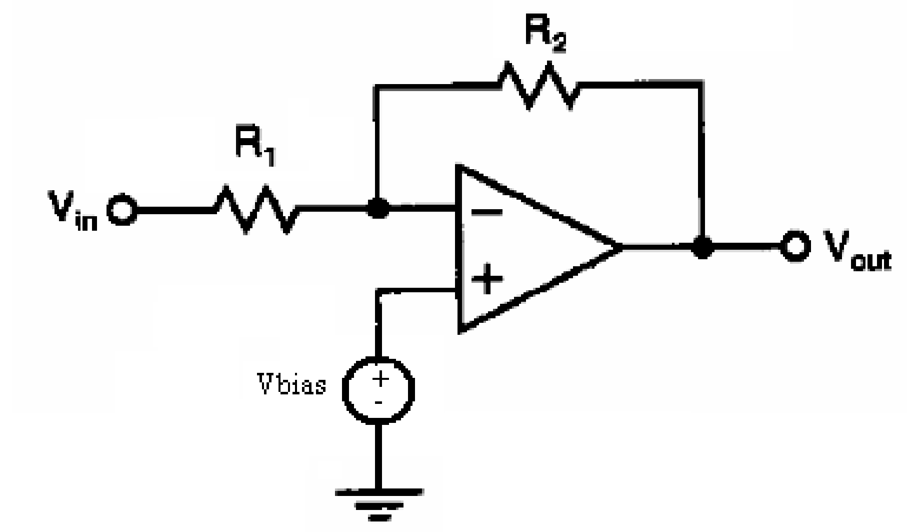
Folded-Cascode Opamp
(pmos-input)



Folded-Cascode Opamp (pmos-input)



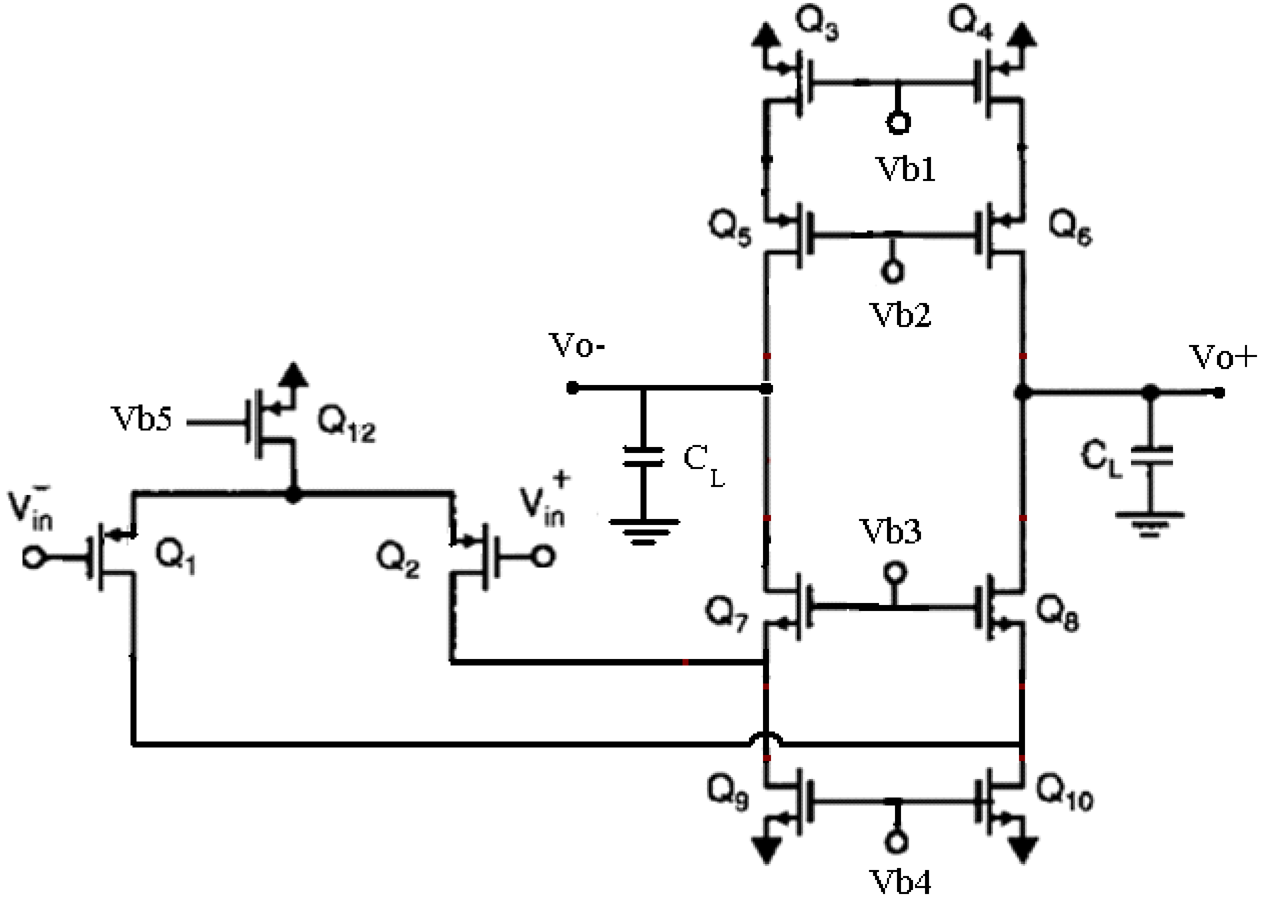
What is the DC voltage of the output node?



In a single-ended opamp, the DC voltage of the output node is determined by the feedback circuit around the opamp.

$$V_{out} = V_{bias} + \frac{R_2}{R_1}\left(V_{bias} - V_{in}\right)$$

Fully Differential Folded-Cascode Opamp



The bias voltages Vb1, Vb4, and Vb5 must be chosen so that the following relation is satisfied!!!

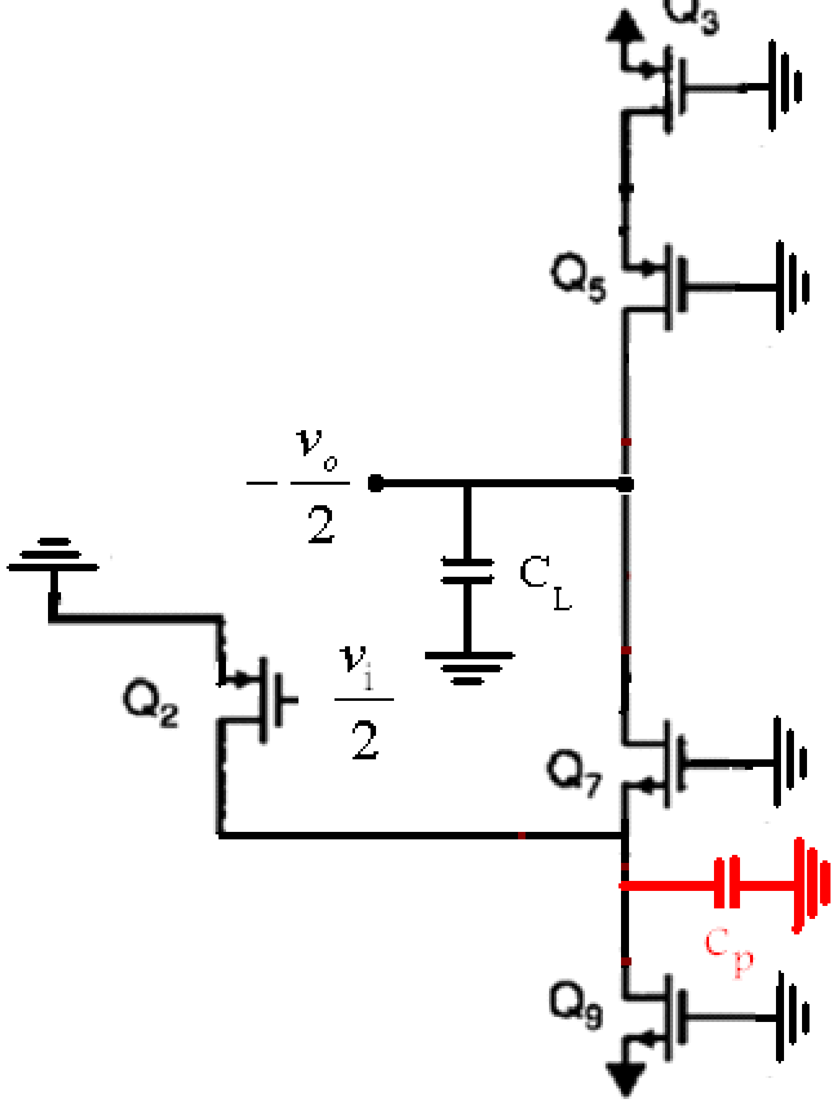
$I_{D9}=0.5I_{D12}+I_{D3}$

The opamp is completely symmetric. So we can use the half-circuit of the opamp for AC analysis.

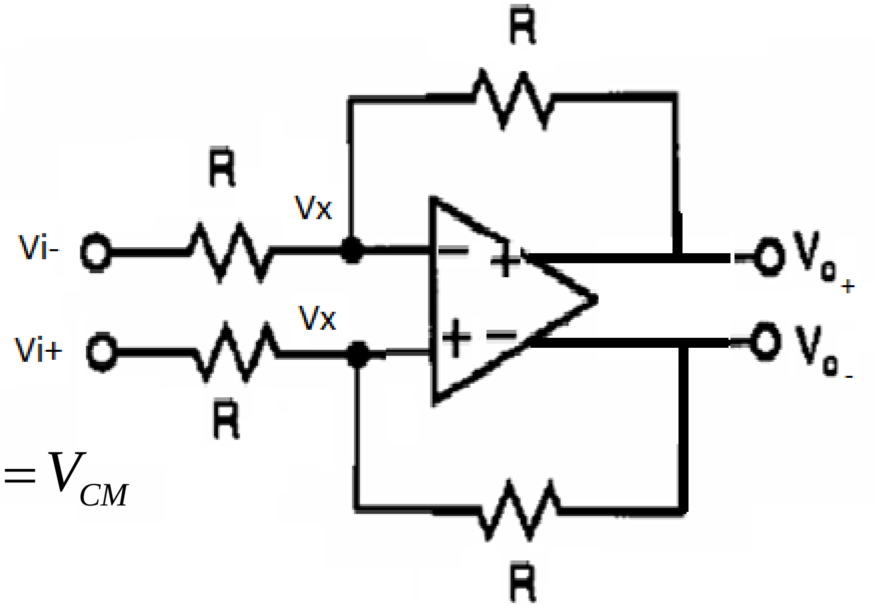
Fully Differential Folded-Cascode Opamp
(half-circuit)

$$\left.\begin{aligned} \omega_{p1} &\cong \frac{1}{r_{out} C_L} \\ A_0 &= g_{m_i} r_{out} \end{aligned}\right\} \Rightarrow \omega_{ta} = \frac{g_{m_i}}{C_L}$$

$$\omega_{p2} \cong \frac{1}{\frac{1}{g_{m_7}} C_p}$$



What is the DC voltage of the output nodes?



$$V_{i+} = V_{i-} = V_{CM}$$

In a single-ended opamp, the DC voltage of the output node is determined by the feedback circuit around the opamp.

$$\left. \begin{aligned} I &= \frac{V_{CM} - V_x}{R} \\ V_{CM} - V_o &= 2RI \end{aligned} \right\} \Rightarrow V_{CM} - V_o = 2(V_{CM} - V_x) \Rightarrow V_{o+} = V_{o-} = V_o = 2V_x - V_{CM}$$

The DC voltage of the output nodes can not be determined!!!

Common-Mode Feedback Circuit
(CMFB Circuit)

In a fully differential opamp, the CMFB circuit is employed inside the opamp to adjust the common-mode voltage of the output nodes identical to a predetermined voltage, Vref.

$$CMFB\ Circuit \Rightarrow \frac{V_{o+} + V_{o-}}{2} = V_{ref}$$

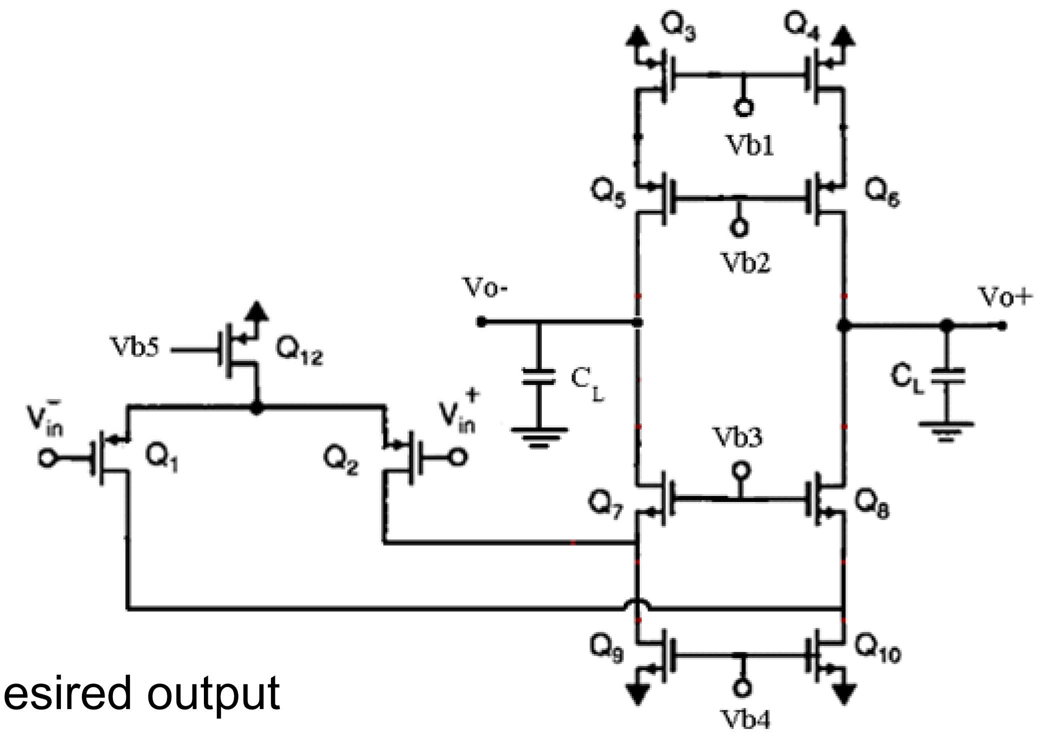
$$KVL\ and\ KCL \Rightarrow V_o = 2V_x - V_{CM}$$

$\Rightarrow$

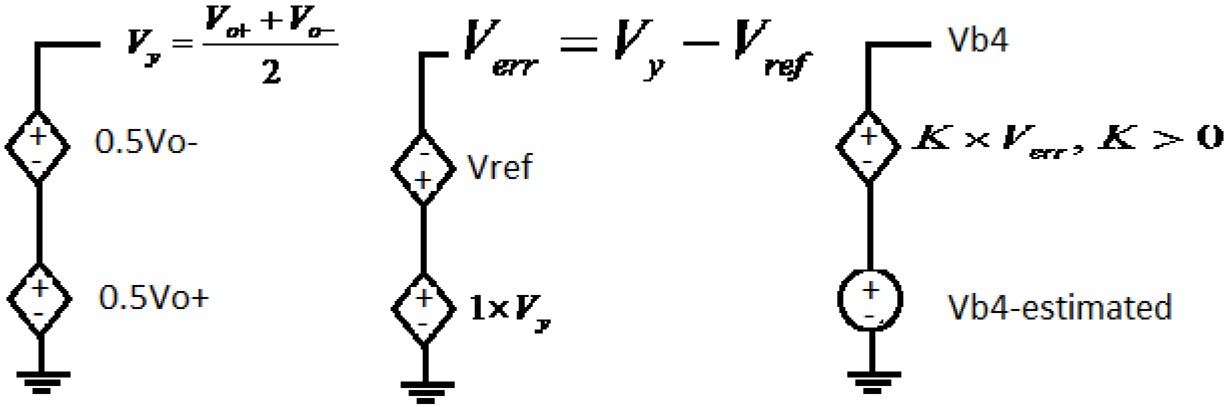
$$V_{o+} = V_{o-} = V_{ref}$$

$$V_x = \frac{V_{ref} + V_{CM}}{2}$$

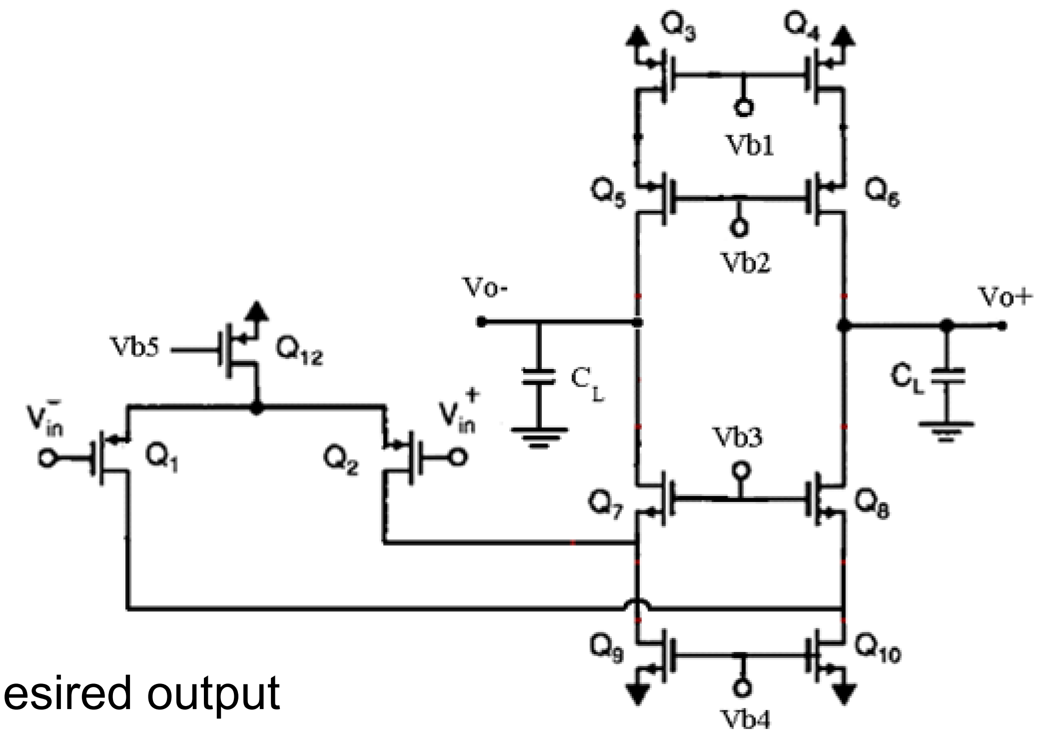
Ideal CMFB Circuit (1)



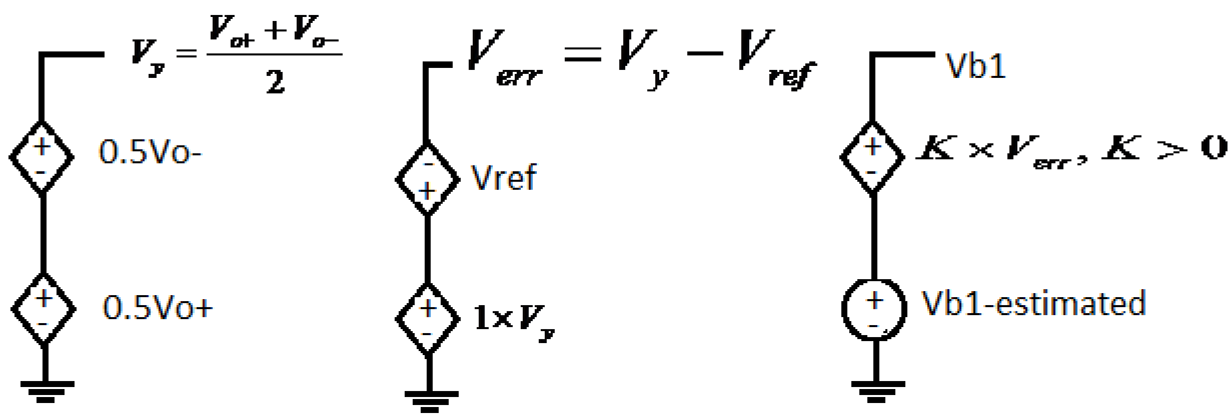
Vref denotes the desired output common-mode voltage.



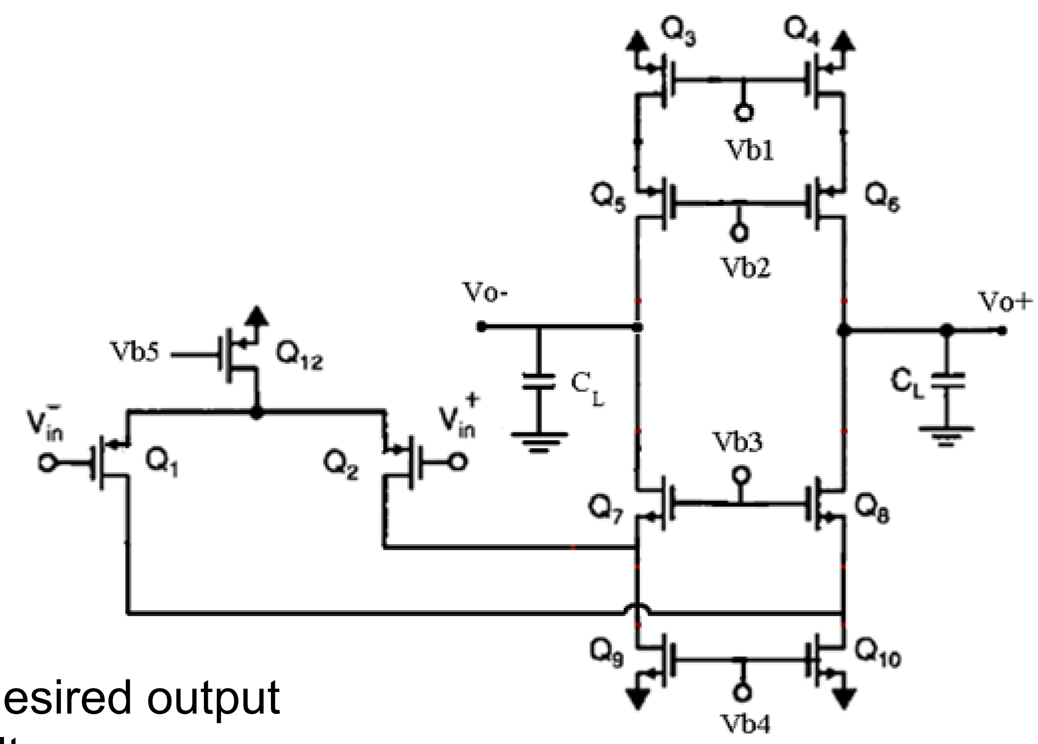
Ideal CMFB Circuit (2)



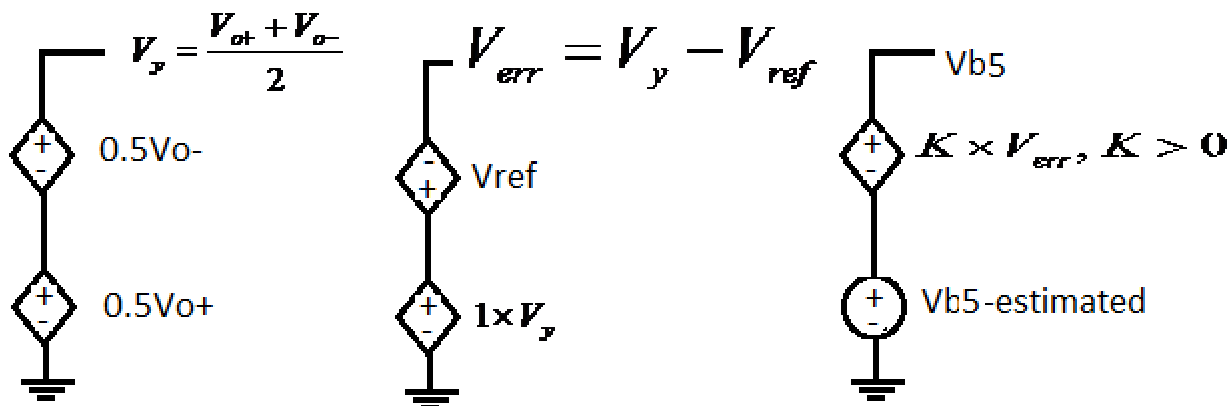
Vref denotes the desired output common-mode voltage.



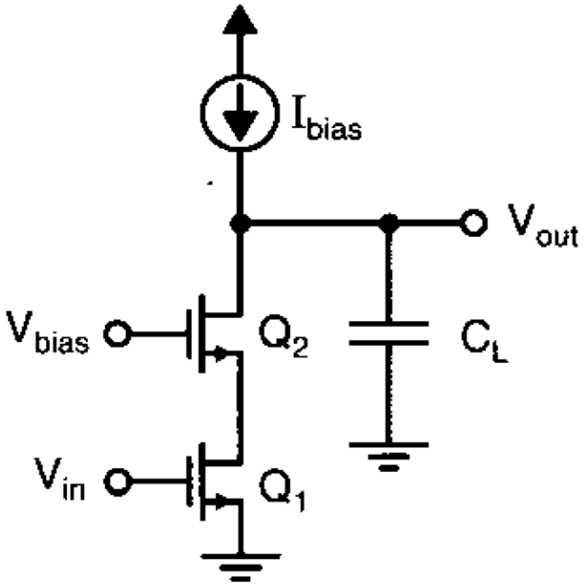
Ideal CMFB Circuit (3)

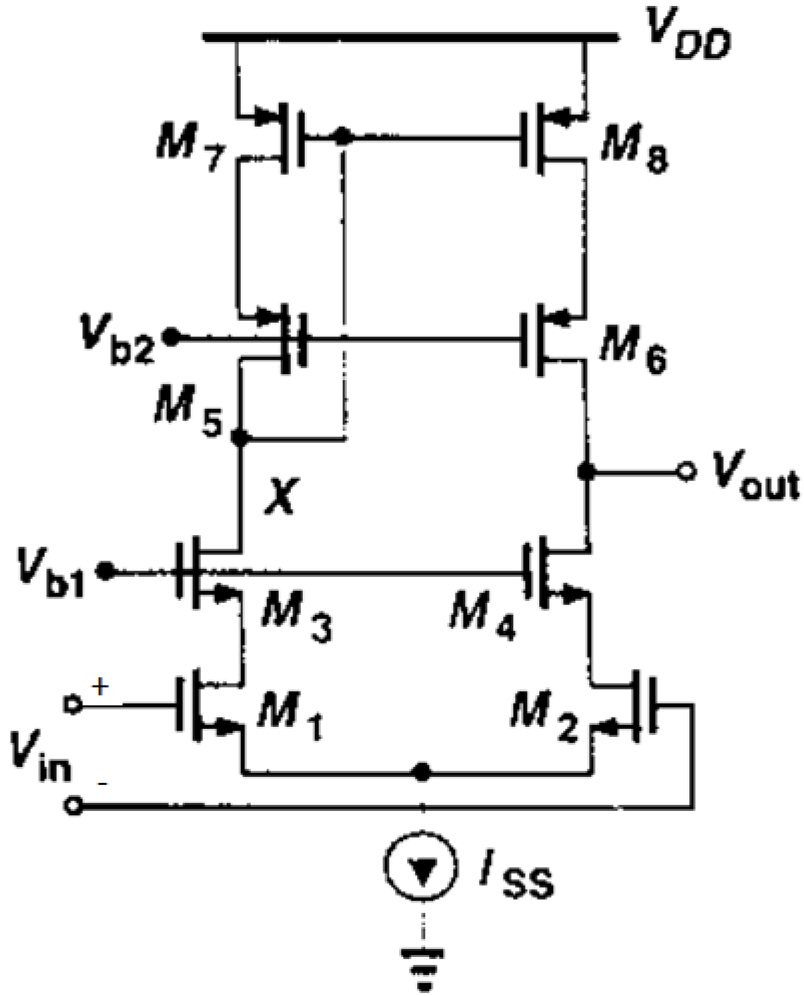


Vref denotes the desired output common-mode voltage.



Single-ended Telescopic Opamp



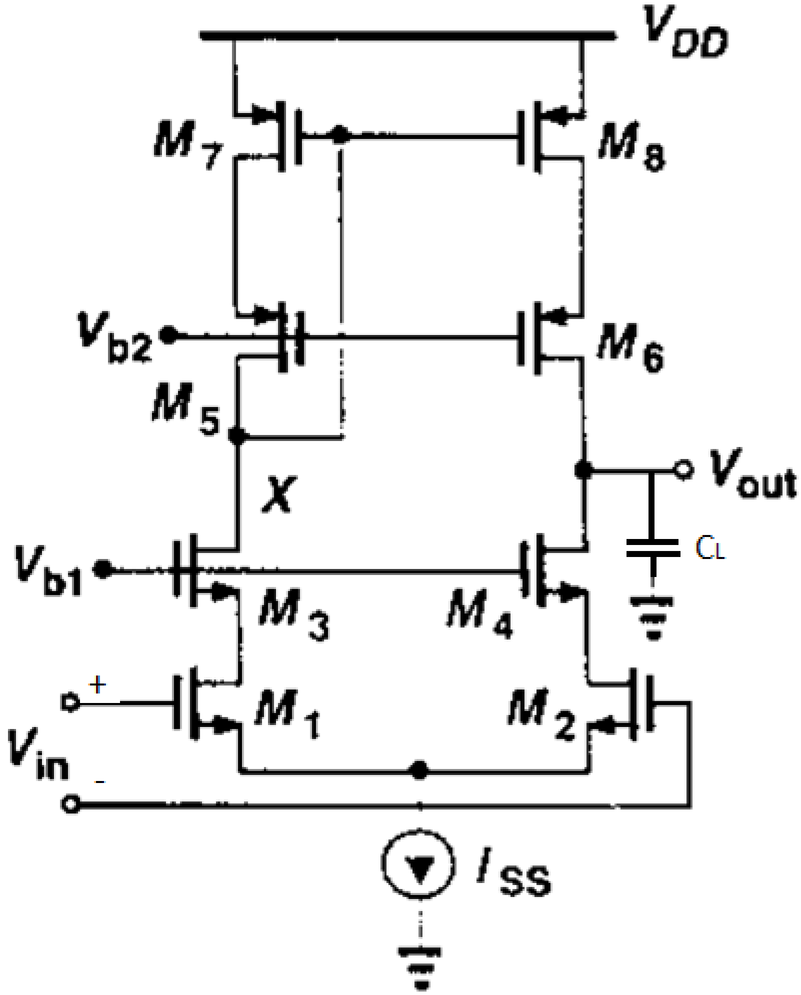


$$i_{sc} = g_{m1} v_i$$

$$r_{out} \cong g_{m4} r_{ds4} r_{ds2} \| g_{m6} r_{ds6} r_{ds8}$$

$$v_o = r_{out} i_{sc} \Rightarrow A_V = g_{m1} r_{out}$$

Slew Rate

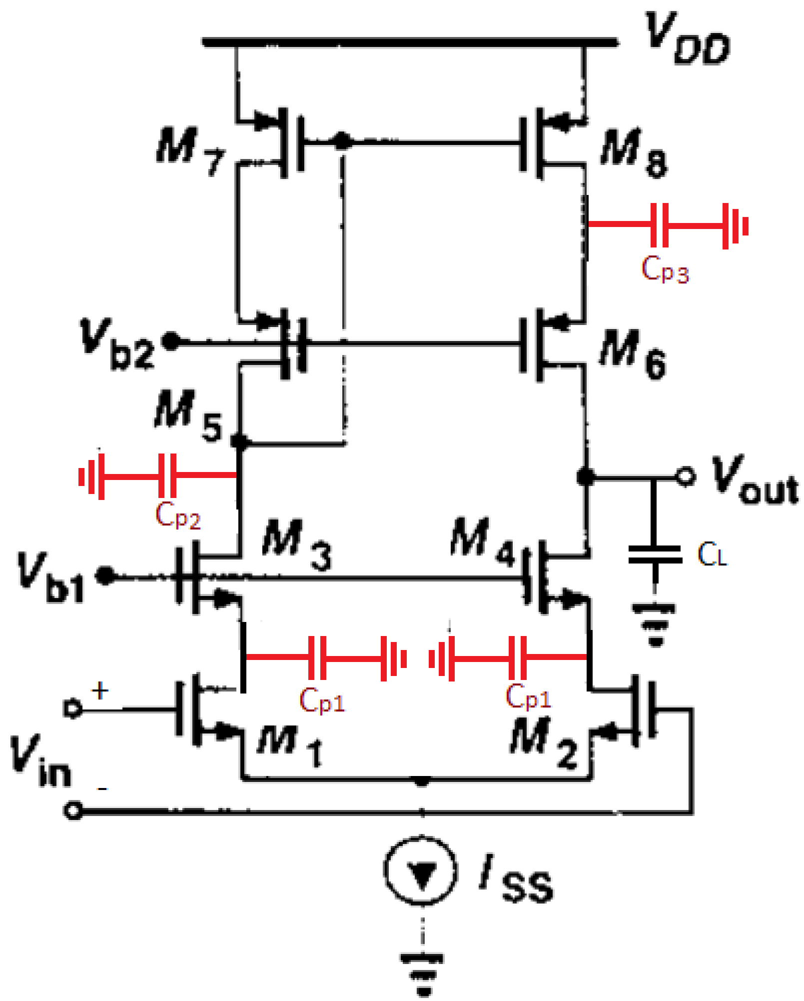


$$SR^+ = SR^- = \frac{I_{SS}}{C_L}$$

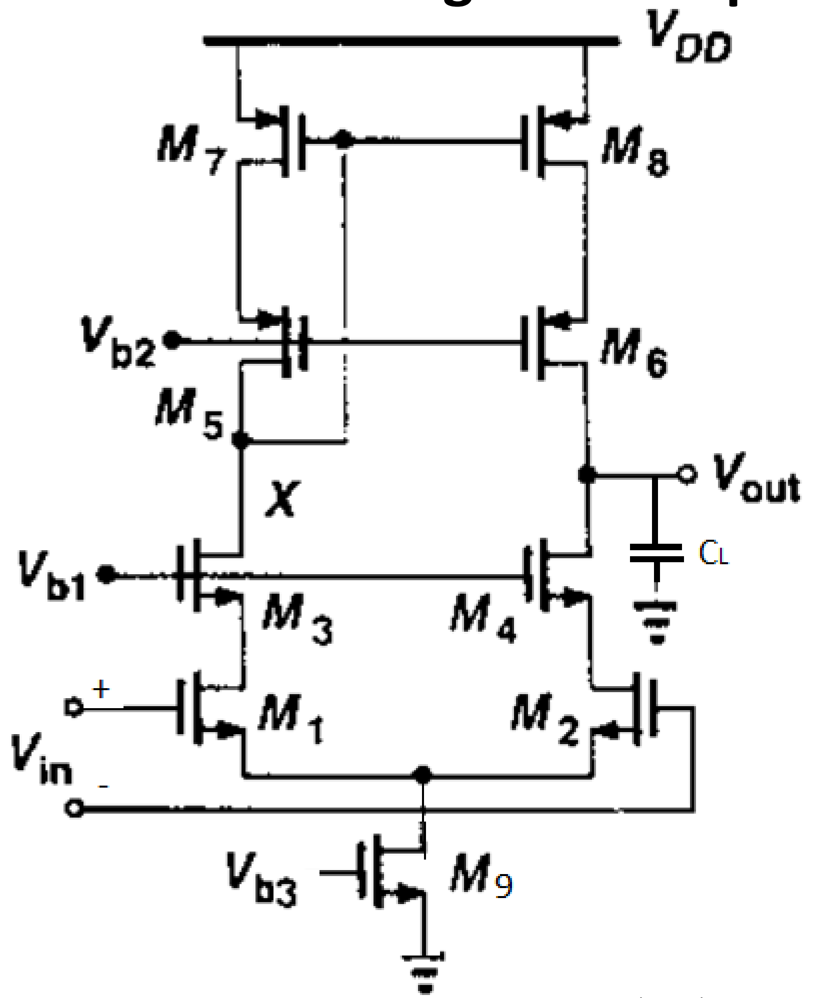
Frequency Response

$$\left.\begin{aligned}\omega_{p1} &\cong \frac{1}{r_{out} C_L} \\ A_0 &= g_{m_i} r_{out}\end{aligned}\right\} \Rightarrow \omega_{ta} = \frac{g_{m_i}}{C_L}$$

$$\omega_{p2} \cong \frac{1}{\frac{1}{g_{m3}} C_{p1} + \frac{1}{g_{m7}} C_{p2} + \frac{1}{g_{m6}} C_{p3}}$$



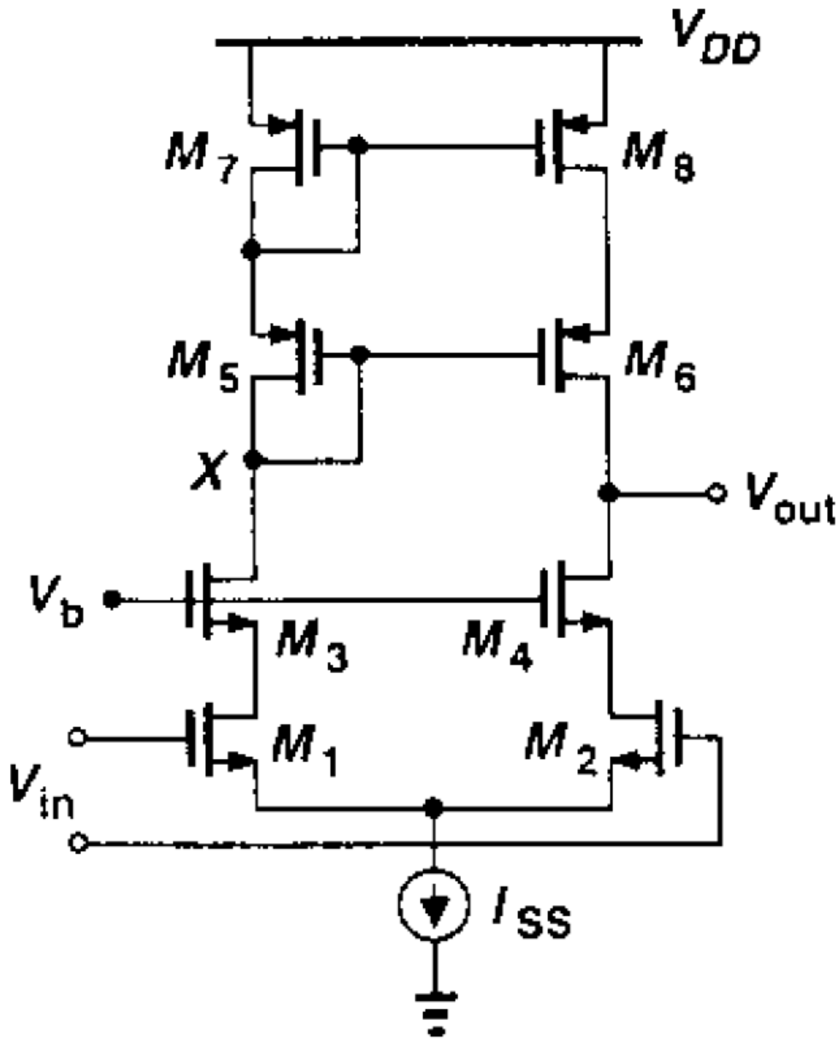
Input common-mode range and output swing



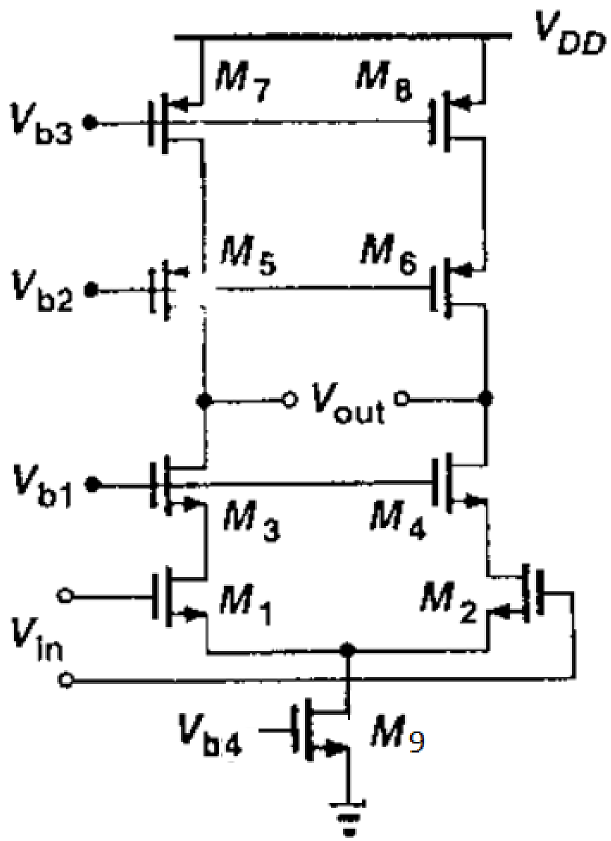
Output swing: $$V_{B1} - V_{tn} \le V_{out} \le V_{B2} + |V_{tp}|$$

Input common-mode range: $V_{tn} + V_{eff1} + V_{eff9} \le V_{cmi} \le V_{B1} - 2V_{tn} - V_{eff3}$

Telescopic Opamp without wide-swing current source



Fully Differential Telescopic Opamp



The bias voltages Vb3 and Vb4 must be chosen so that the following relation is satisfied!!!

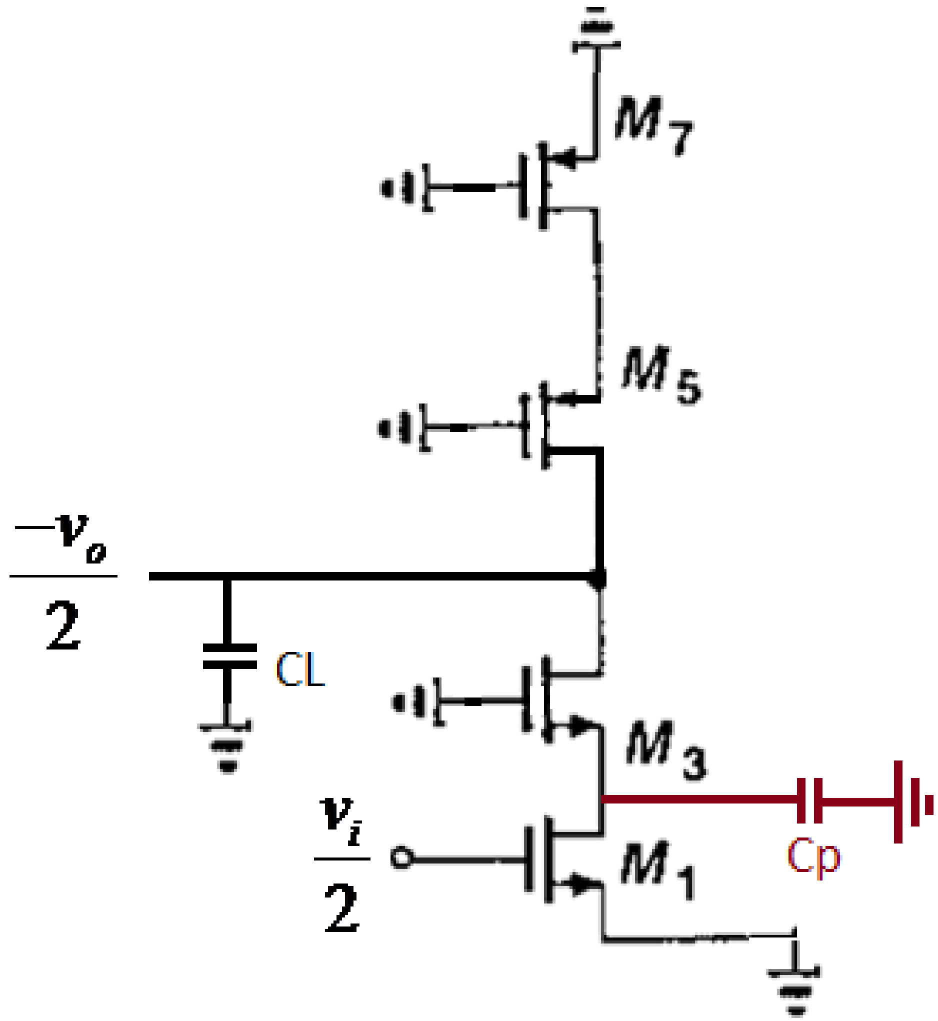
$I_{D7}=0.5I_{D9}$

The opamp is completely symmetric. So we can use the half-circuit of the opamp for AC analysis.

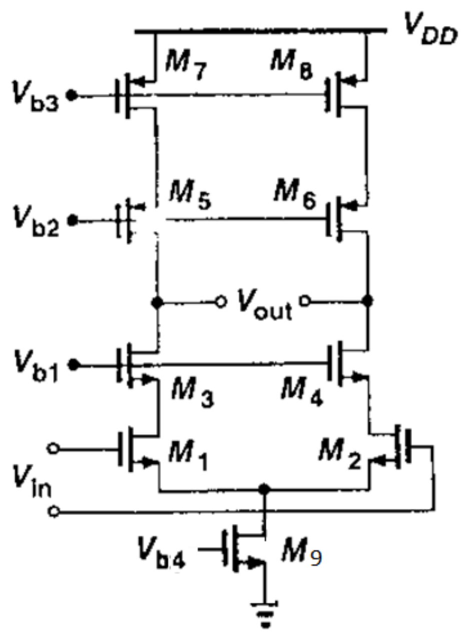
Fully Differential Telescopic Opamp
(half-circuit)

$$\left.\begin{aligned}\omega_{p1} &\cong \frac{1}{r_{out}C_L}\\ A_0 &= g_{m1}r_{out}\end{aligned}\right\} \Rightarrow \omega_{ta} = \frac{g_{m1}}{C_L}$$

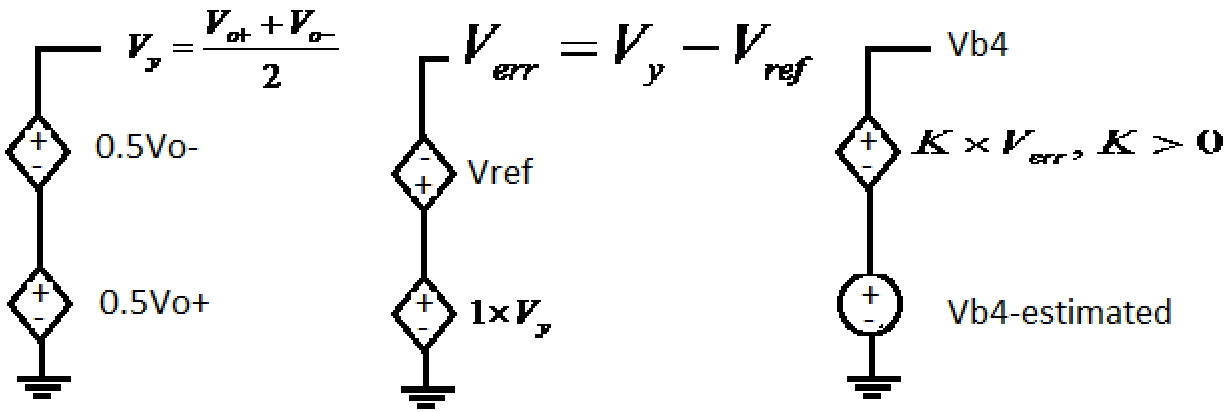
$$\omega_{p2} \cong \frac{1}{\frac{1}{g_{m3}}C_p}$$



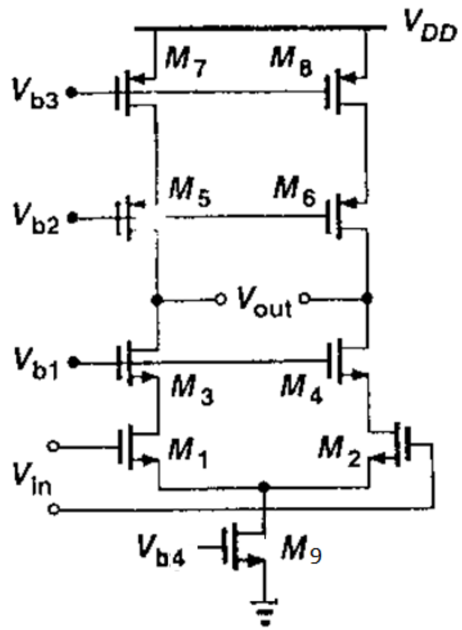
Ideal CMFB Circuit (1)



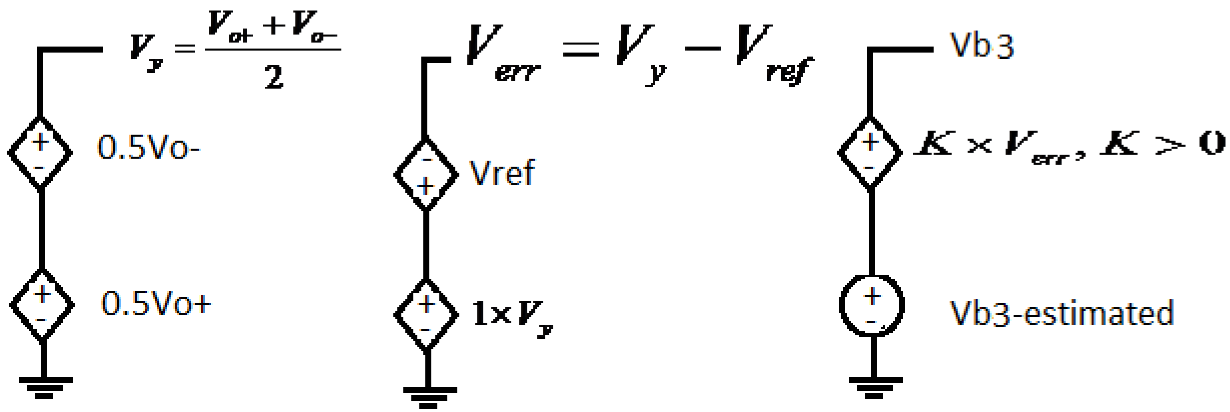
Vref denotes the desired output common-mode voltage.



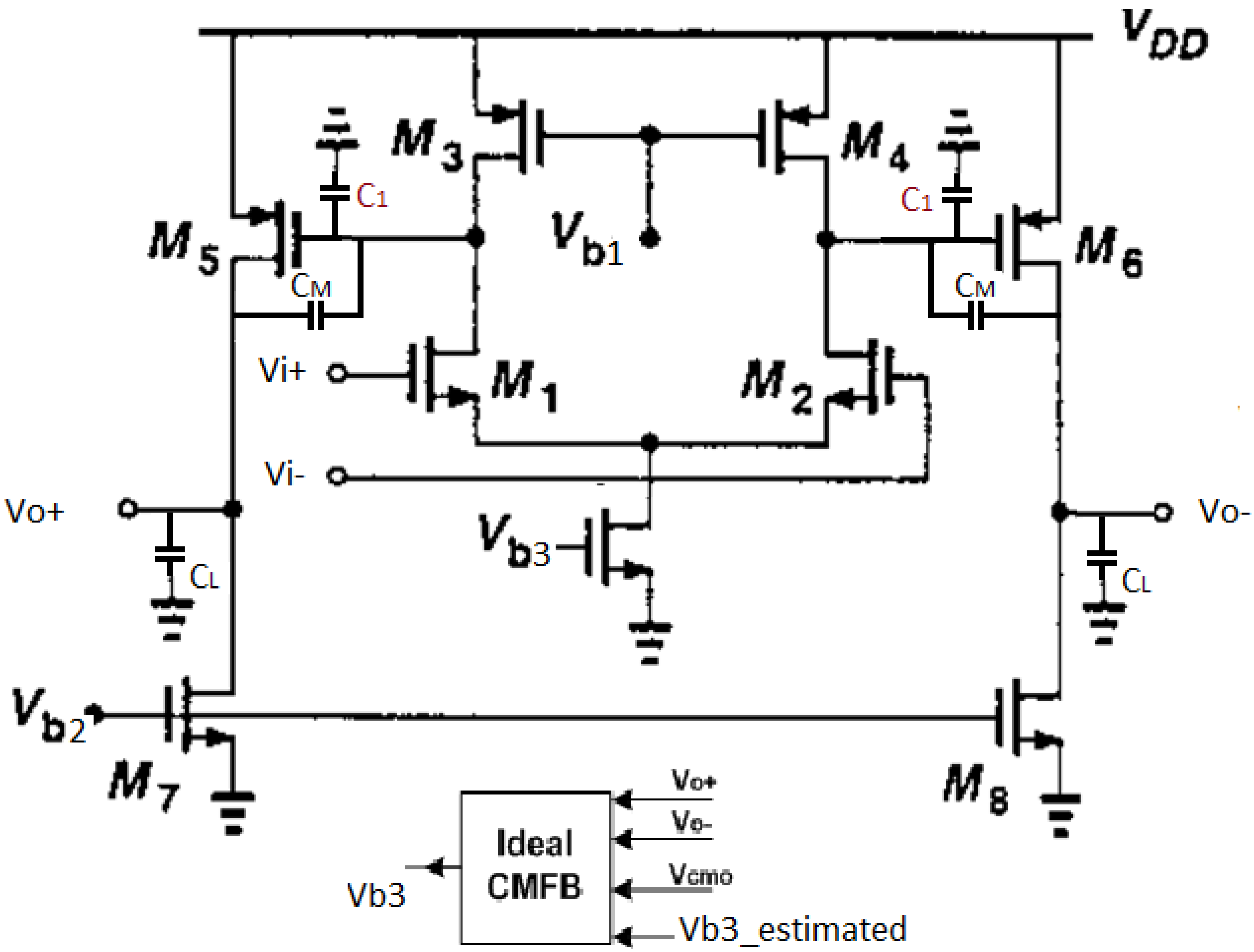
Ideal CMFB Circuit (2)



Vref denotes the desired output common-mode voltage.



Fully Differential Two-Stage Opamp (nmos input)



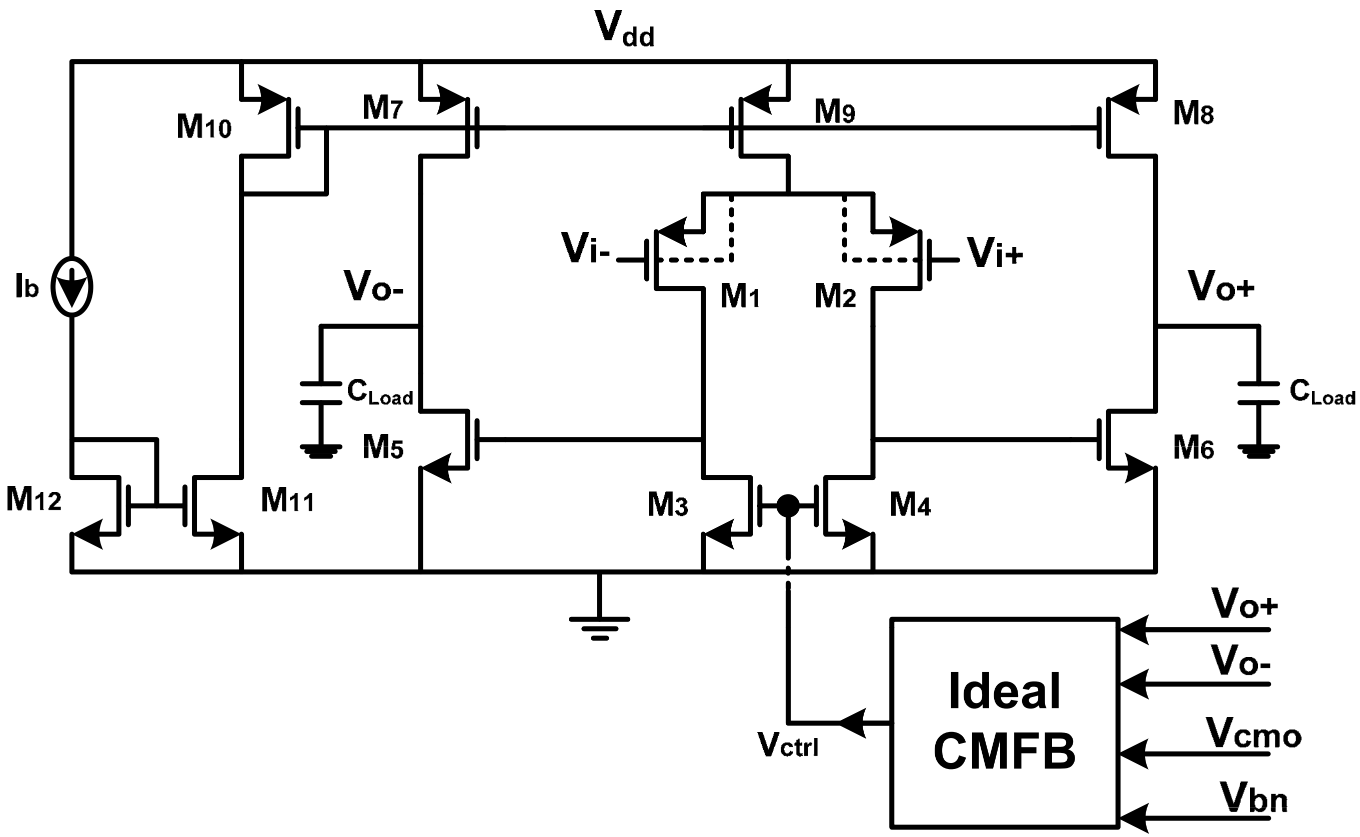
$$A_0 = g_{m1}R_1 g_{m5}R_2$$

$$\omega_{ta} = \frac{g_{m1}}{C_M}$$

$$\omega_{p2} \cong \frac{g_{m5}}{C_1 + C_L}$$

C1 denotes the parasitic capacitance.

Fully Differential Two-Stage Opamp
(pmos input)

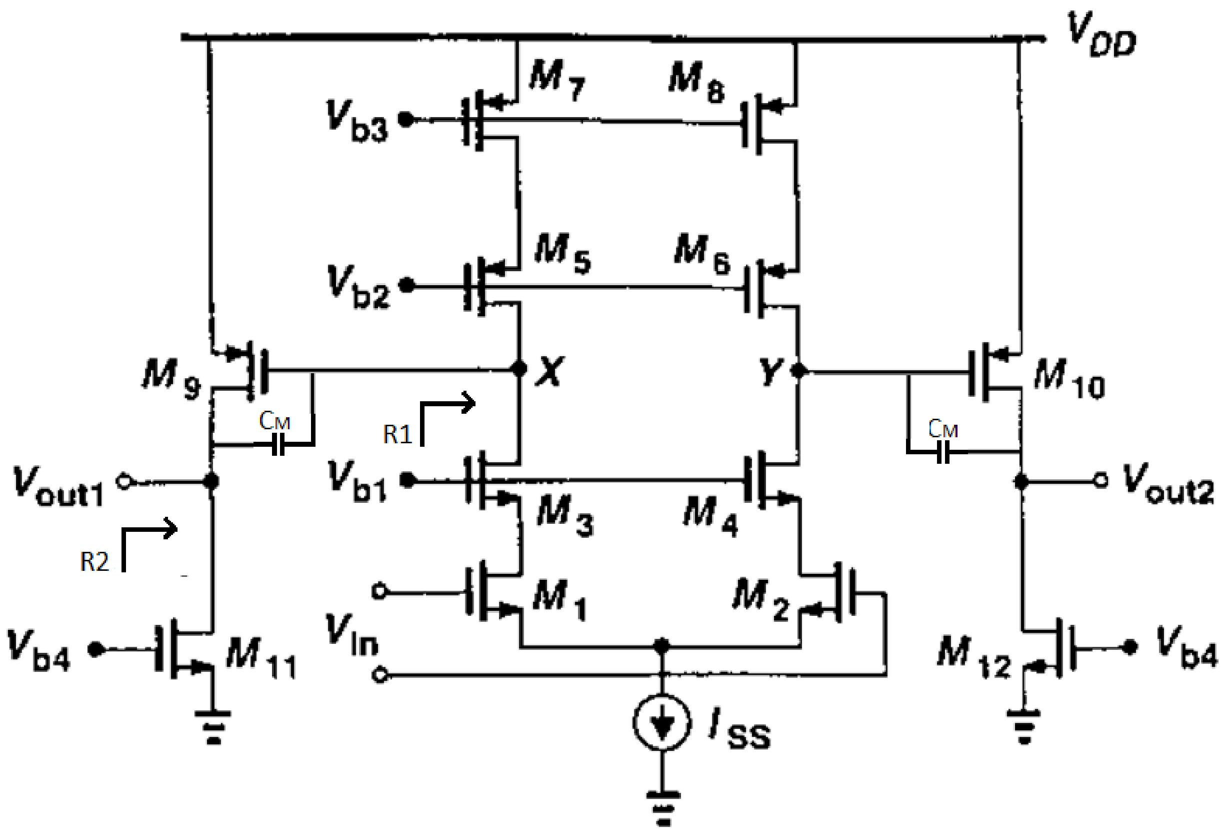


Fully Differential Two-Stage Opamp (First Stage: Telescopic Cascode)

$$A_0 = g_{m1} R_1 g_{m9} R_2$$

$$\omega_{ta} = \frac{g_{m1}}{C_M}$$

$$\omega_{p2} \cong \frac{g_{m9}}{C_1 + C_L}$$

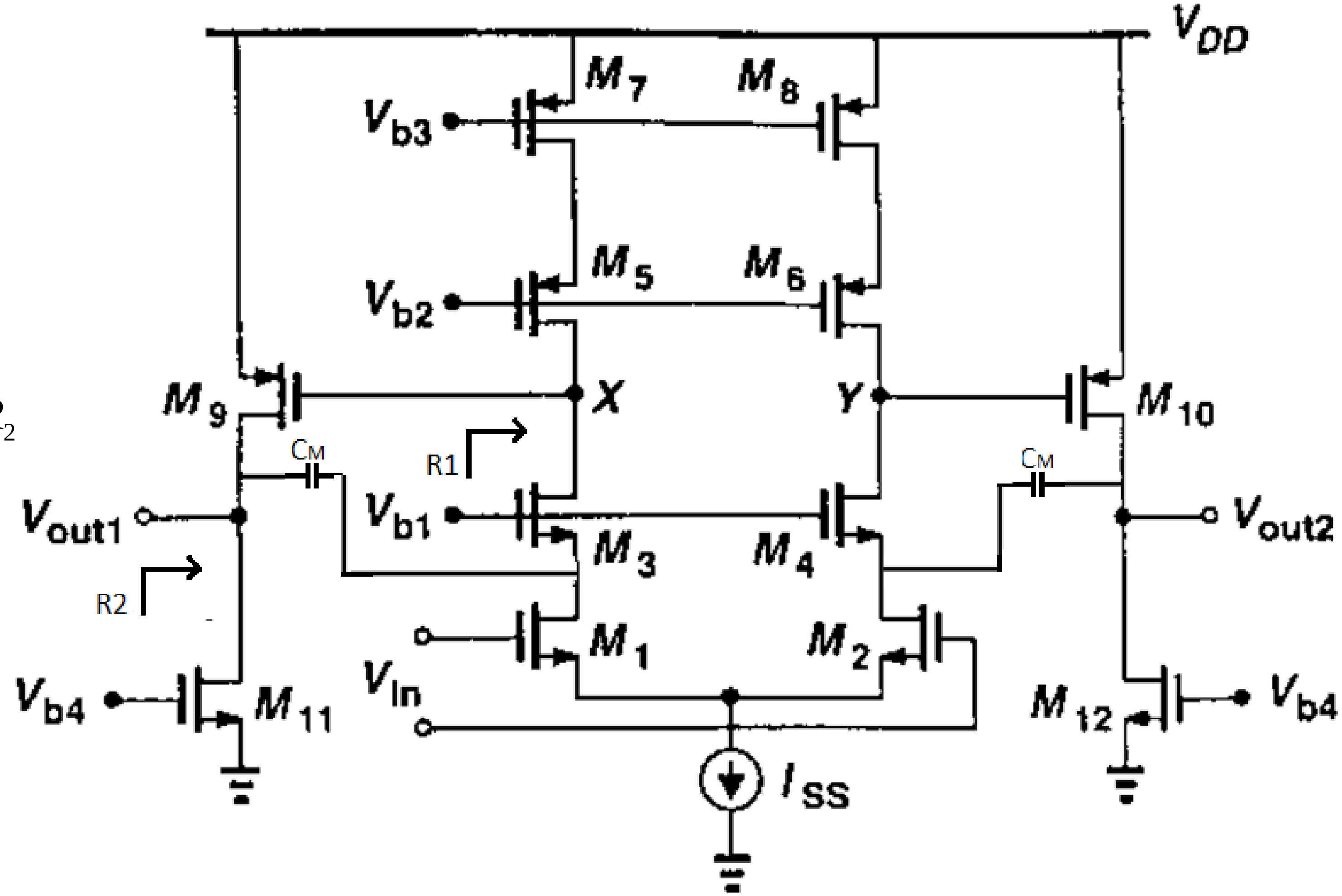


C1 denotes the parasitic capacitance at node X.
Miller compensation method is utilized.

Fully Differential Two-Stage Opamp
(Cascode-Miller Compensation)

$$A_0 = g_{m1} R_1 g_{m9} R_2$$

$$\omega_{ta} = \frac{g_{m1}}{C_M}$$

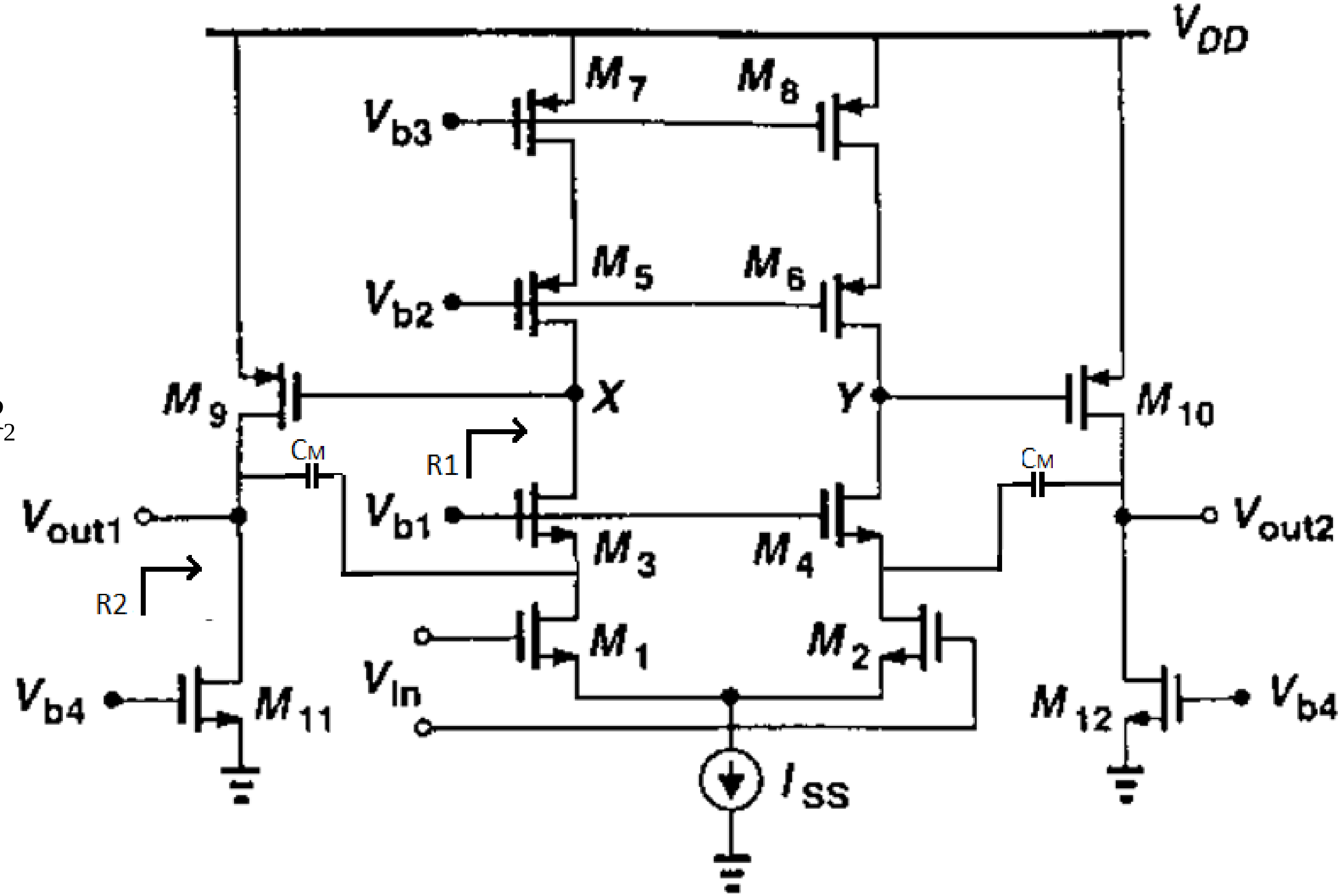


Cascode-Miller compensation method is utilized. For understanding more details, you should study the literatures.

Fully Differential Two-Stage Opamp
(Cascode-Miller Compensation)

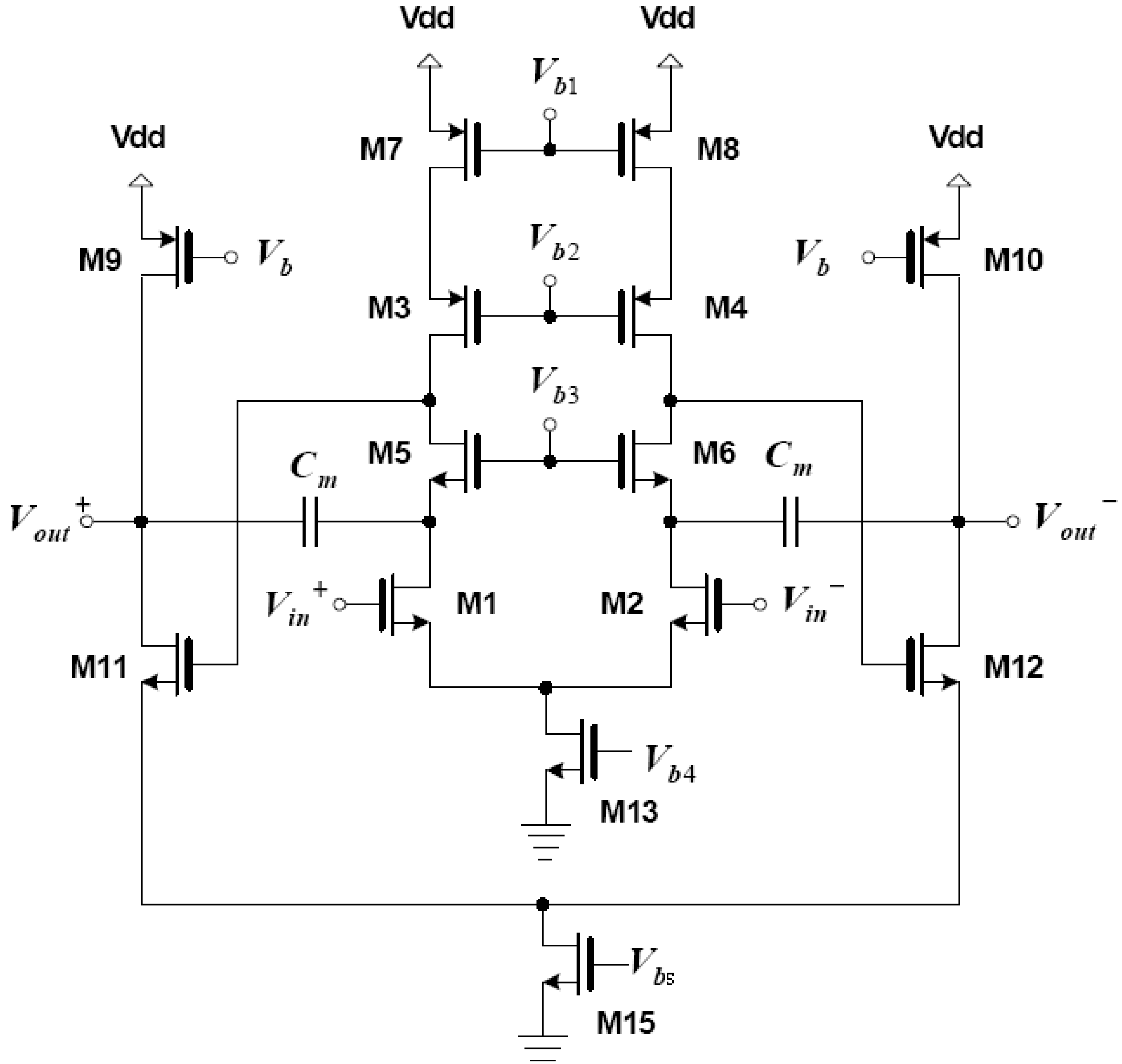
$$A_0 = g_{m1}R_1 g_{m9}R_2$$

$$\omega_{ta} = \frac{g_{m1}}{C_M}$$

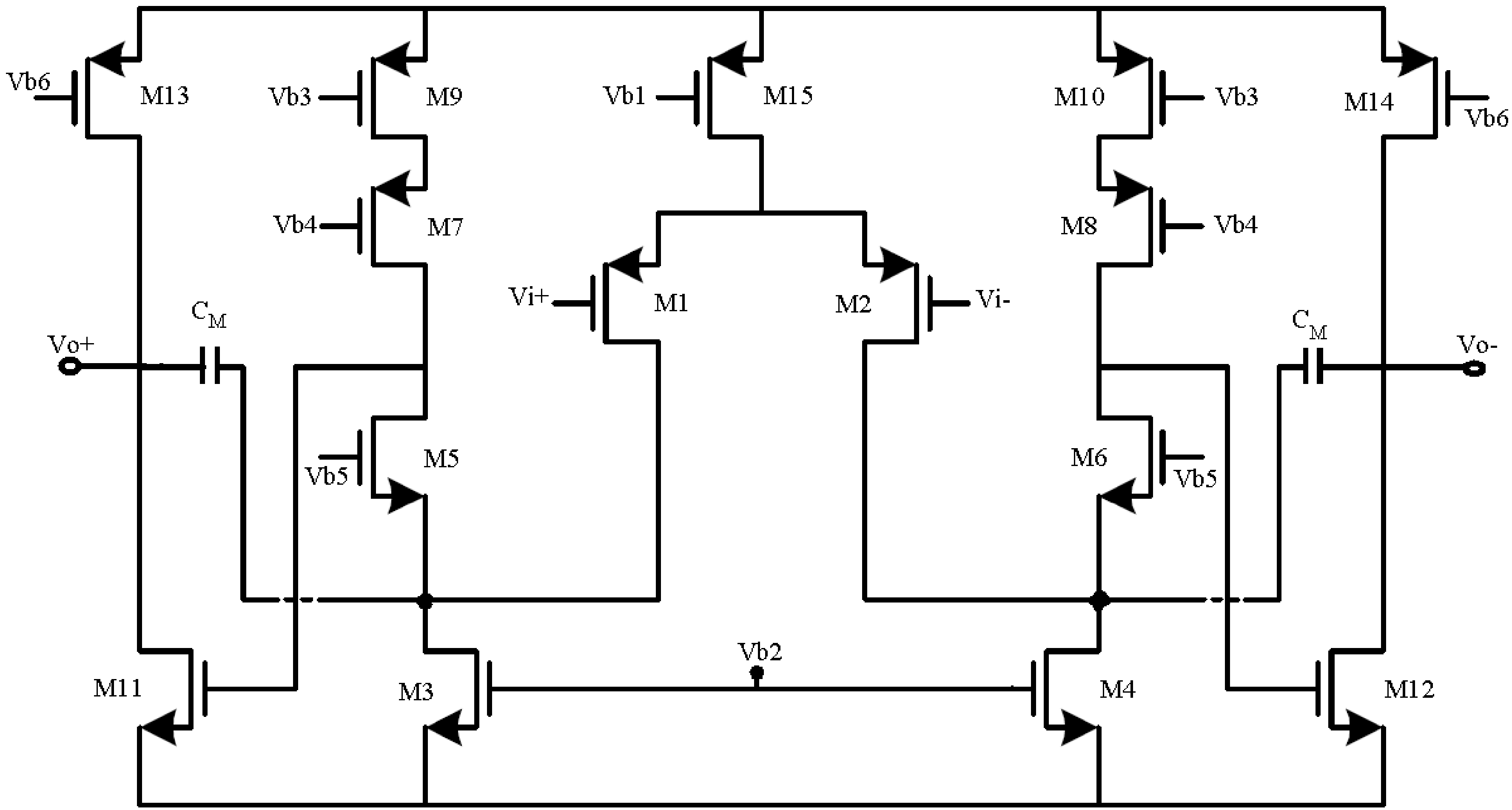


Cascode-Miller compensation method is utilized. For understanding more details, you should study the literatures.

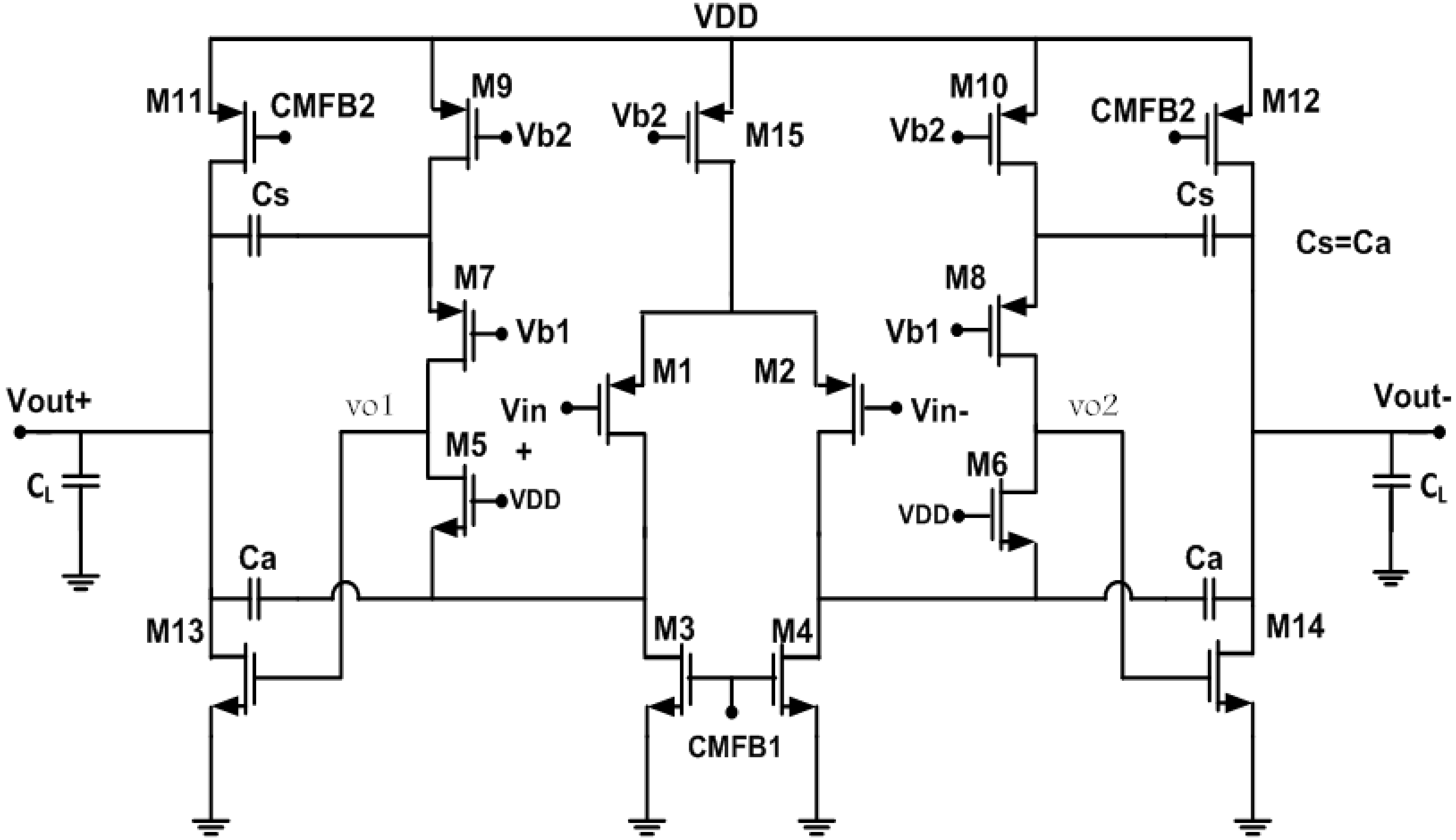
Fully Differential Two-Stage Opamp (Improving CMRR)



Fully Differential Two-Stage Opamp
(First Stage: Folded-Cascode)

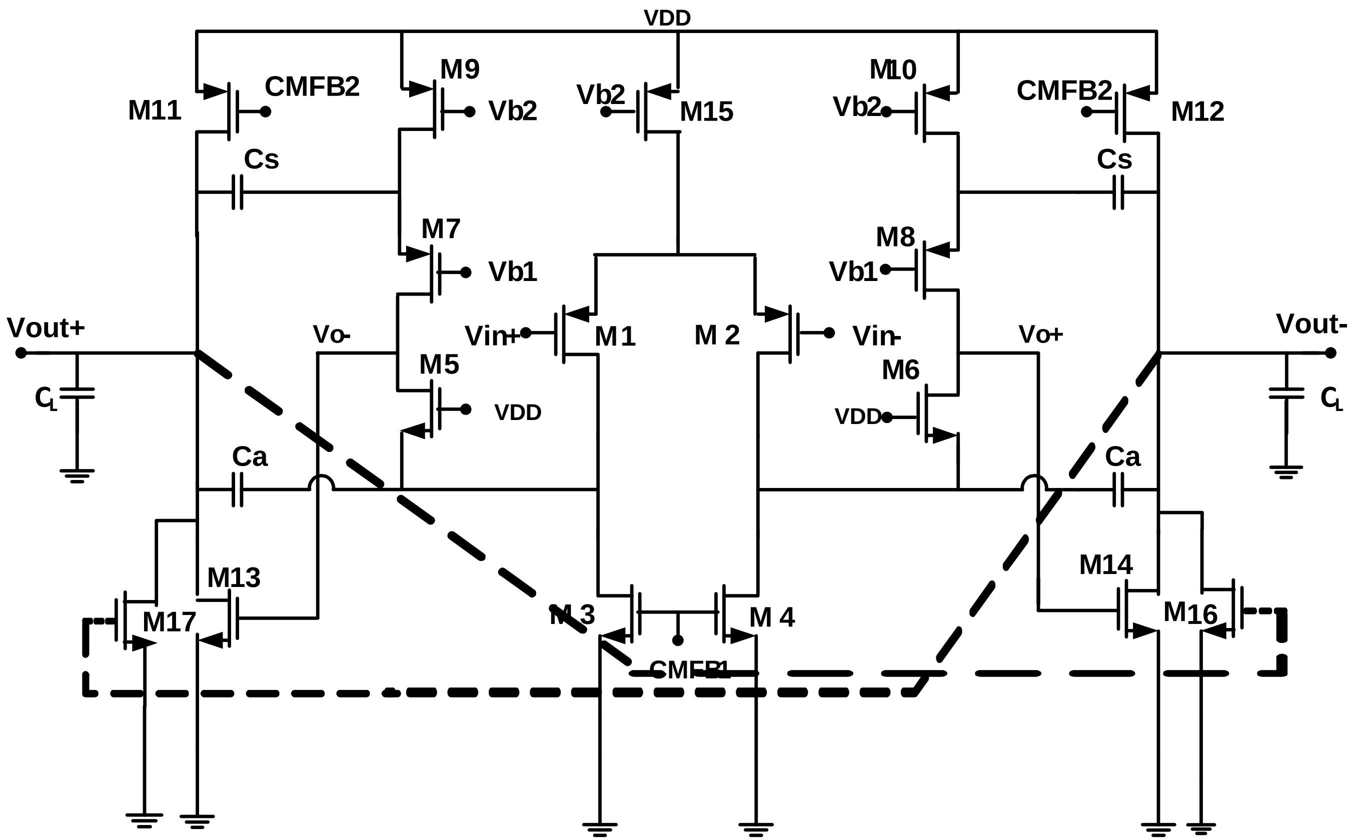


Continued
(Another Schematic for the Previous Opamp)



- In this opamp, two CMFB circuits are utilized.
- The Hybrid-Cascode Compensation method is utilized.

Employing Positive Feedback for DC-Gain Enhancement



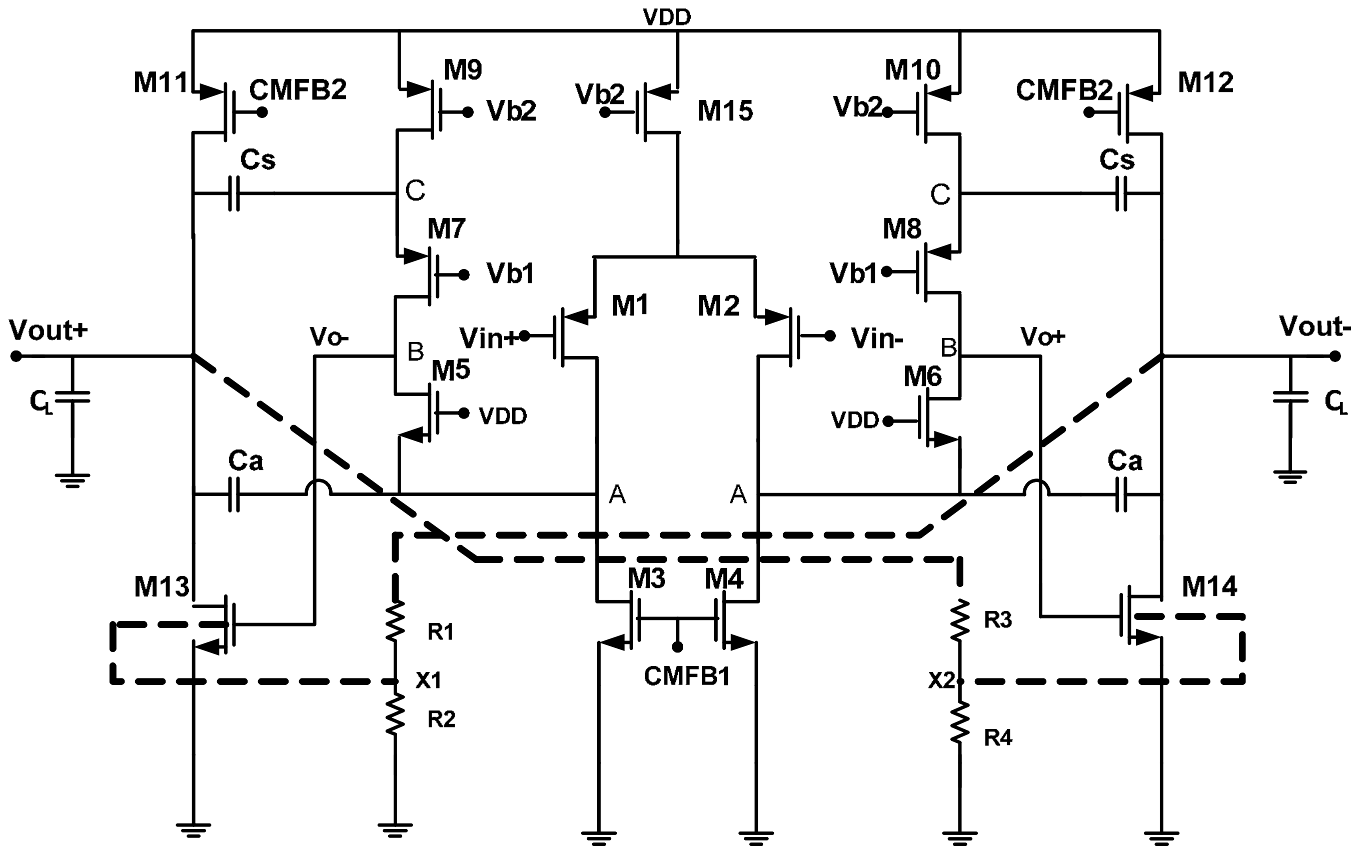
$$A_d = g_{m1} R_{out1} \frac{g_{m13} R_{out2}}{1 - g_{m17} R_{out2}}$$

$$R_{out1} = g_{m7} r_{ds7} r_{ds9} \| [g_{m5} r_{ds5} (r_{ds1} \| r_{ds3})]$$

$$R_{out2} = r_{ds17} \| r_{ds13} \| r_{ds11}$$

This technique will not affect the UGBW and stability. It does not also increse the power dissipation.

Employing Positive Feedback and Body-Driven Techniques for DC-Gain Enhancement



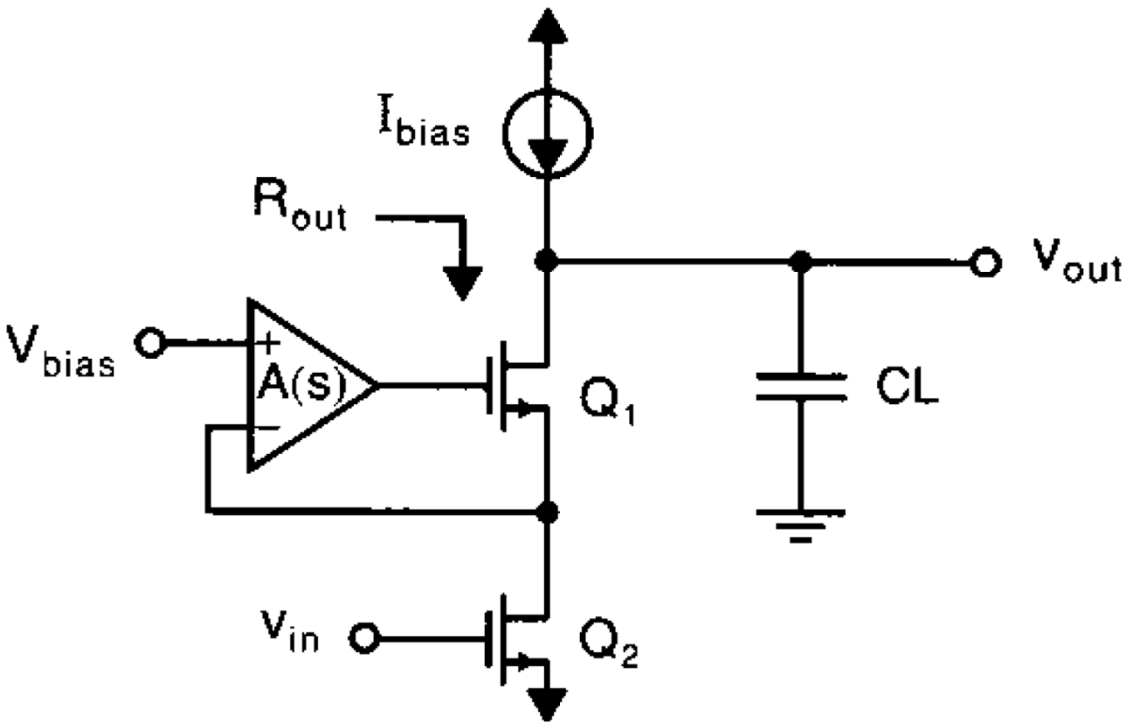
$$A_{dc} = g_{m1} R_{out1} \frac{g_{m13} R_{out2}}{1 - g_{mb13} R_{out2} K}$$

$$R_{out1} = g_{m7} r_{ds7} r_{ds9} \| [g_{m5} r_{ds5} (r_{ds1} \| r_{ds3})]$$

$$K = \frac{R_2}{R_1 + R_2}$$

$$R_{out2} = r_{ds11} \| r_{ds13}$$

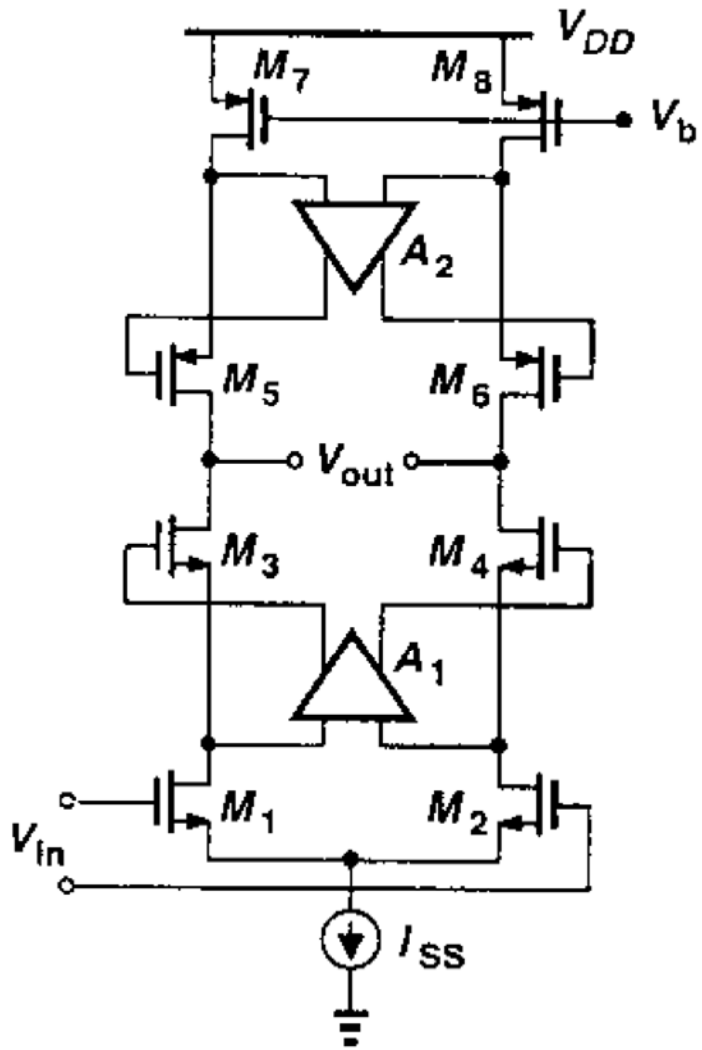
Gain-Boosting Opamp

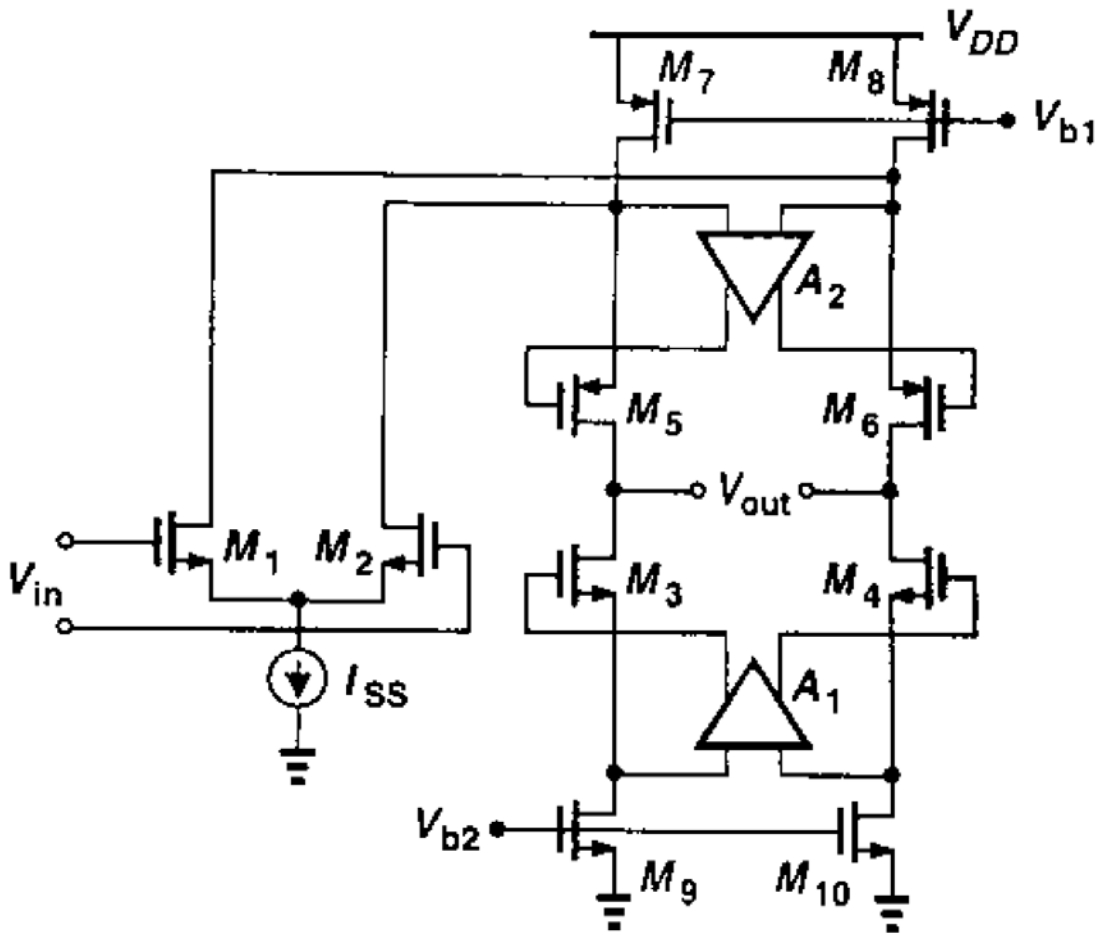


It is proven that the auxiliary amplifier will not affect the performance of the main amplifier if the following relation is satisfied.

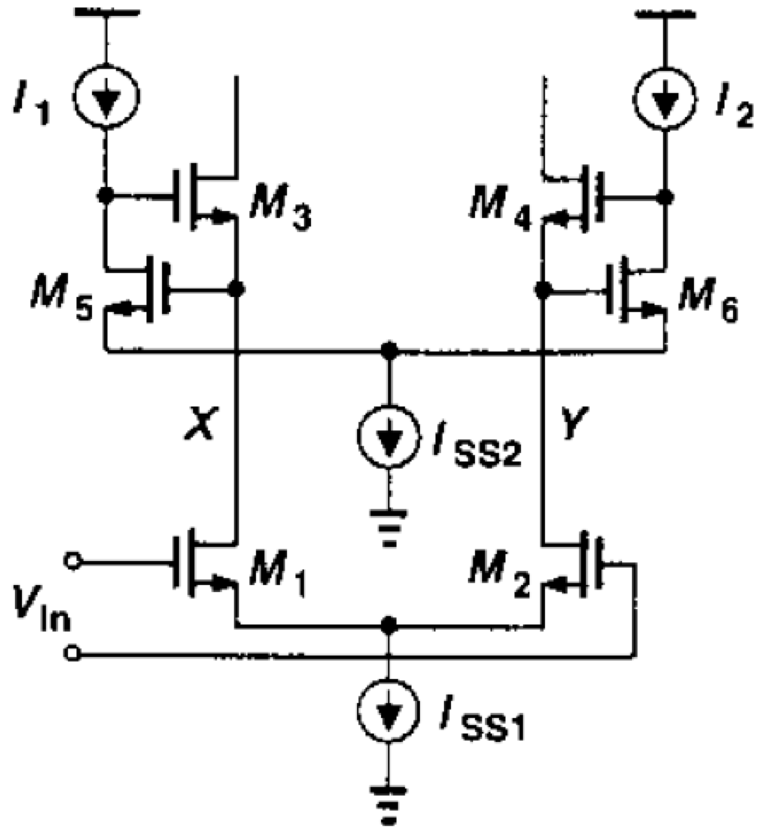
$$UGBW_{Auxiliary\ Amplifier} > UGBW_{Main\ Amplifier}$$

Gain-Boosting Opamp

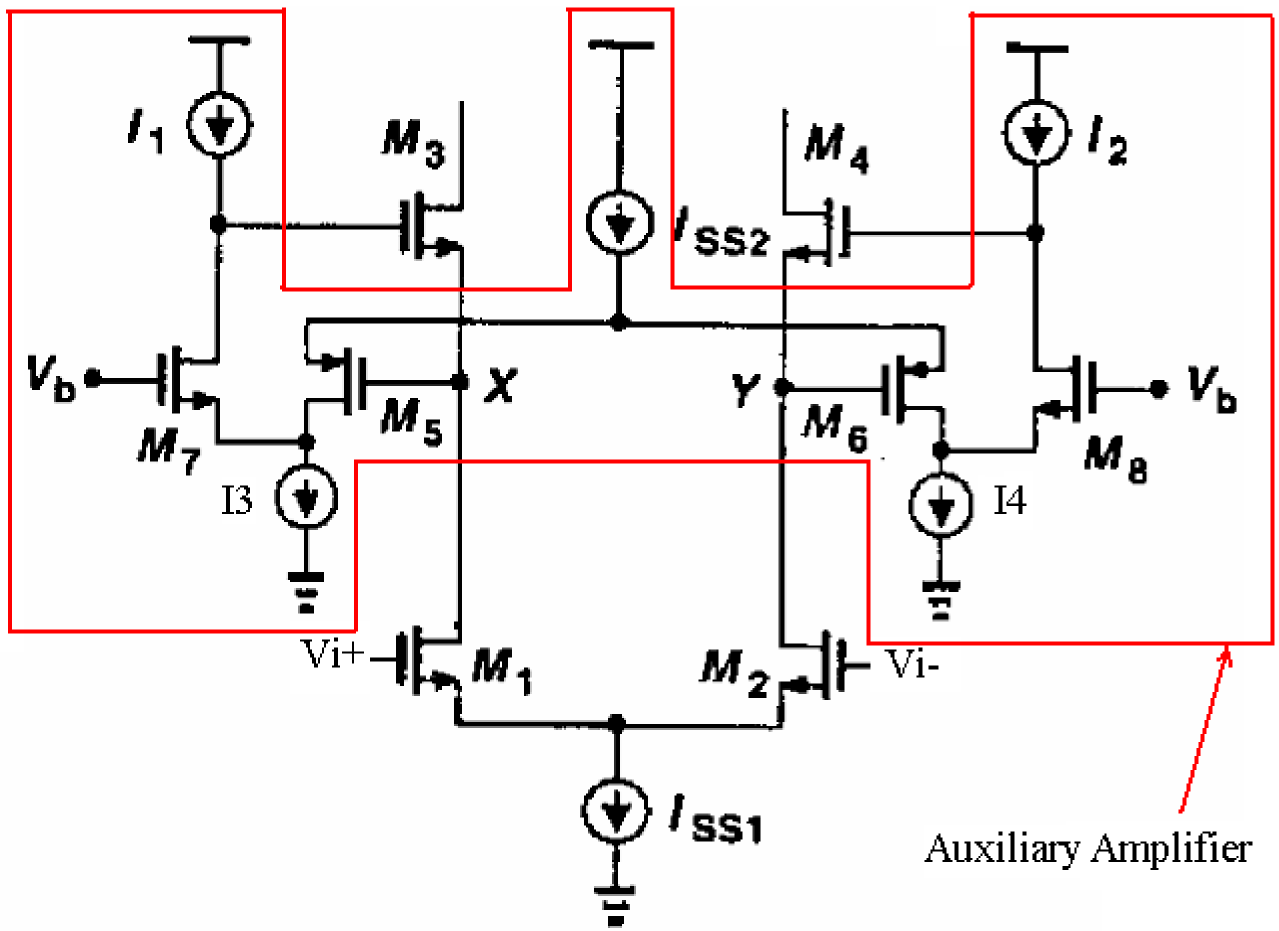




Differential Pair as an Auxiliary Opamp



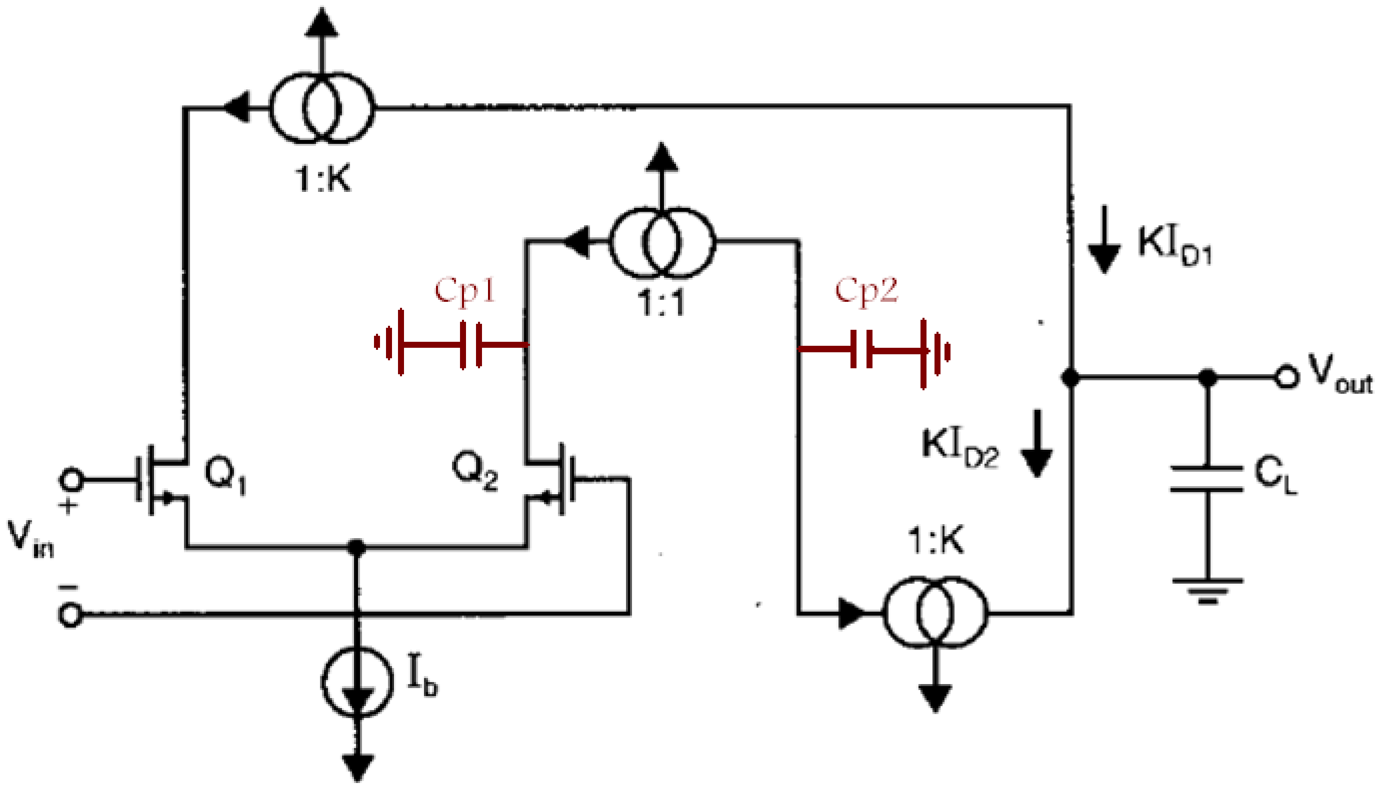
Folded-Cascode Circuit as an Auxiliary Opamp



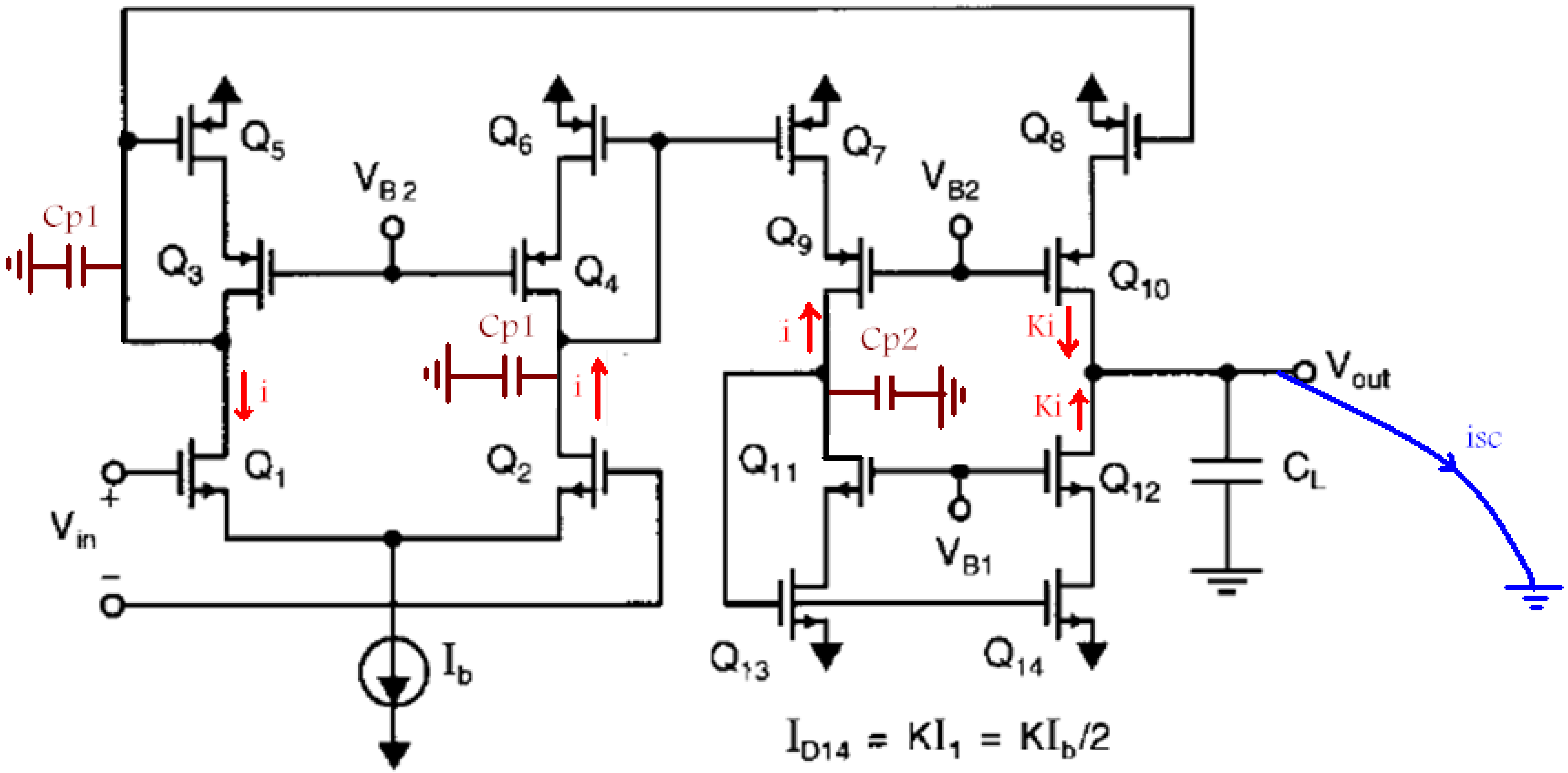
Comparison of Performance of Various Opamp Topologies

	Gain	Output Swing	Speed	Power Dissipation	Noise
Telescopic	Medium	Low	Highest	Low	Low
Folded-Cascode	Medium	Medium	High	Medium	Medium
Two-Stage	High	Highest	Low	Medium	Low
Gain-Boosted	High	Medium	Medium	High	Medium

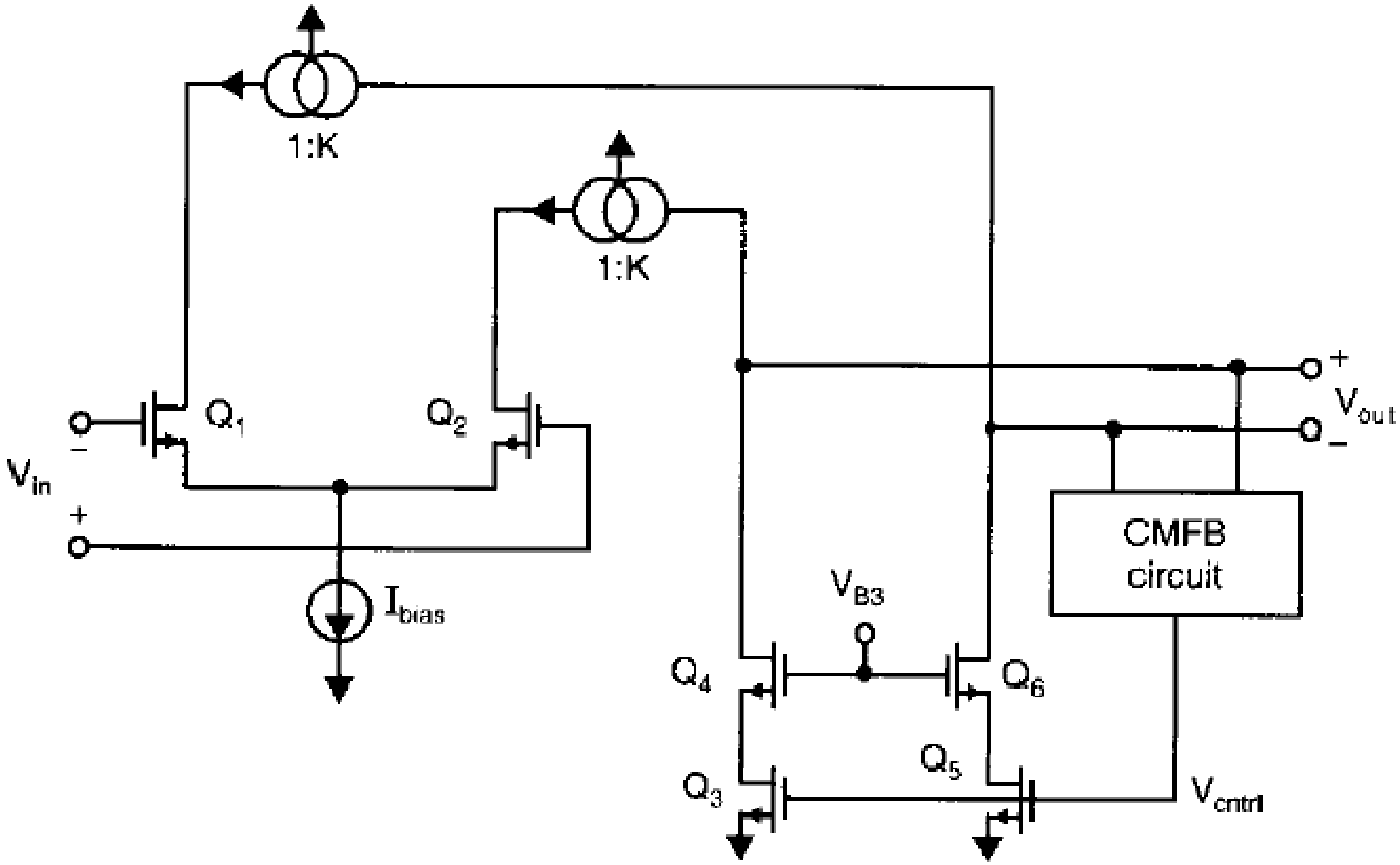
Single-Ended Current-Mirror Opamp



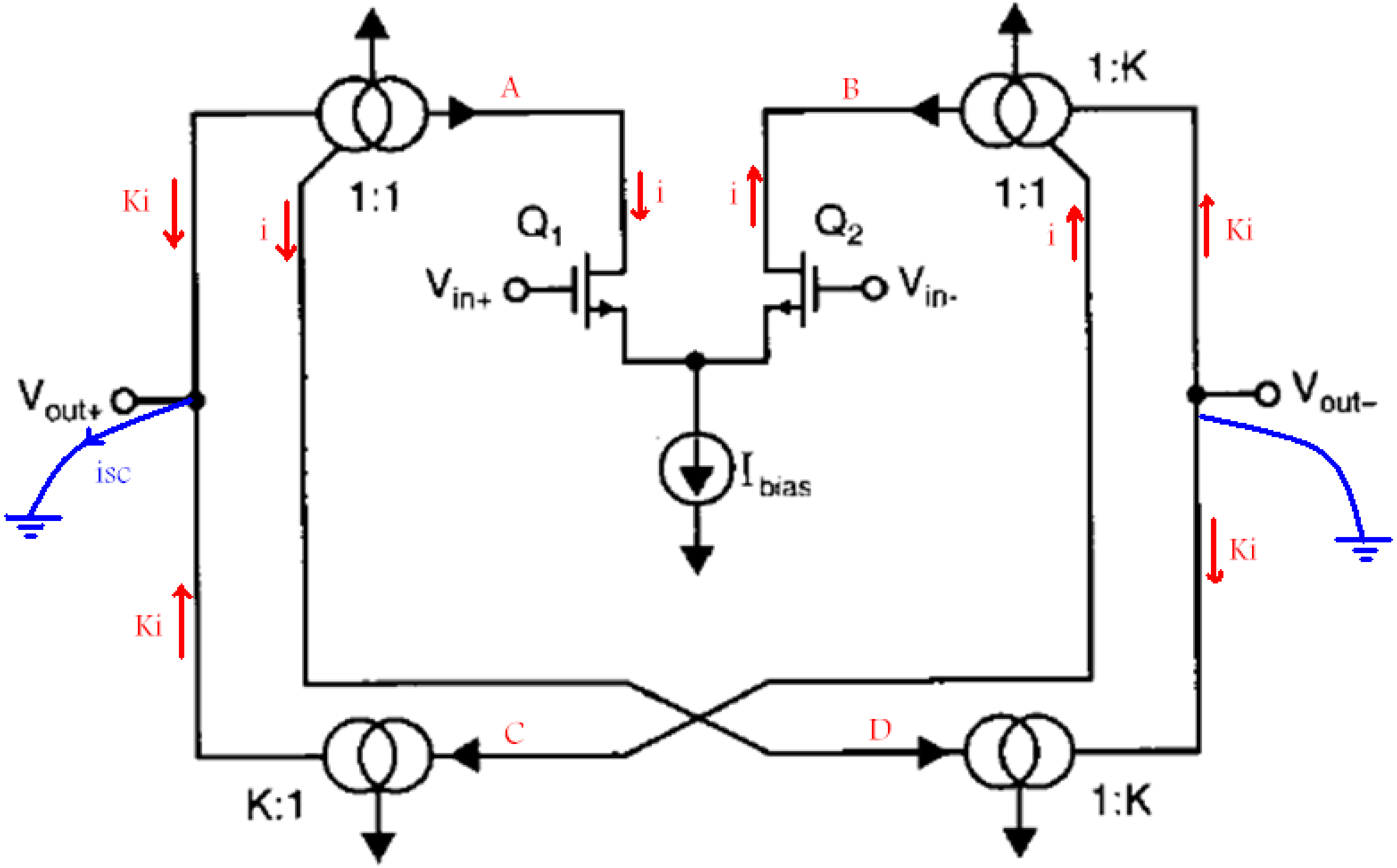
Current-Mirror Opamp with Wide-Swing Cascode Current Sources



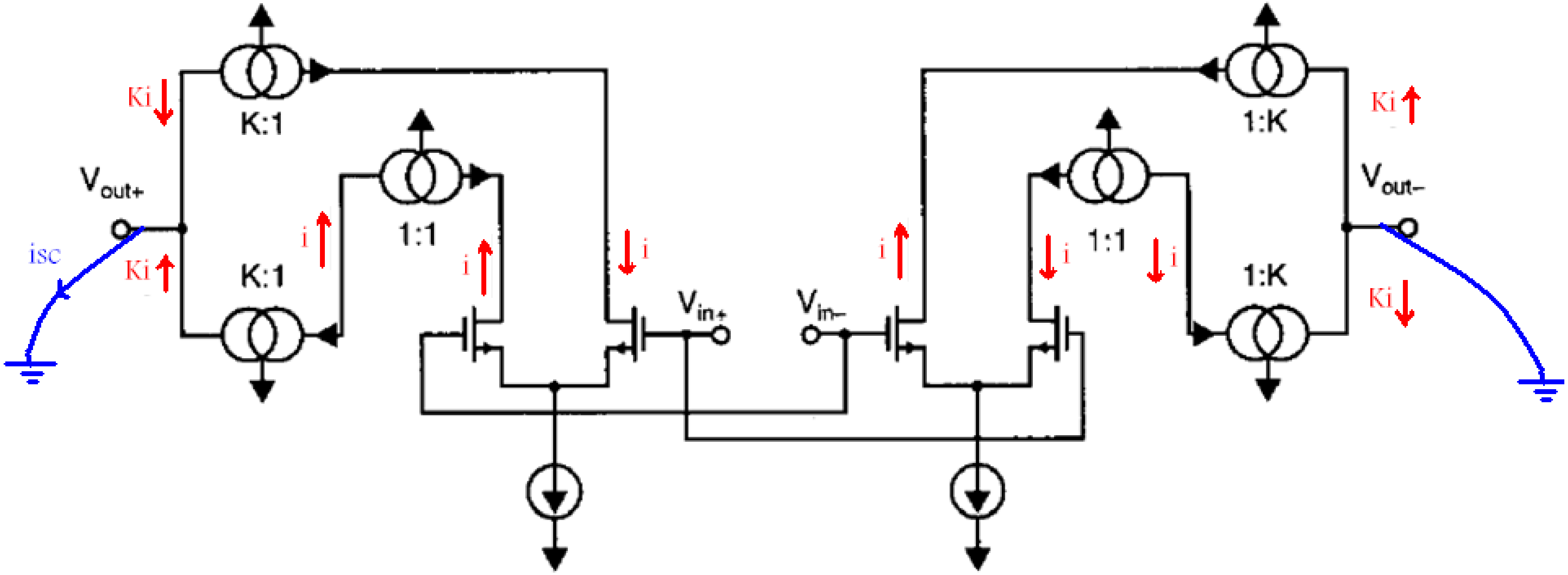
Fully Differential Current-Mirror Opamp



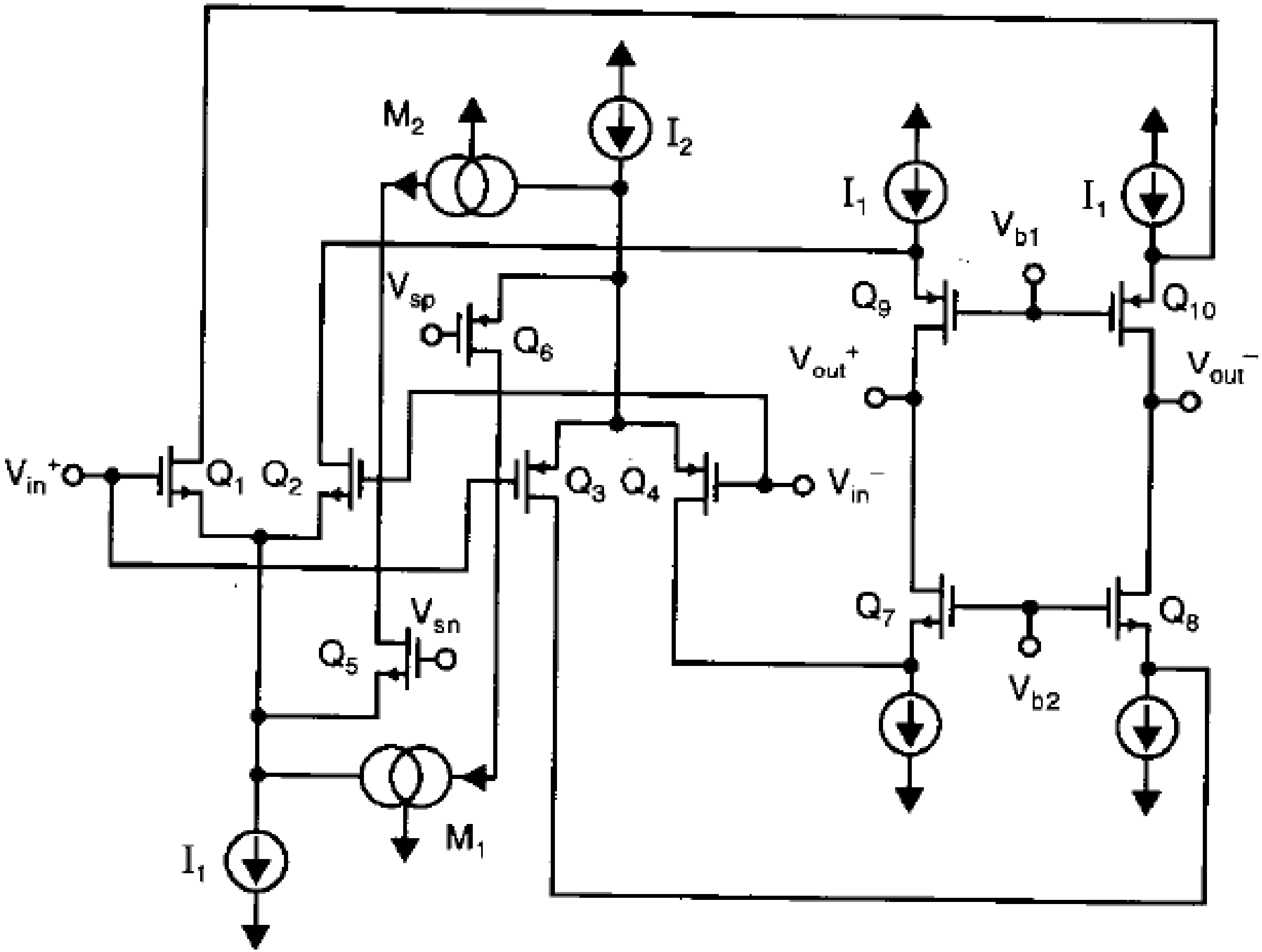
Fully Differential Opamp with Bidirectional Output Drive.



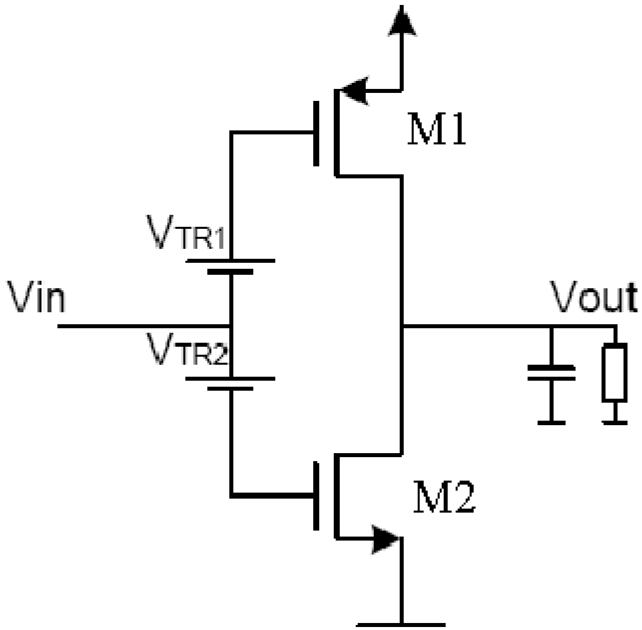
Fully Differential Opamp Composed of Two Single-Ended Output Current-Mirror Opamps



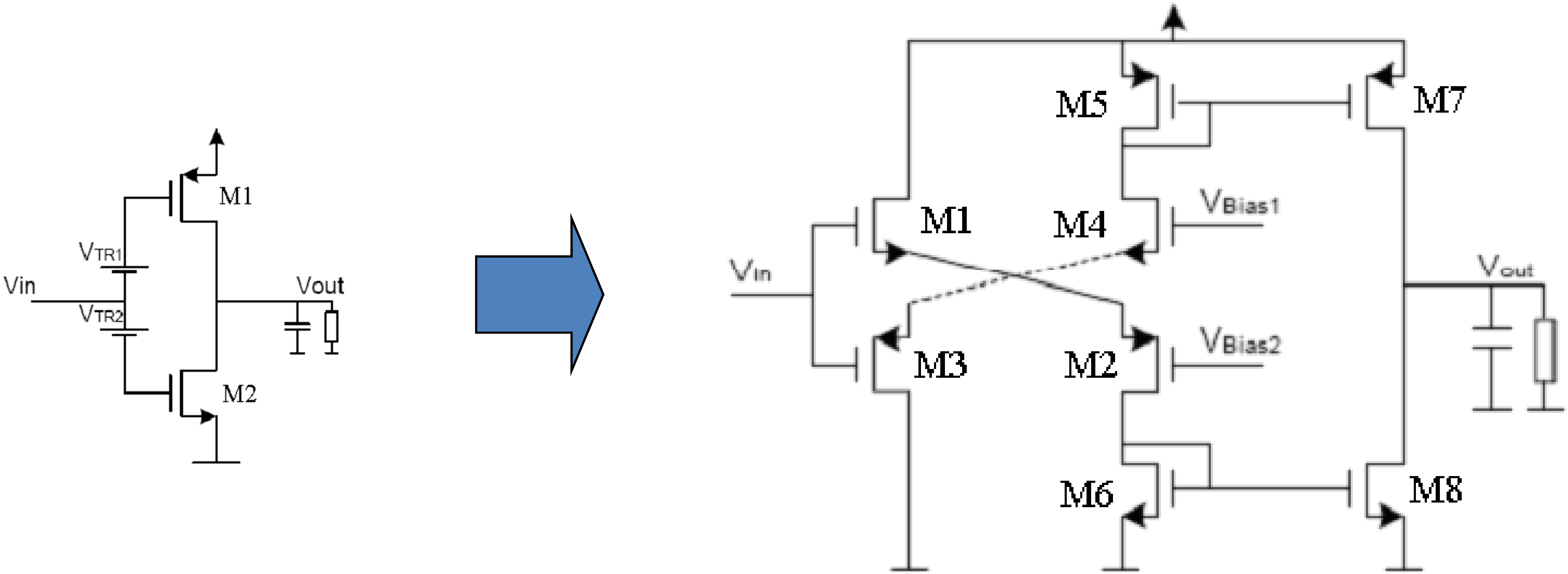
An Opamp Having Rail-to-Rail input Common-Mode Voltage Range.



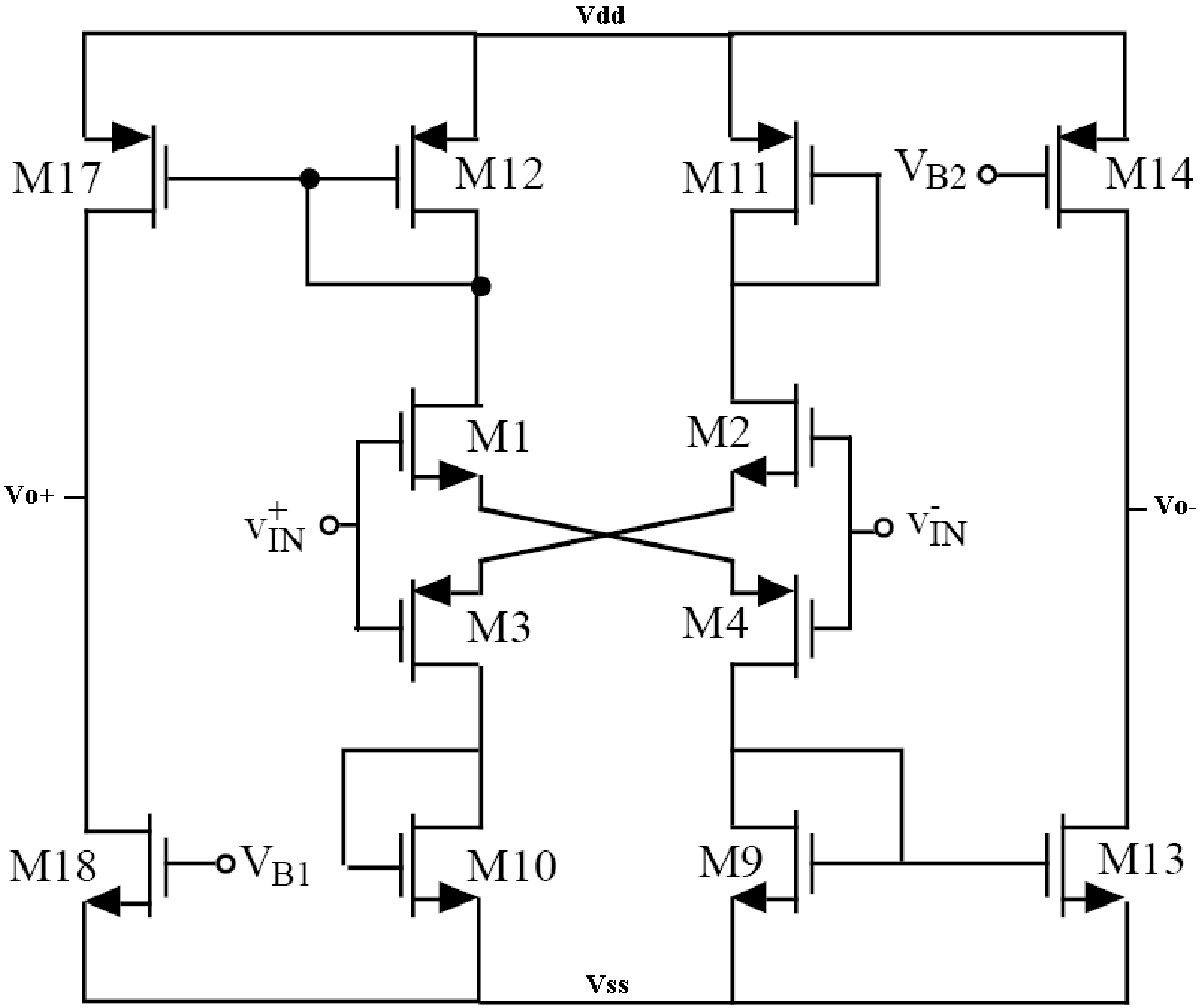
Wide-Swing Class AB Amplifier



Realization of the Previous Amplifier

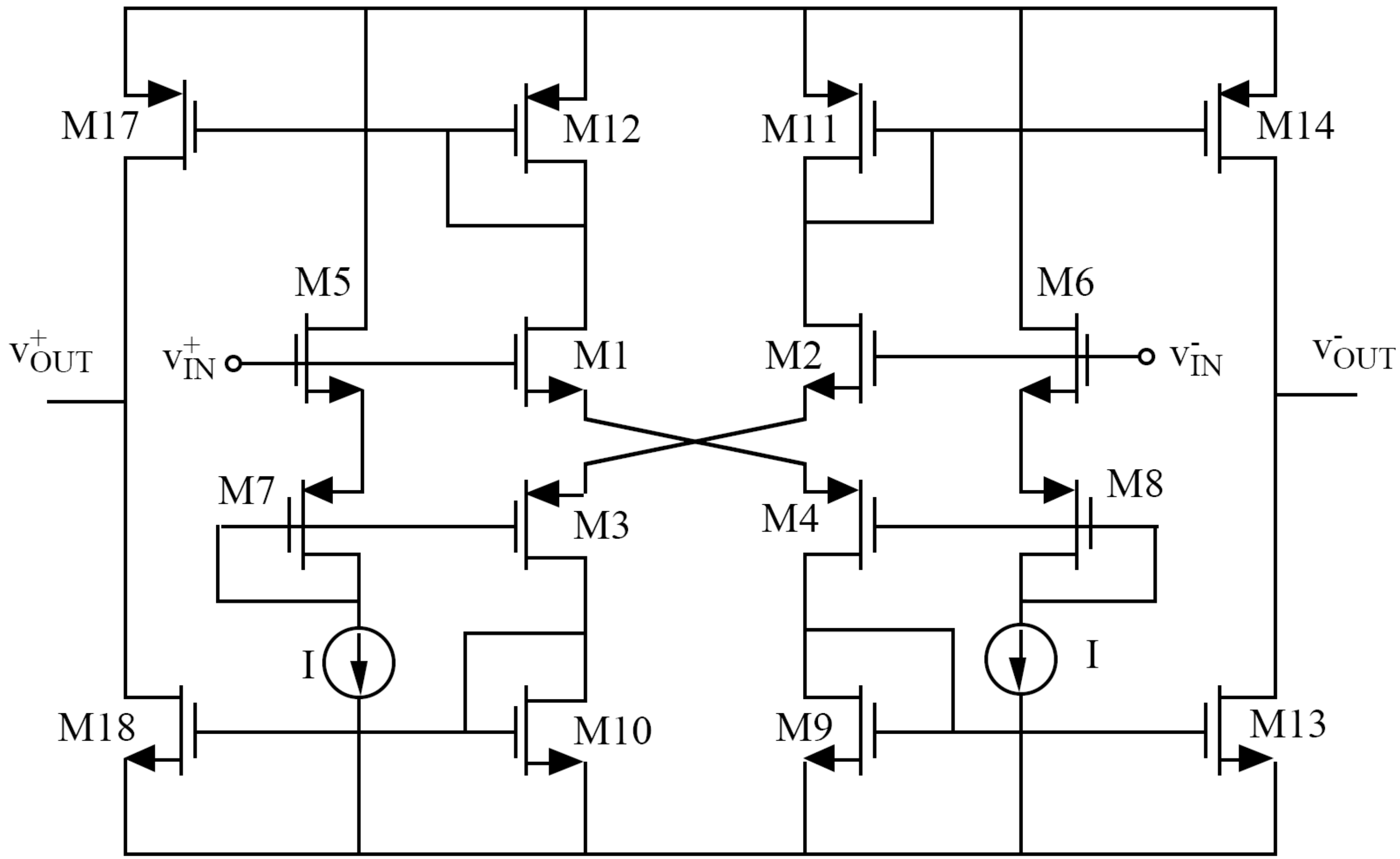


Previous Amplifier (Fully Differential)



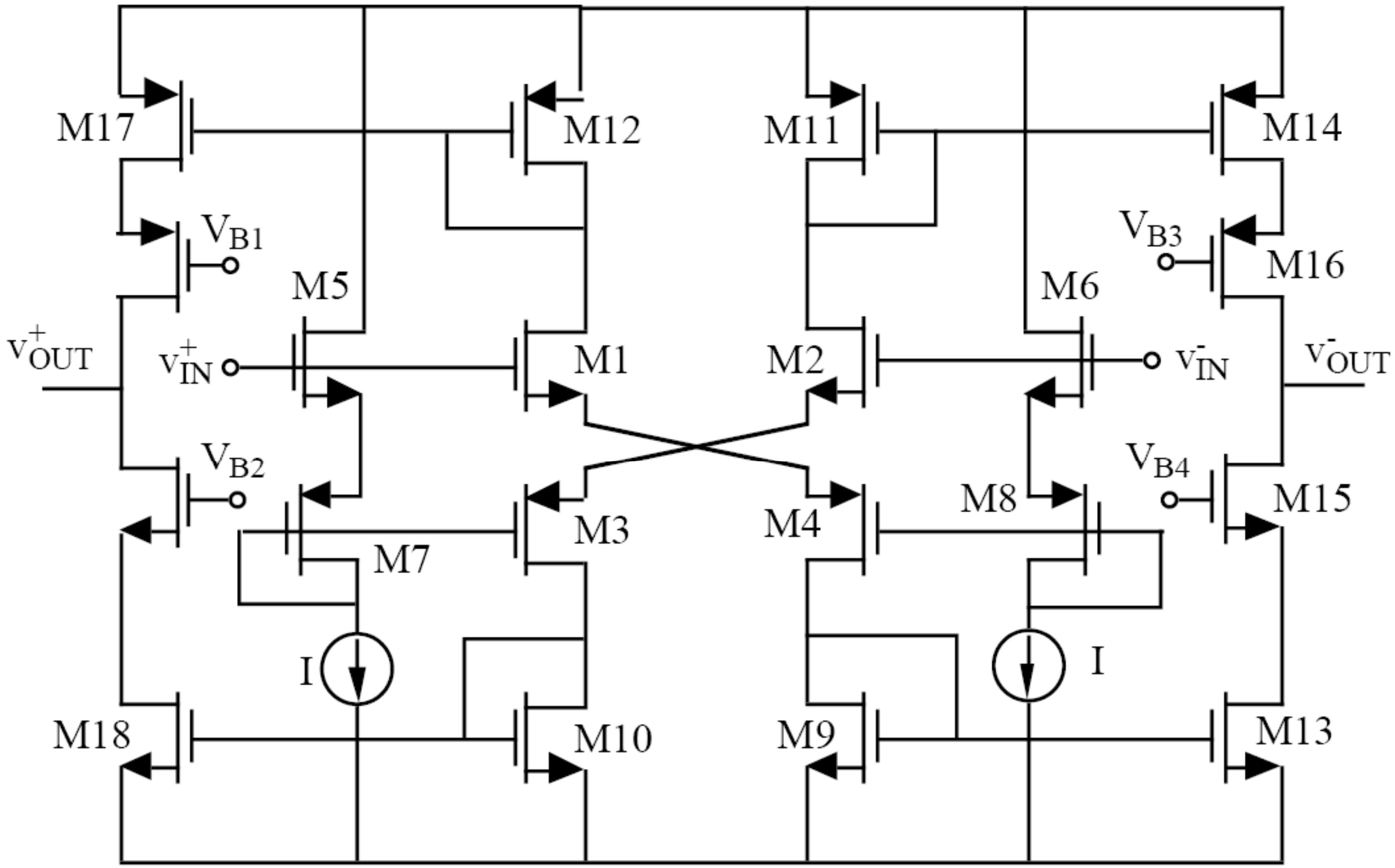
Problem: DC levels of input voltages incompatible

Fully Differential Class AB Opamp



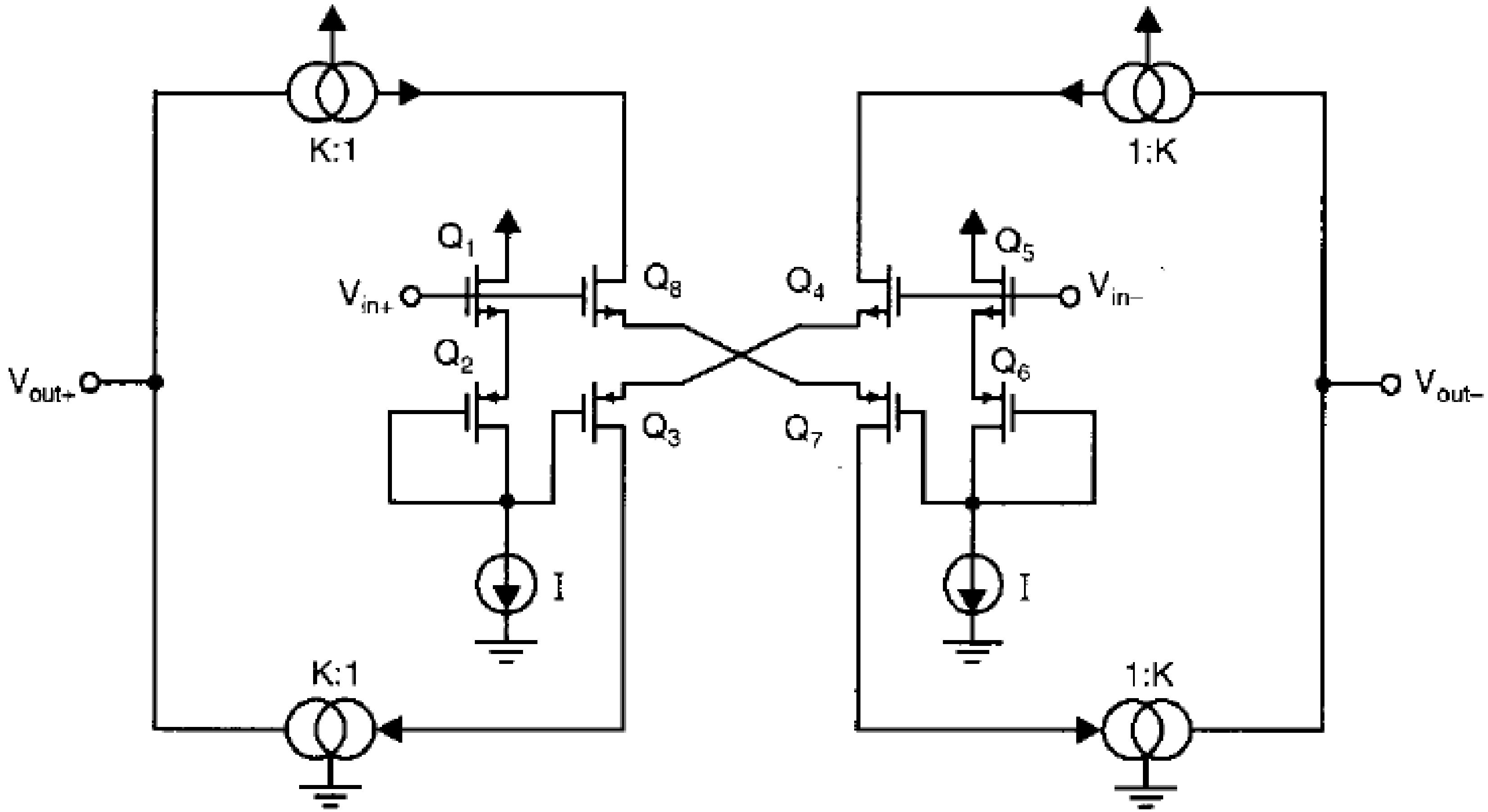
DC problem solved, but amplifier has low gain

Fully Differential Class AB Opamp

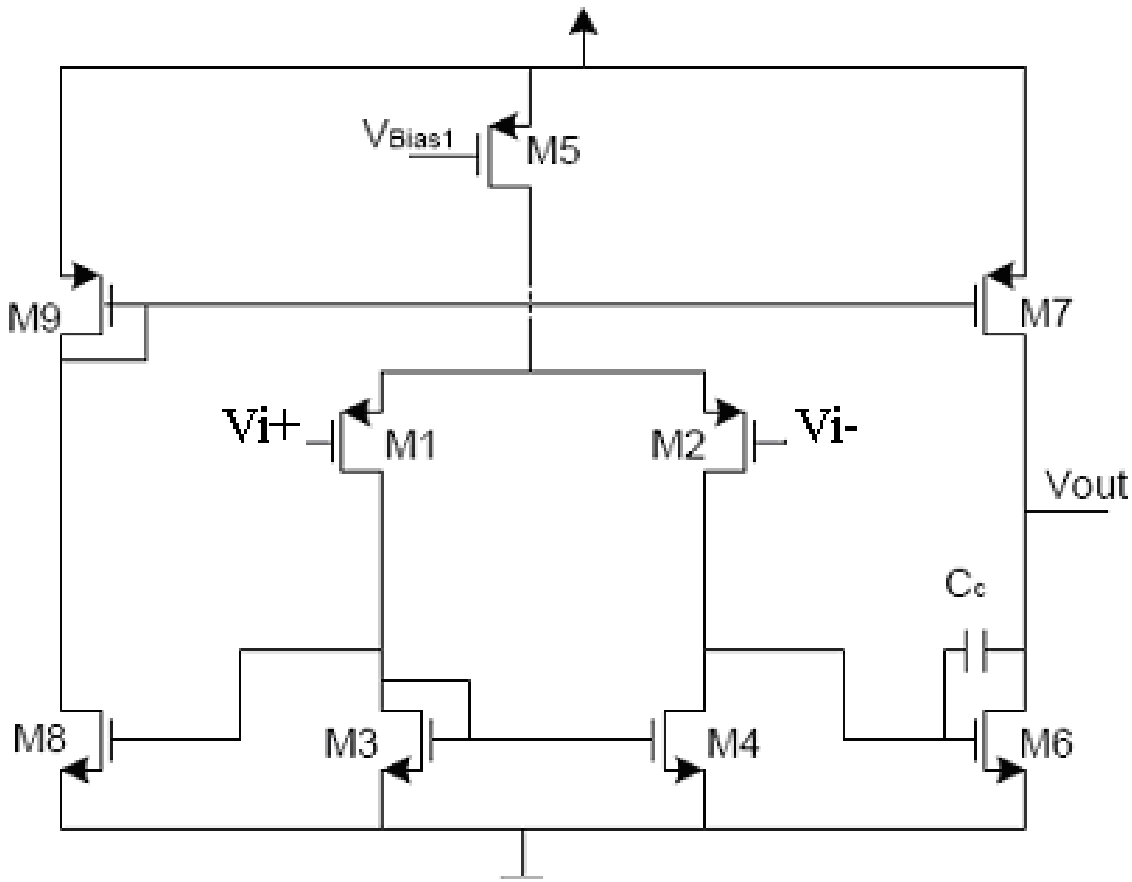


Gain improved using cascode

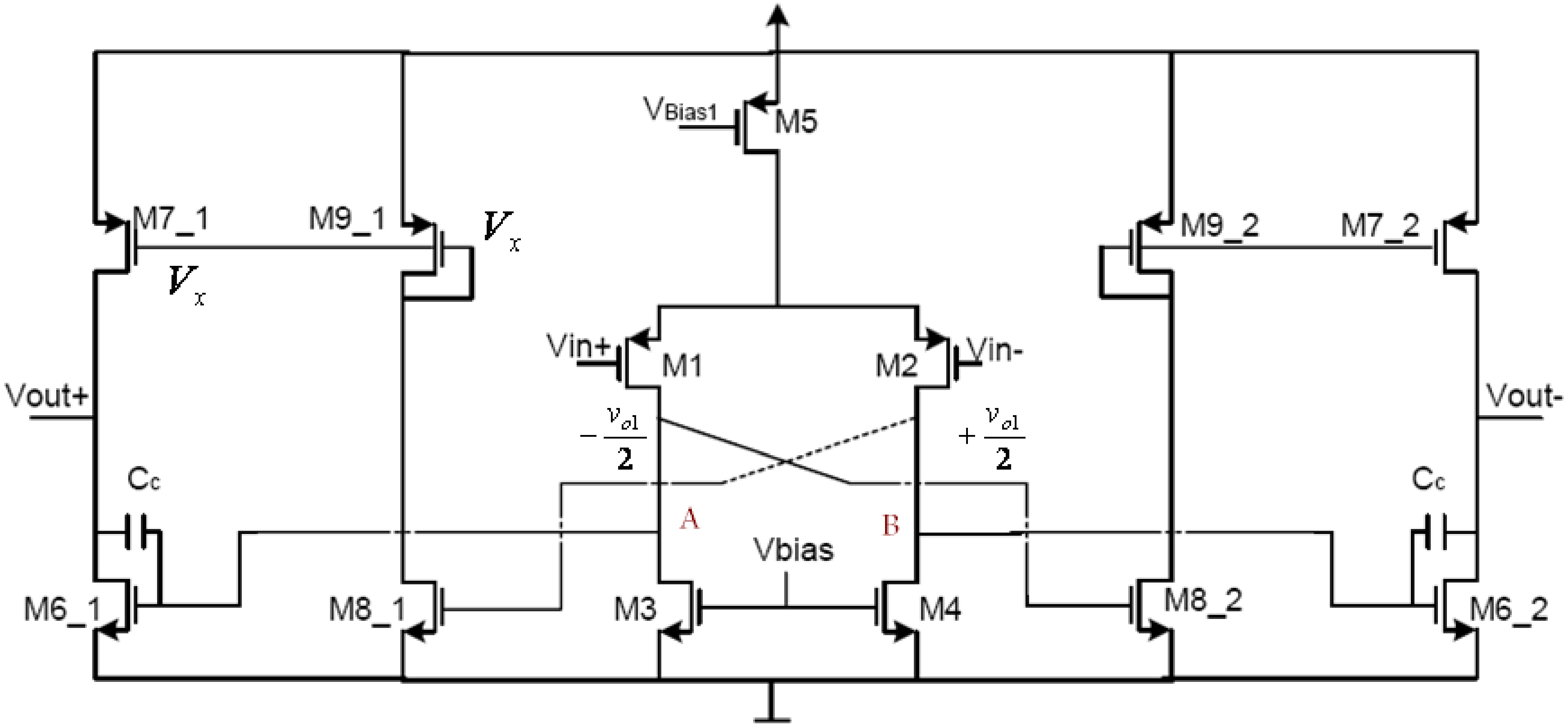
Another Schematic



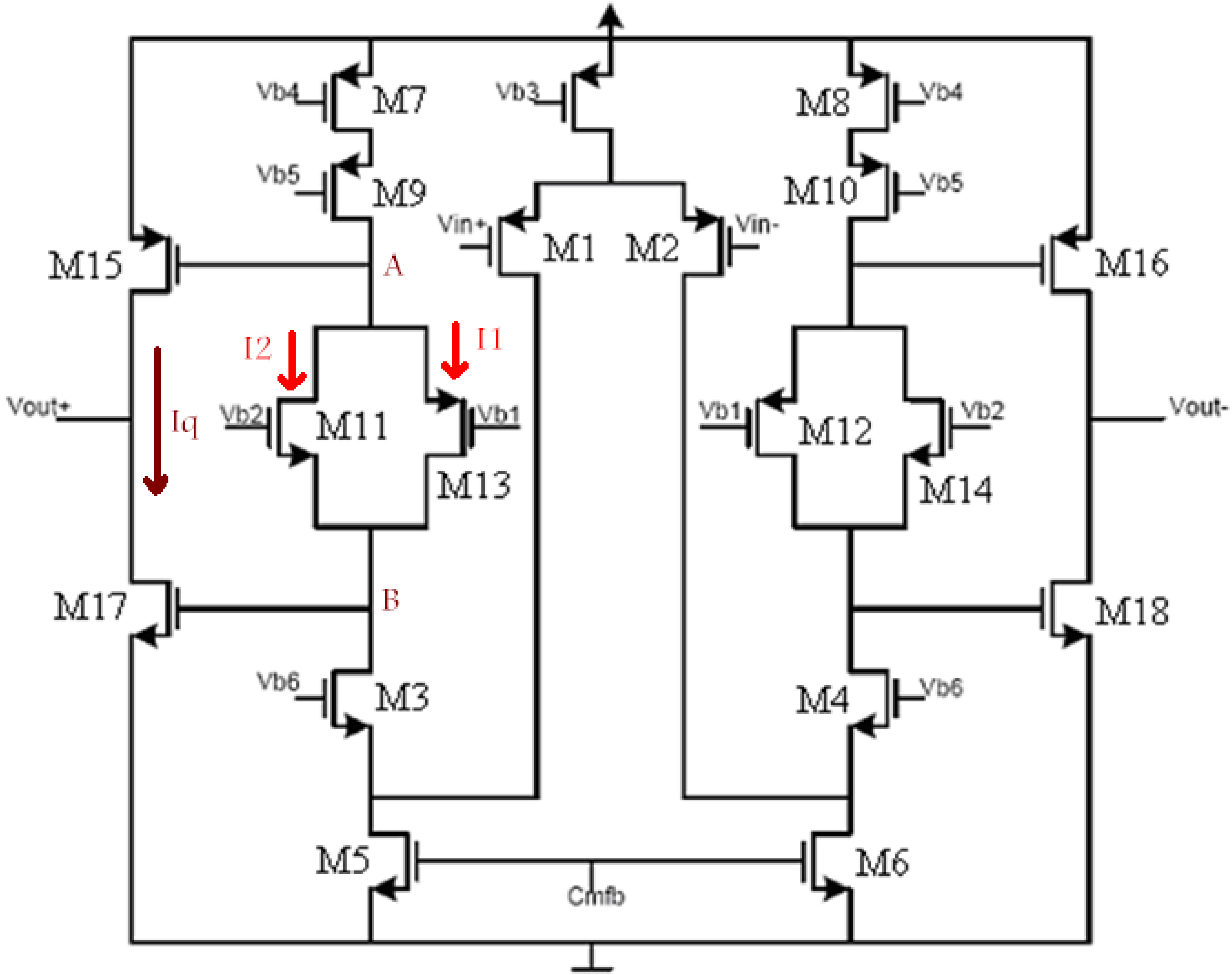
Single-Ended Class AB Opamp



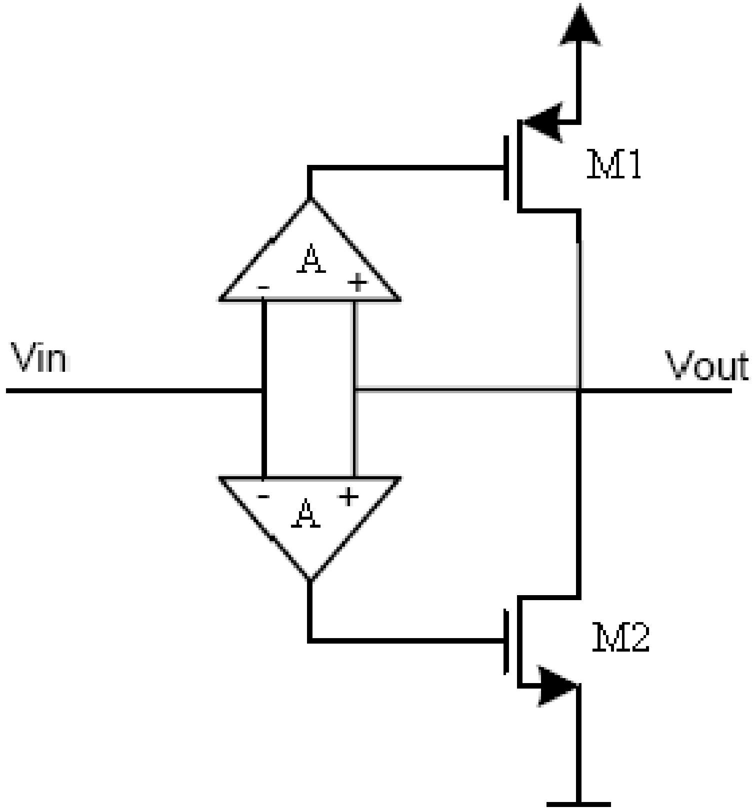
Fully Differential Class AB Opamp



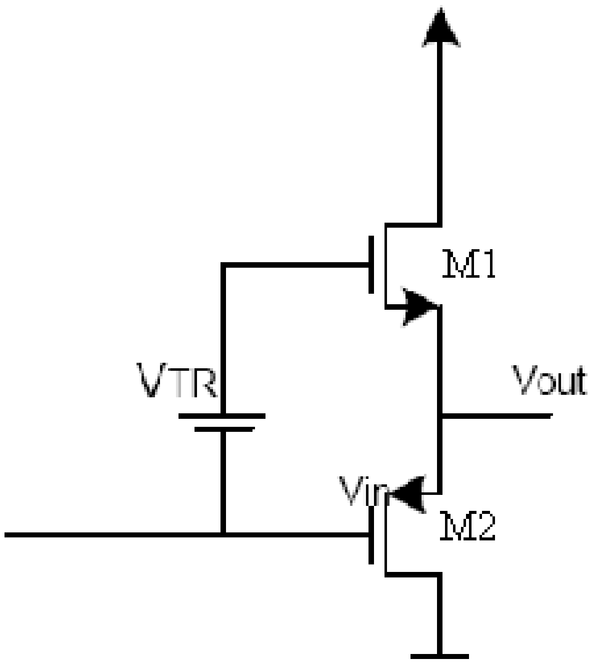
Fully Differential Class AB Opamp
(Hogervorst opamp)

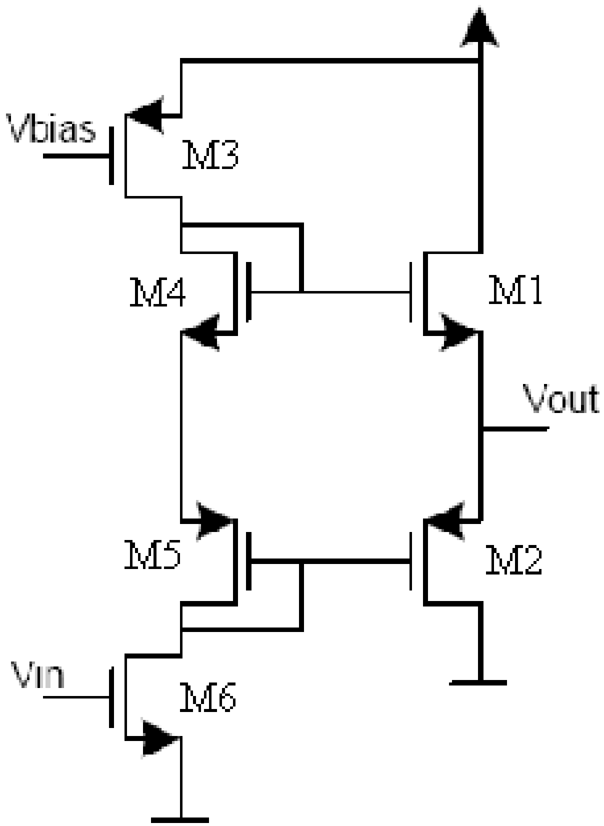


Very Low-Output Impedance Class AB Amplifier



Very Low-Output Impedance Class AB Amplifier





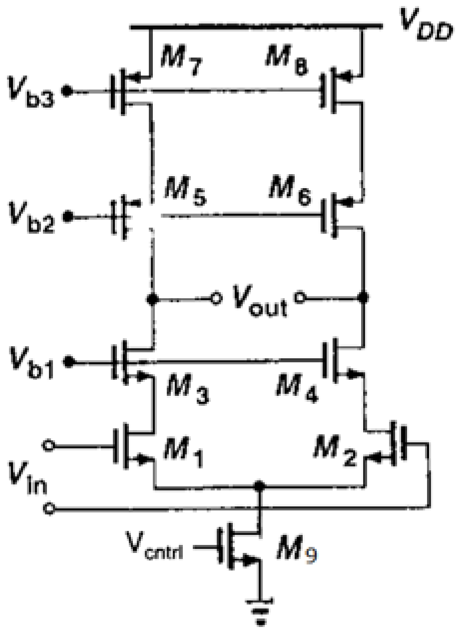
Common-Mode Feedback Circuits

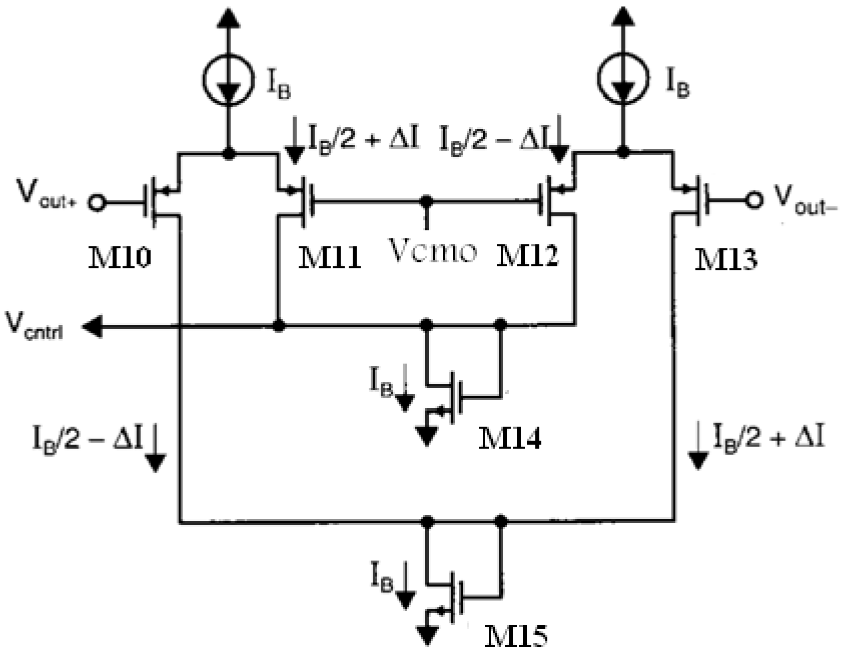
Common-mode-feedback (CMFB) circuitry is often the most difficult part of the opamp to design.

There are two types of CMFB circuit:

- ❖Continuous-time CMFB
- ❖Discrete-time CMFB

Continuous-time CMFB Circuit





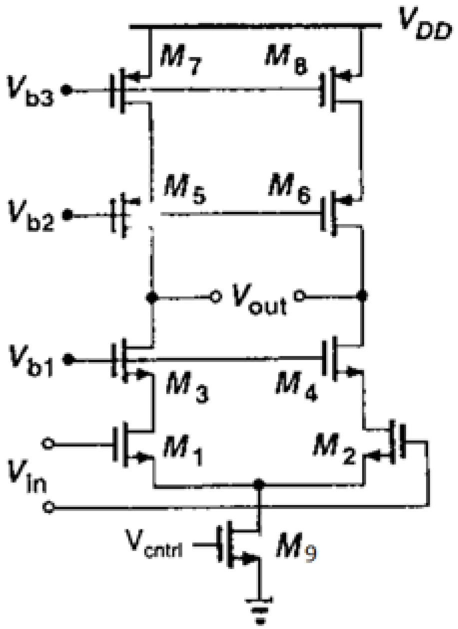
Vcmo denotes the desired output common-mode voltage.

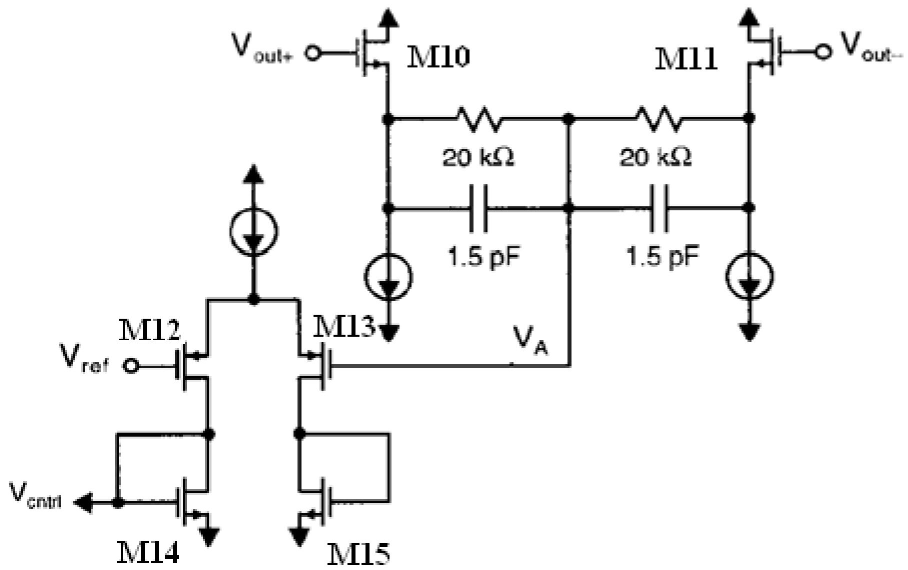
Vcm denotes the output common-mode voltage. $V_{CM} = \dfrac{V_{out+} + V_{out-}}{2}$

Small-signal analysis

$$\left.\begin{aligned} \frac{V_{ctrl}}{V_{CM}} &= \frac{g_{m10}}{g_{m14}} \\ \frac{V'_{CM}}{V_{ctrl}} &\cong -\frac{1}{2} g_{m9} R_{out} \\ R_{out} &\cong g_{m6} r_{ds6} r_{ds8} \end{aligned}\right\} \Rightarrow loop\ gain = \frac{V'_{CM}}{V_{CM}} = -\frac{g_{m10} g_{m9} g_{m6}}{2 g_{m14}} r_{ds6} r_{ds8}$$

Continuous-time CMFB Circuit





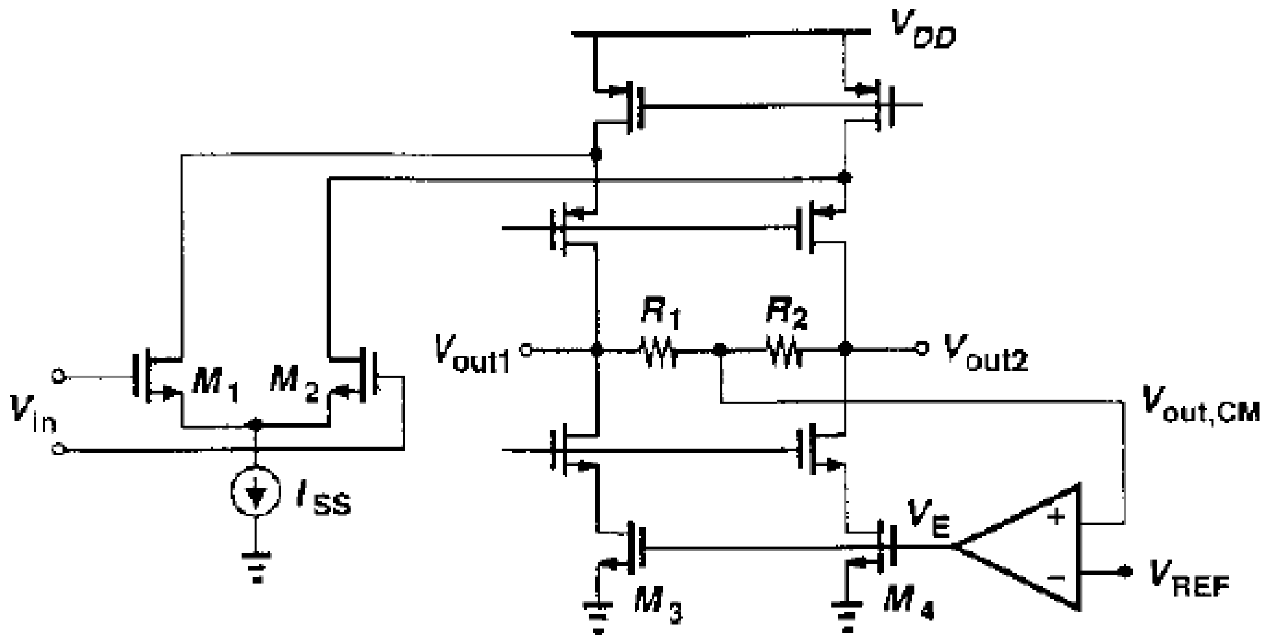
$$V_A = V_{CM} - V_{eff10} - V_{tn}$$

$$V_{ref} = V_{CMO} - V_{eff10} - V_{tn}$$

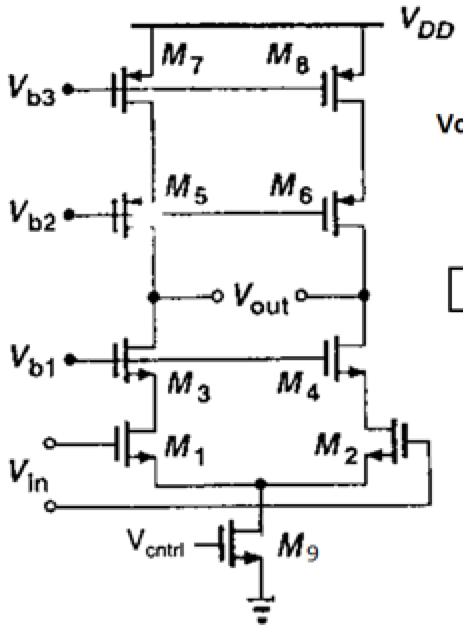
Small-signal analysis

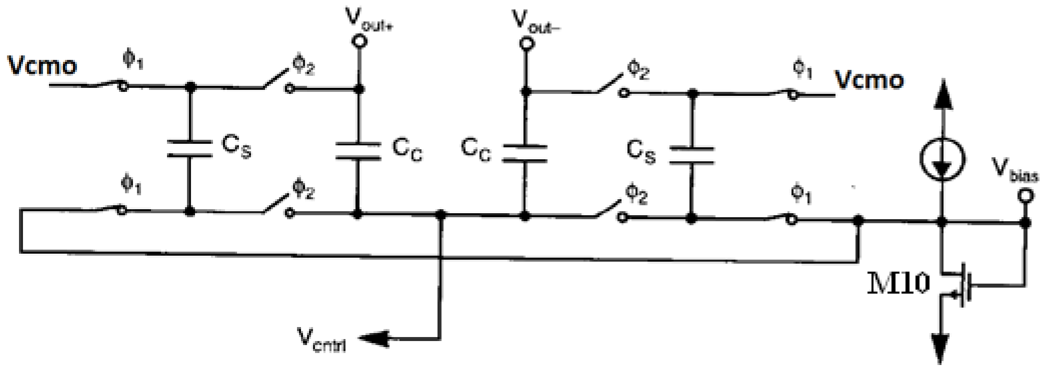
$$\left.\begin{array}{l} \dfrac{V_{ctrl}}{V_{CM}} = \dfrac{g_{m13}}{2g_{m14}} \\ \dfrac{V'_{CM}}{V_{ctrl}} \cong -\dfrac{1}{2} g_{m9} R_{out} \\ R_{out} \cong g_{m6} r_{ds6} r_{ds8} \end{array}\right\} \Rightarrow loop\ gain = \frac{V'_{CM}}{V_{CM}} = -\frac{g_{m13} g_{m9} g_{m6}}{4 g_{m14}} r_{ds6} r_{ds8}$$

An Incorrect Continuous-time CMFB Circuit



Discrete-time CMFB Circuit





It is suggested to choose the values of CC and Cs so that the following relation as follows:

$$0.1C_C < C_S < 0.25C_C$$

Performing a few manipulations, we have:

$$V_{ctrl}(z) = \frac{\dfrac{C_S}{C_S + C_C} z^{-1}}{1 - \dfrac{C_C}{C_S + C_C} z^{-1}} \left(V_{bias}(z) - V_{cmo}(z)\right) + V_{CM}(z)$$