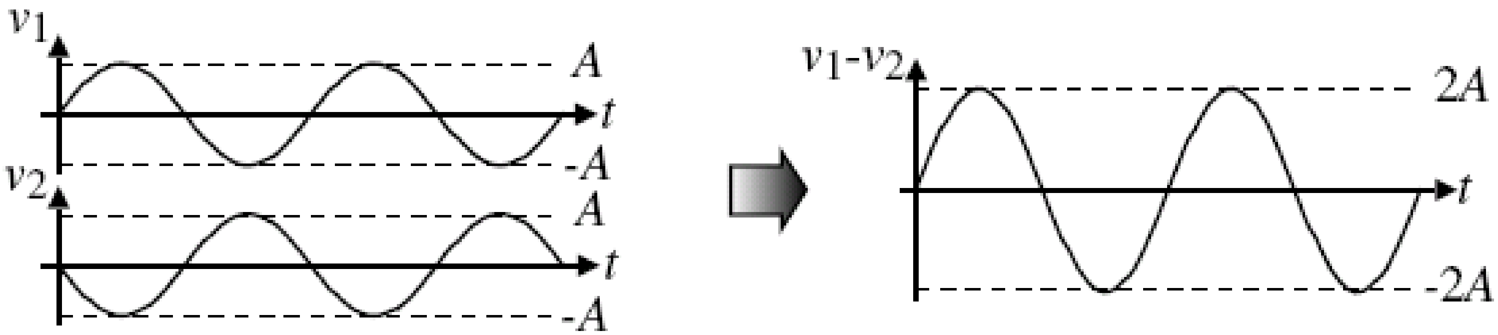
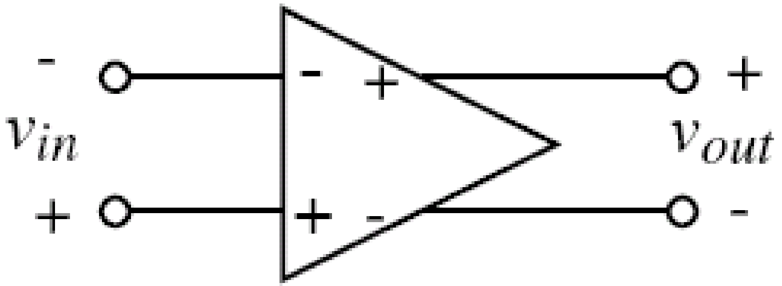
Common mode feedback for fully differential amplifiers

Differential amplifiers

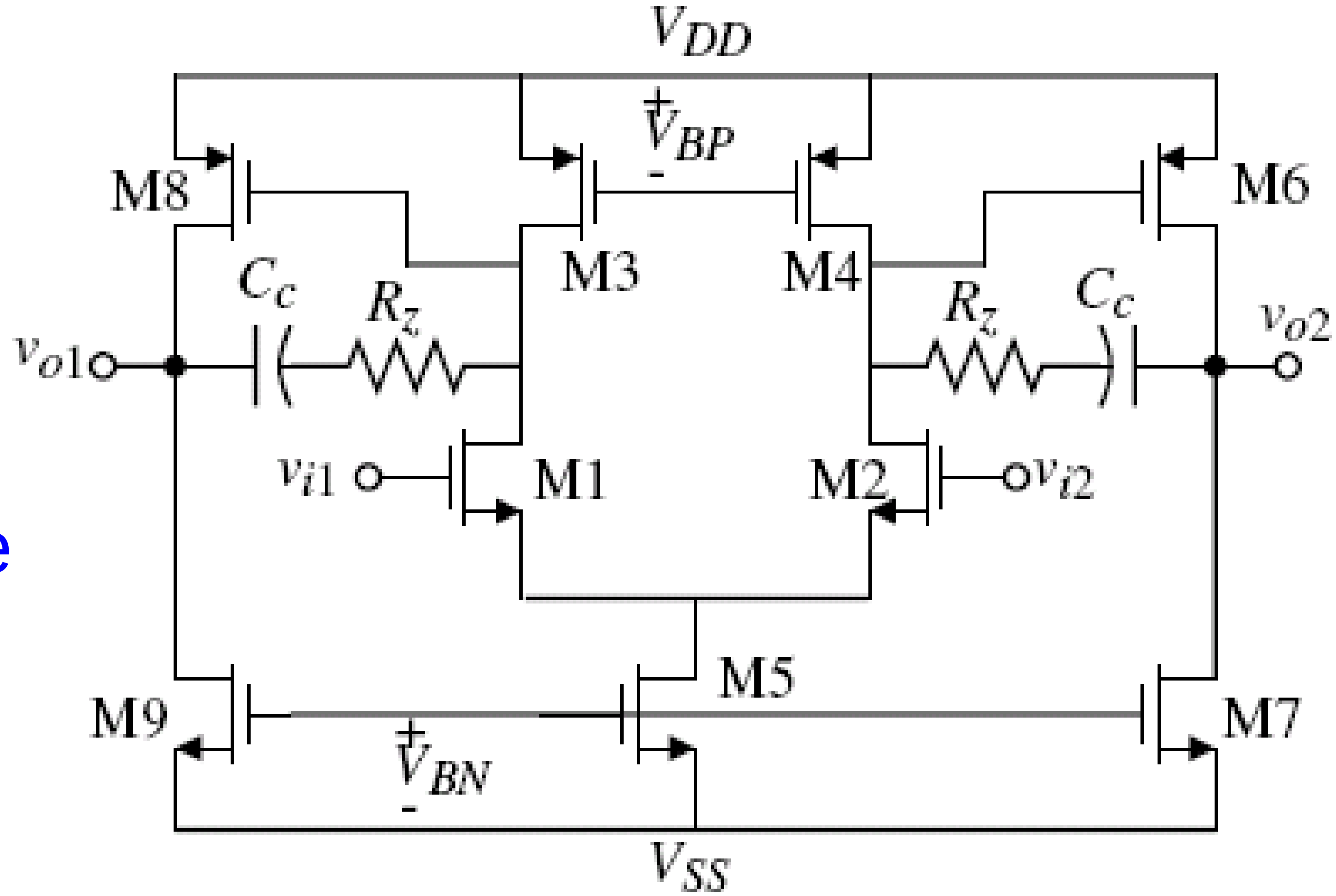
- Cancellation of common mode signals including clock feed-through
- Cancellation of even-order harmonics
- Double differential signal swing, SNR↑3dB



Symbol:



Two-Stage, Miller, Differential-In, Differential-Out Op Amp

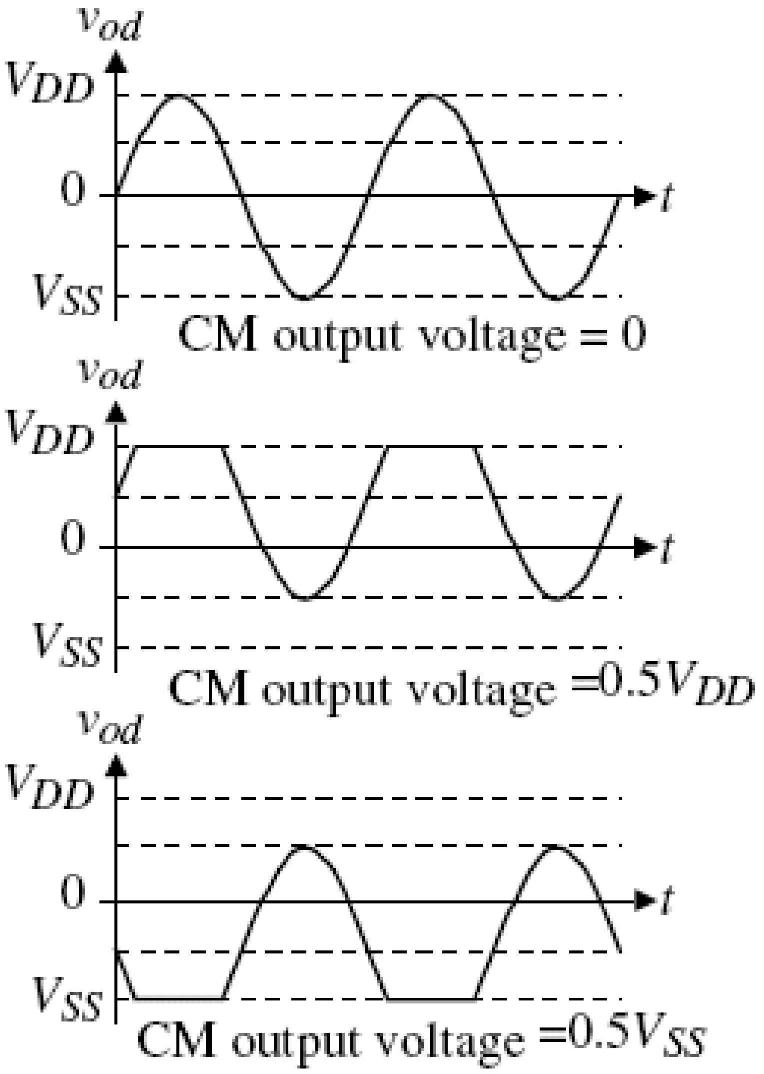


peak-to-peak output voltage ≤ 2·OCMR

Output common mode range (OCMR) $= V_{DD} - V_{SS} - V_{SDPsat} - V_{DSNsat}$

Common Mode Output Voltage Stabilization

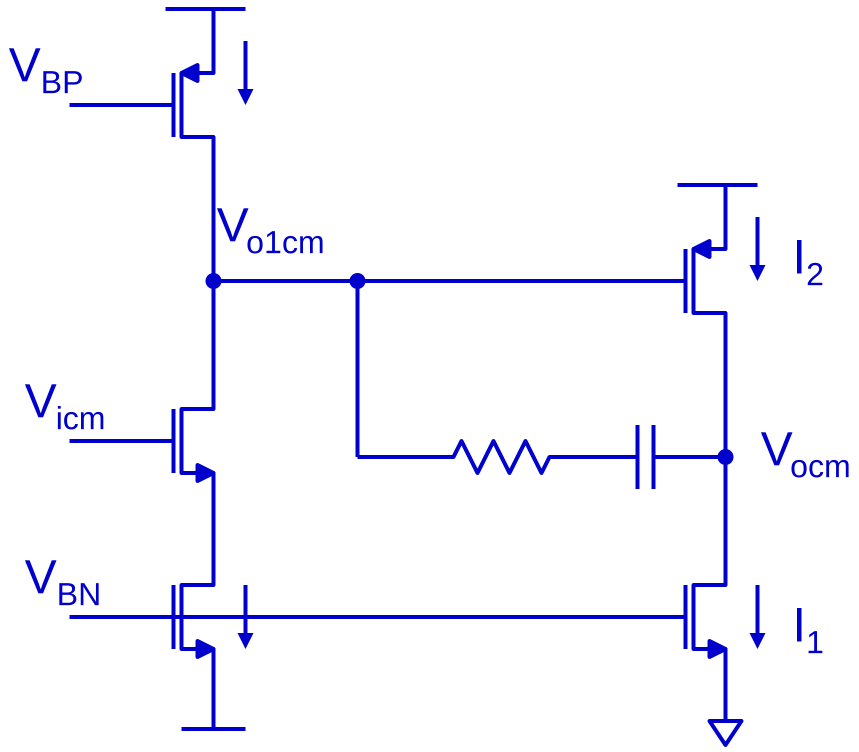
Common mode drift at output causes differential signals move into triode region

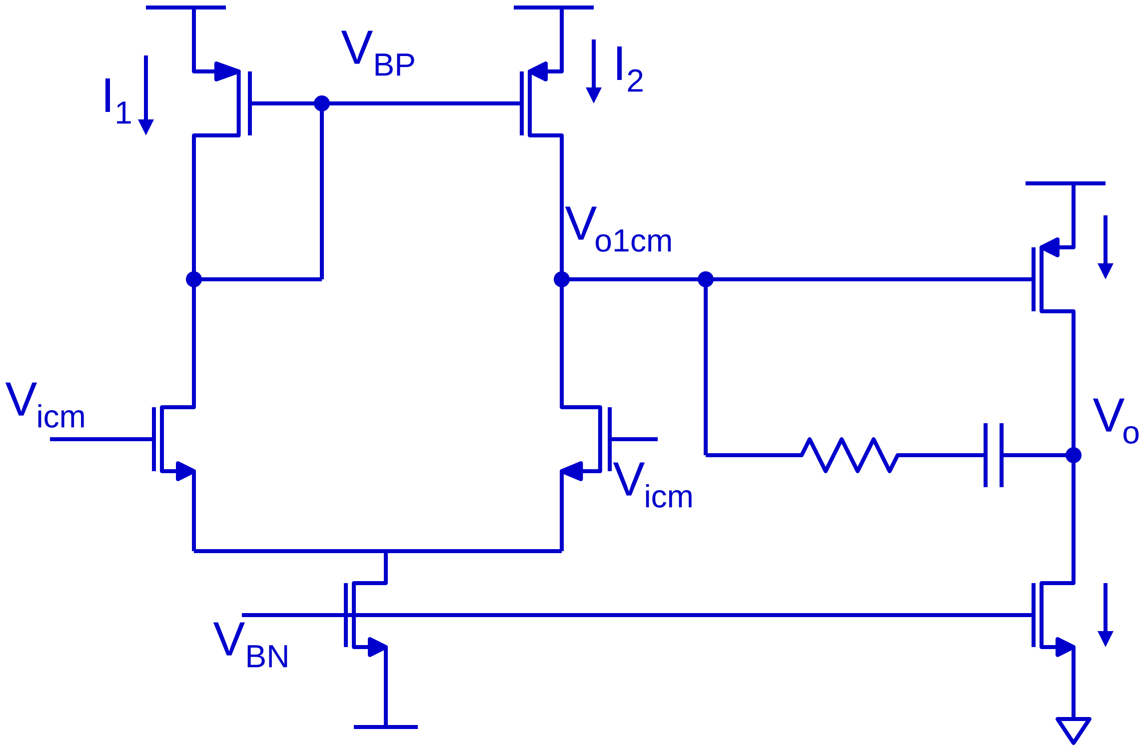


Common Mode feedback

- All fully differential amplifier needs CMFB
- Common mode output, if uncontrolled, moves to either high or low end, causing triode operation
- Ways of common mode stabilization:
  - external CMFB
  - internal CMFB

Common mode equivalent



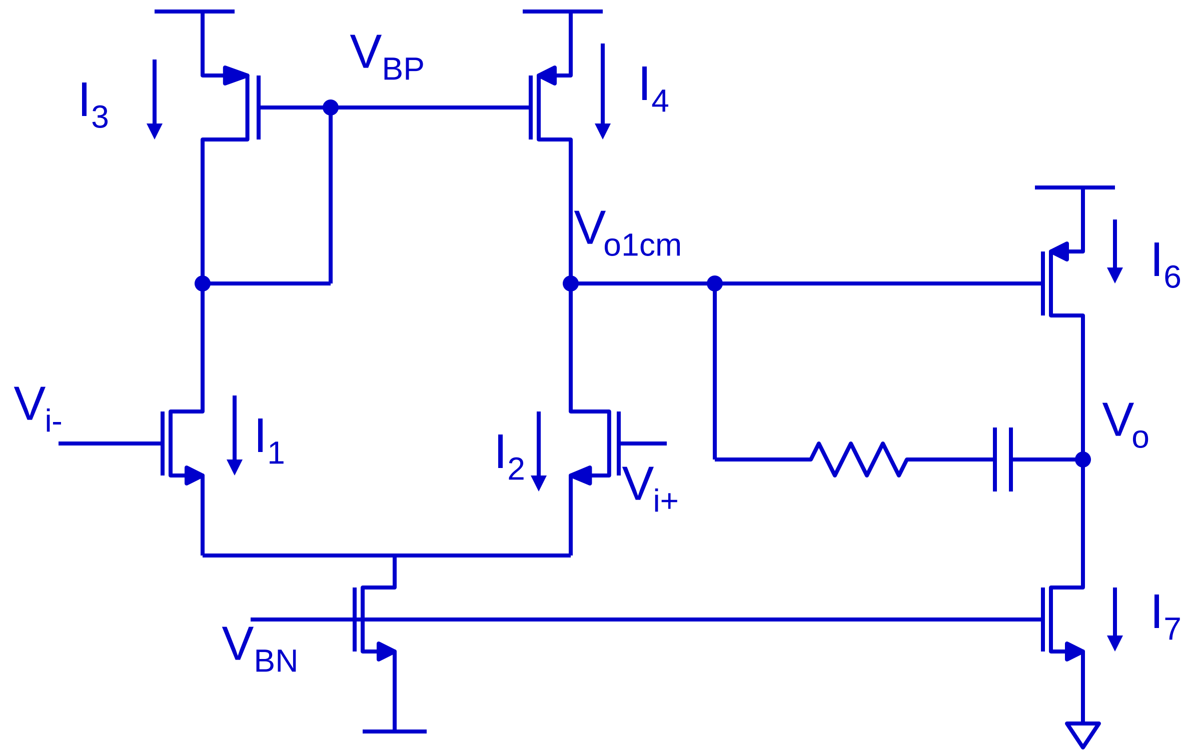


What about single ended?

Does it have the same problem?

Does it require feedback stabilization?

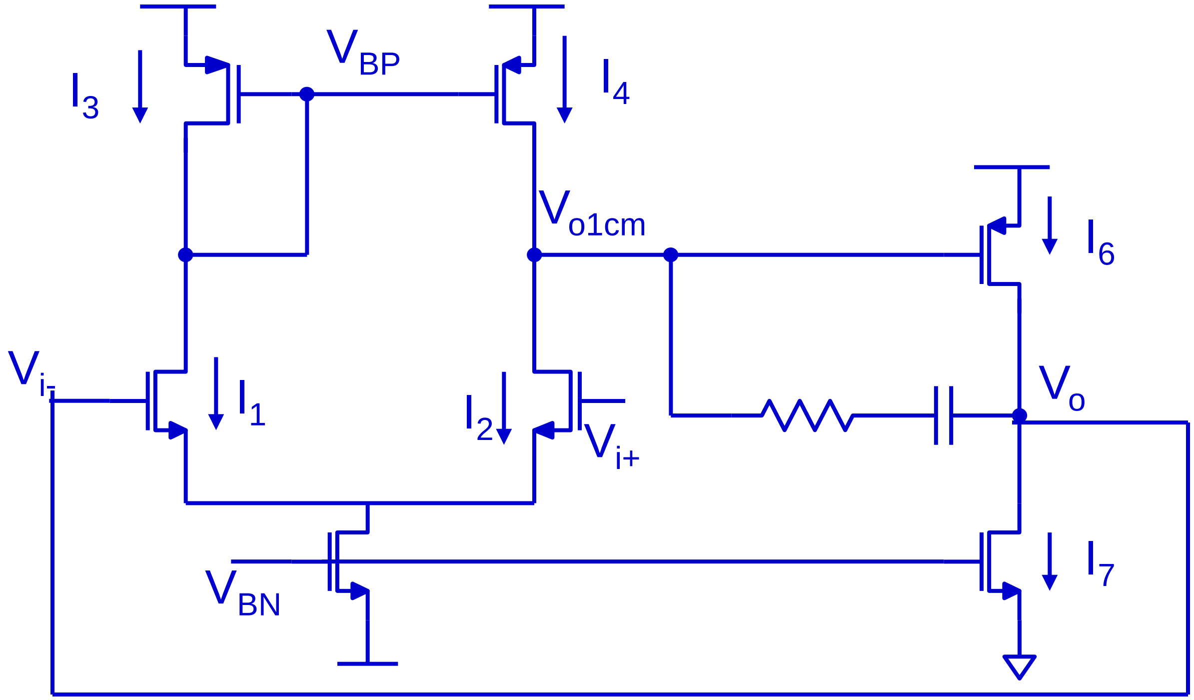
Yes, to all three questions

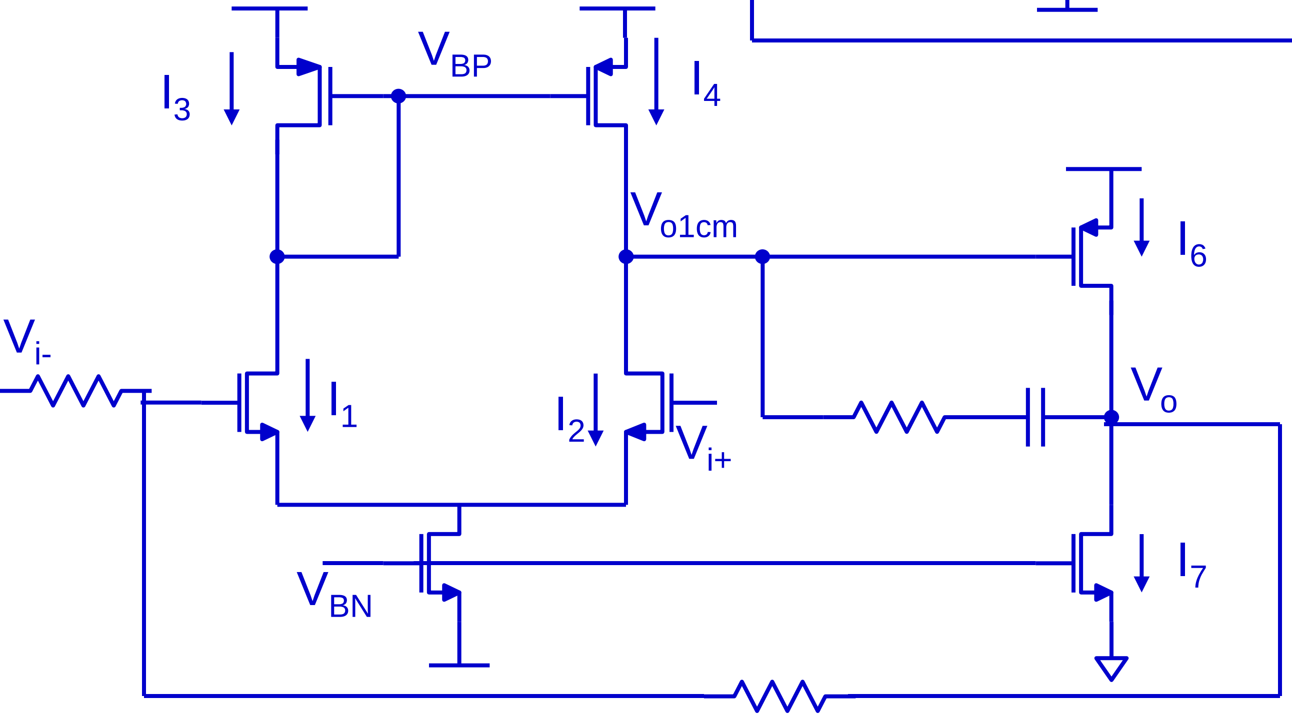


To match I1 and I3, the diode connection provides the single stage positive feedback to automatically generate Vg3.

The match between I2 and I4, and I6 and I7 is a two stage problem and requires negative feedback: needs feedback from Vo to Vi-.

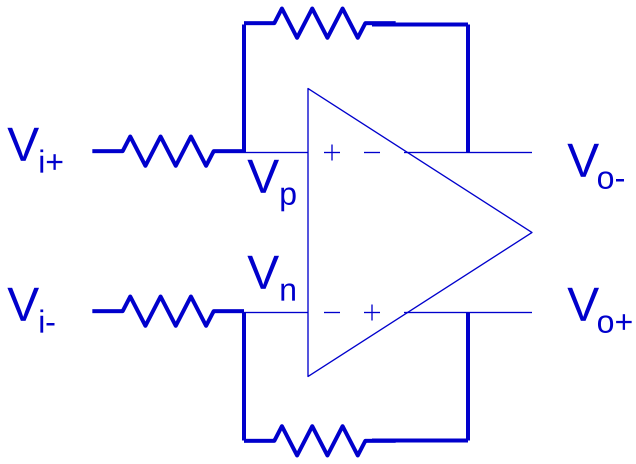
All op amps must be used in feedback configuration!





Buffer connection or resistive feedback provides the needed negative feedback

Fully differential amplifiers are also used in feedback configuration.



$$\frac{V_{i+}-V_p}{R_i}=\frac{V_p-V_{o-}}{R_b}, \quad \frac{V_{i-}-V_n}{R_i}=\frac{V_n-V_{o+}}{R_b}$$

$$\frac{V_{i+}-V_{i-}-(V_p-V_n)}{R_i}=\frac{V_p-V_n+(V_{o+}-V_{o-})}{R_b}$$

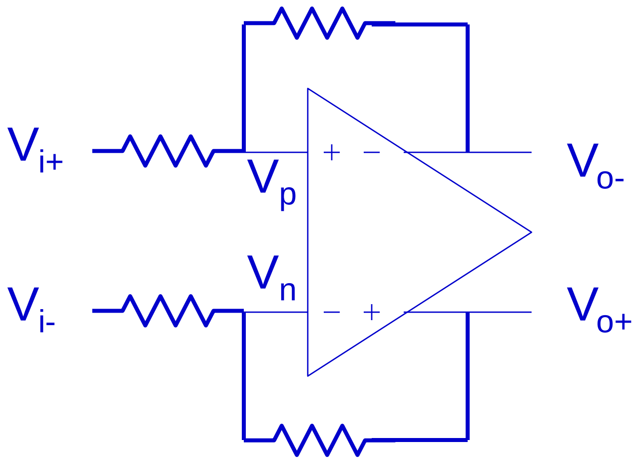
If amplifier gain is high, V_p-V_n is ≈ 0,

$$\frac{V_{i+}-V_{i-}}{R_i}=\frac{(V_{o+}-V_{o-})}{R_b}, \text{ and } V_{o+}-V_{o-}=\frac{R_b}{R_i}(V_{i+}-V_{i-})$$

Hence, differential signal is well defined.

But when you add the first two equations

$$\frac{V_{i+} - V_p}{R_i} = \frac{V_p - V_{o-}}{R_b}, \quad \frac{V_{i-} - V_n}{R_i} = \frac{V_n - V_{o+}}{R_b}$$



You get:

$$\frac{V_{i+} + V_{i-} - (V_p + V_n)}{R_i} = \frac{V_p + V_n - (V_{o+} + V_{o-})}{R_b}$$

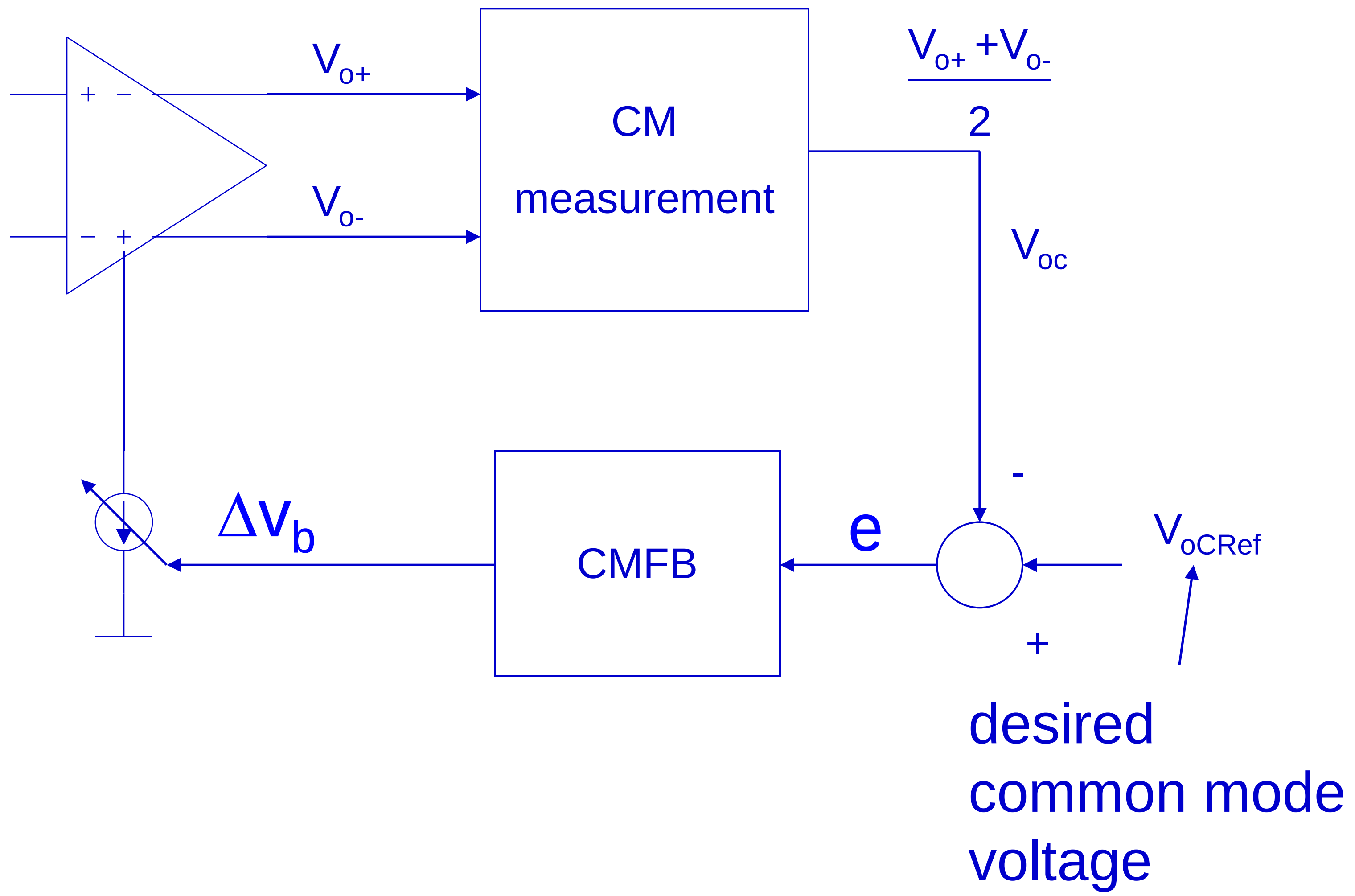
Solving for $V_{o+} + V_{o-}$,

$$V_{o+} + V_{o-} = -\frac{R_b}{R_i}(V_{i+} + V_{i-}) + \frac{R_b + R_i}{R_i}(V_p + V_n)$$

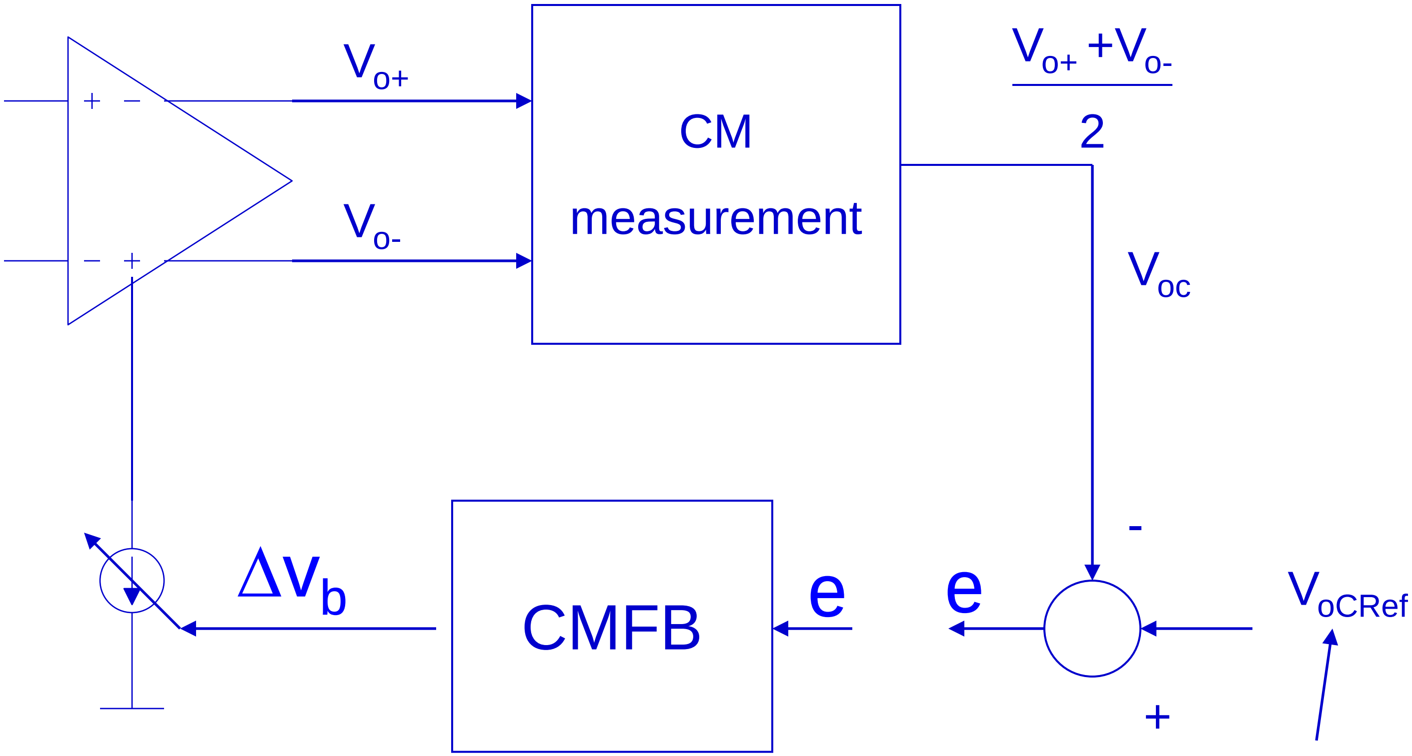
Since V_p+V_n is undefined, V_{o+}+V_{o-} is undefined.

Basic concept of CMFB:

Since diff feedback and diff input uses Vin+ and Vin-, CMFB has to be applied to somewhere else: like a bias current



Basic concept of CMFB:

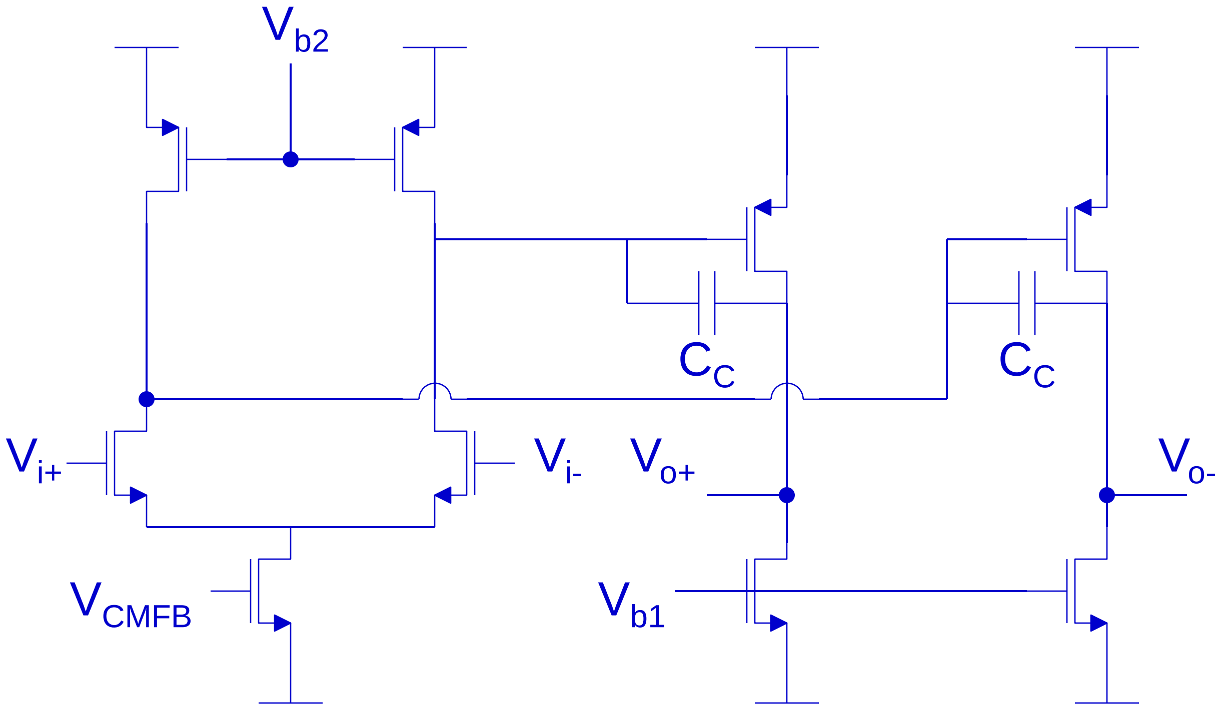


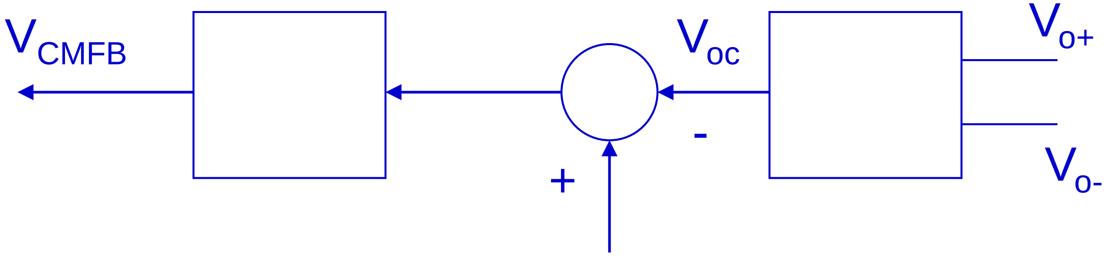
Find transfer function from e to V_{oc}: $A_{CMF}(s)$

Find transfer function from an error source to V_{oc}: $A_{err}(s)$

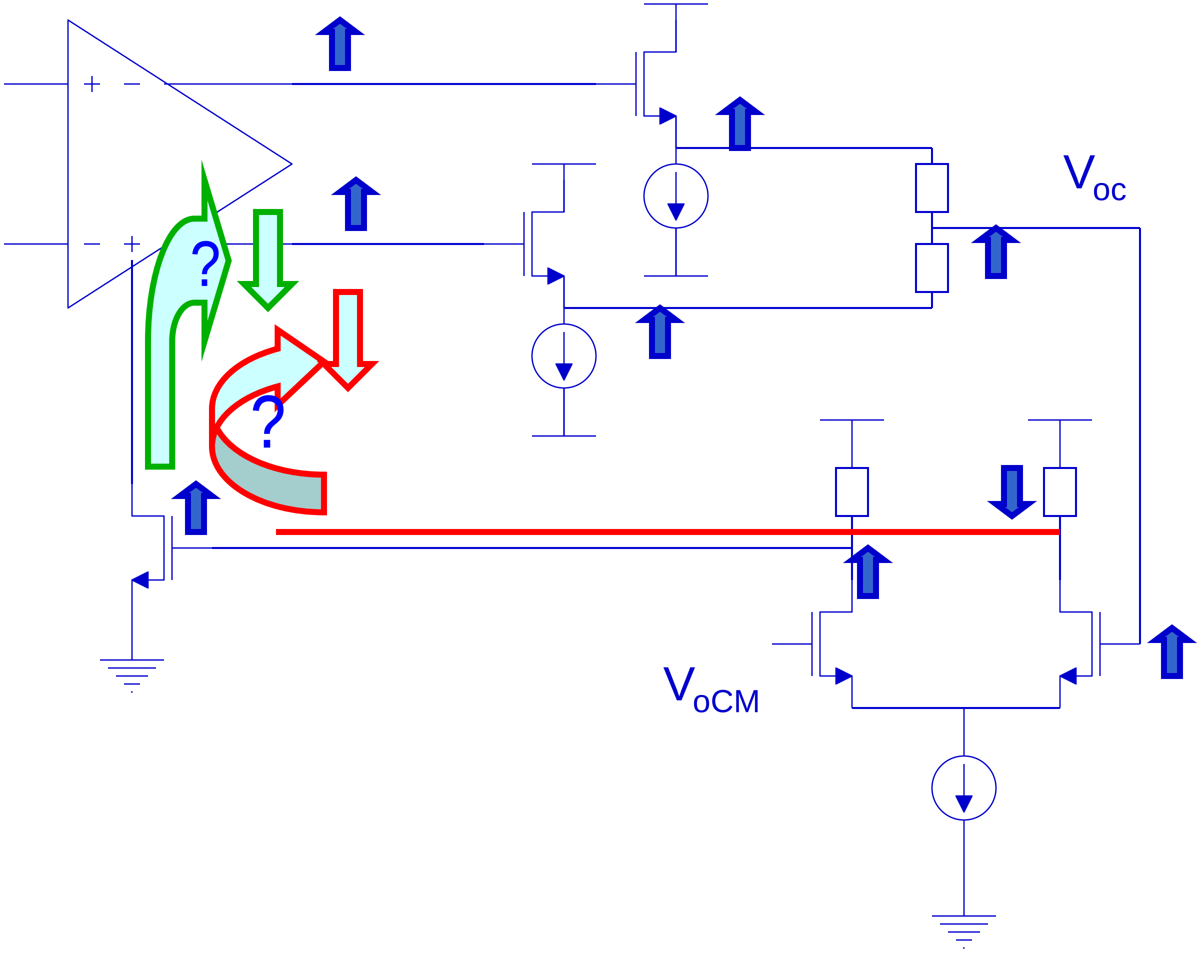
V_{oc} error due to error source: $err^*A_{err}(0)/A_{CMF}(0)$

example



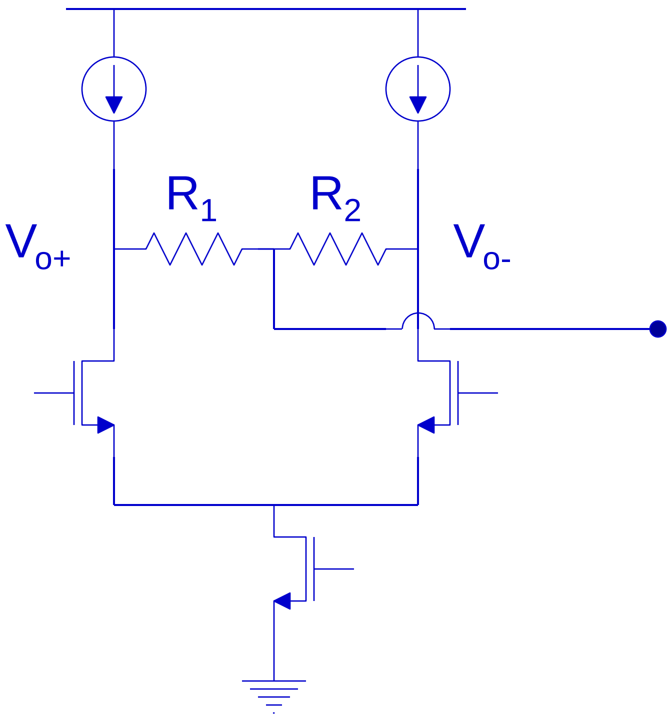


Example



Need to make sure to have negative feedback

Resistive C.M. detectors:



$$\frac{V_{o+} + V_{o-}}{2}, \text{if } R_1 = R_2$$

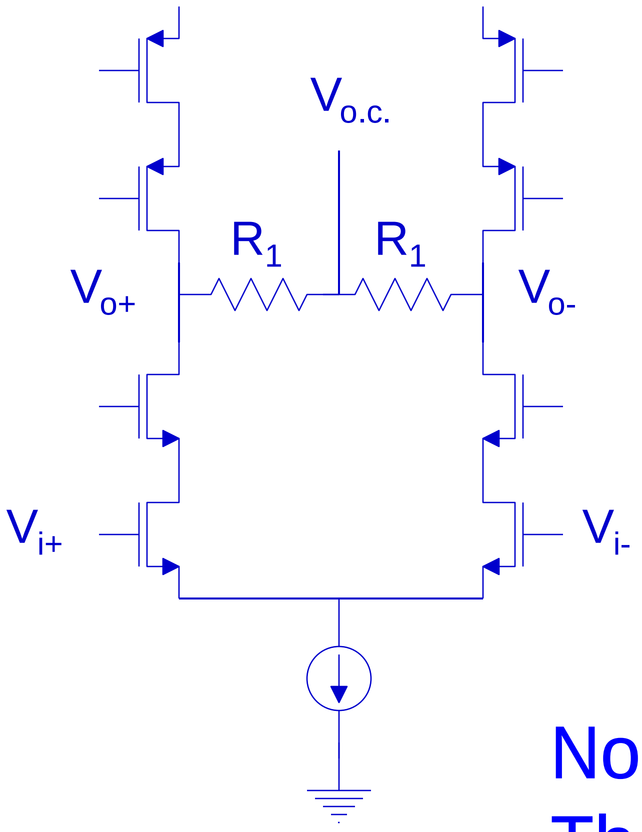
Prob : resistive loading effect.

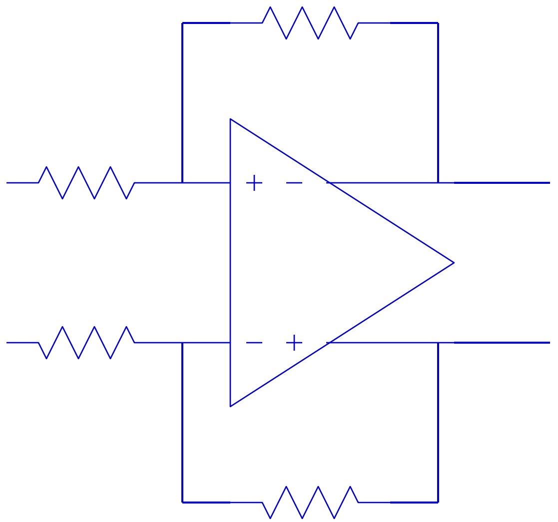
use R_1, R_2 very large

- difficult to achieve

- especially when V_o is at an cascoded node

Resistive C.M. detectors:

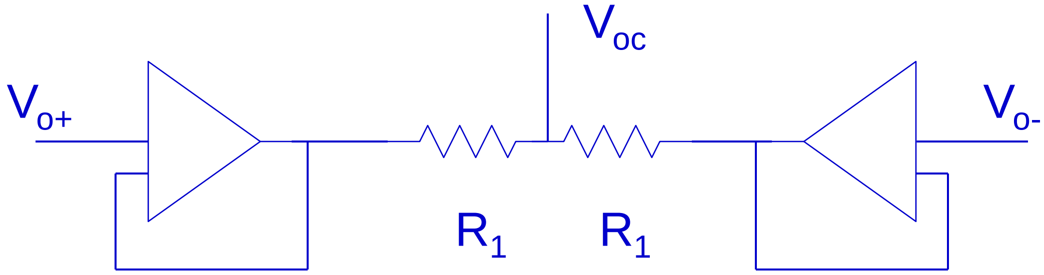




Not recommended.

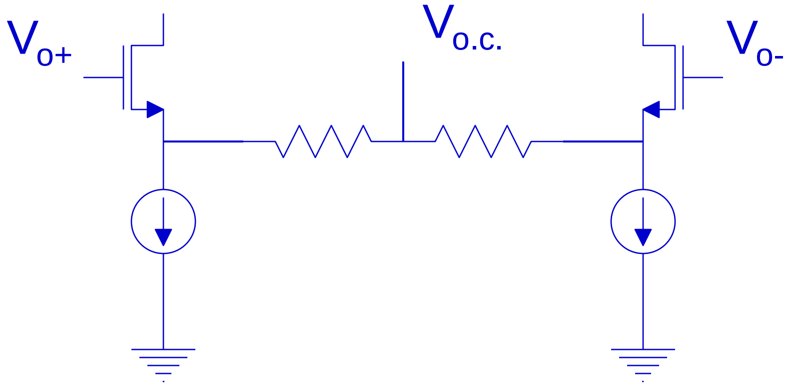
The resistive loading kills gain.

Buffer V_{o+}, V_{o-} before connecting to R_1.



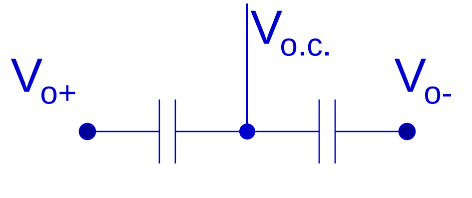
Simple implementation:

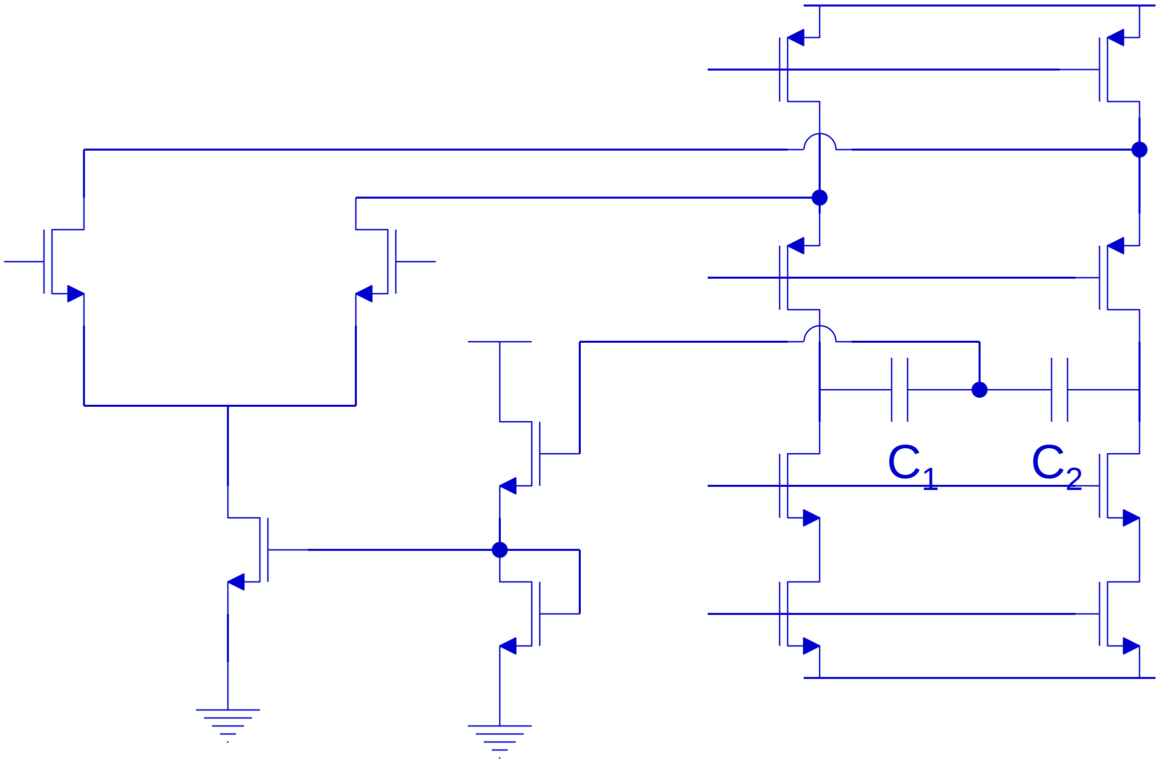
source follower



* Gate capacitance is added to your amp load.

Why not:





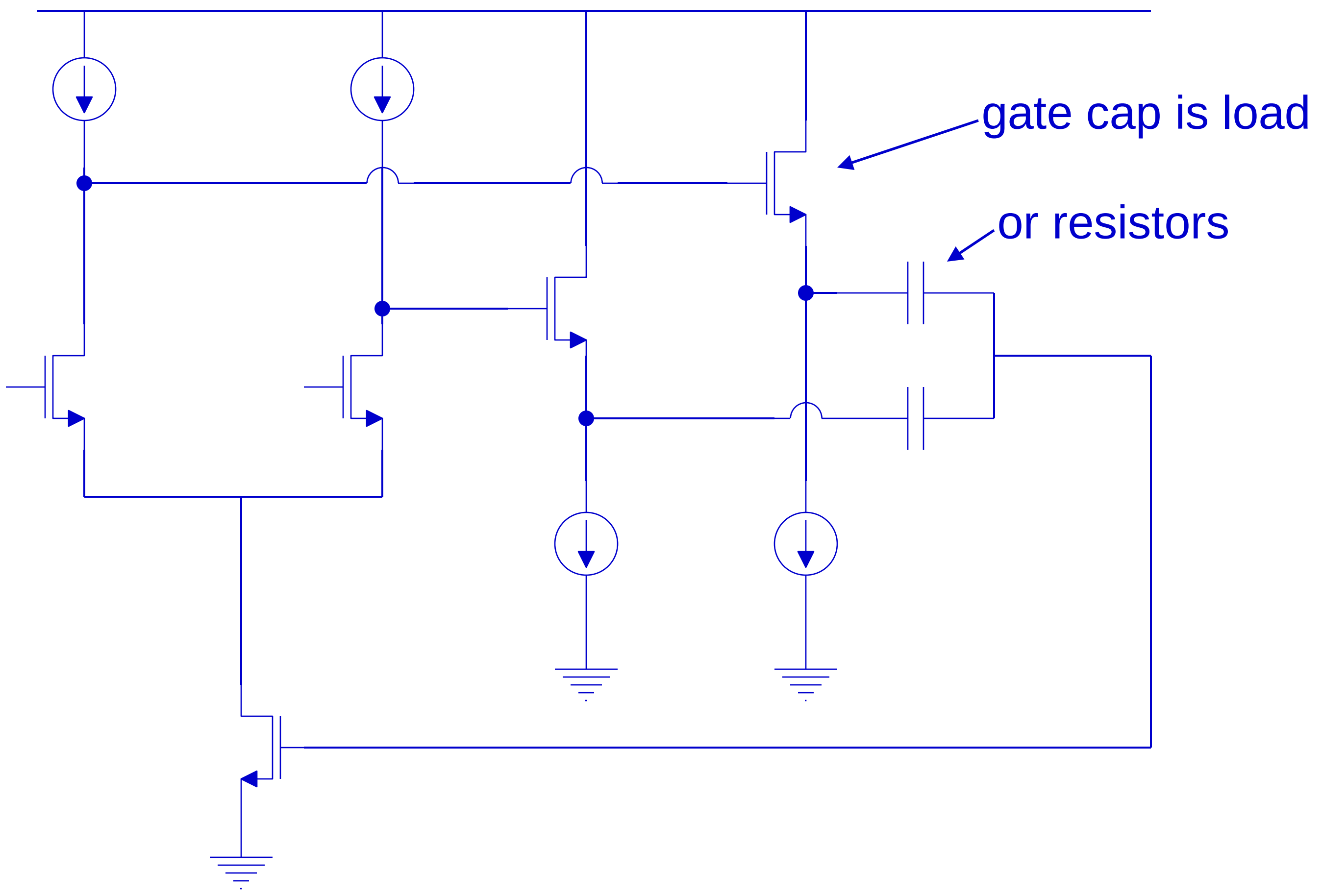
$$\frac{V_{o+} + V_{o-}}{2}, \text{if } C_1 = C_2$$

Prob : at high freq.

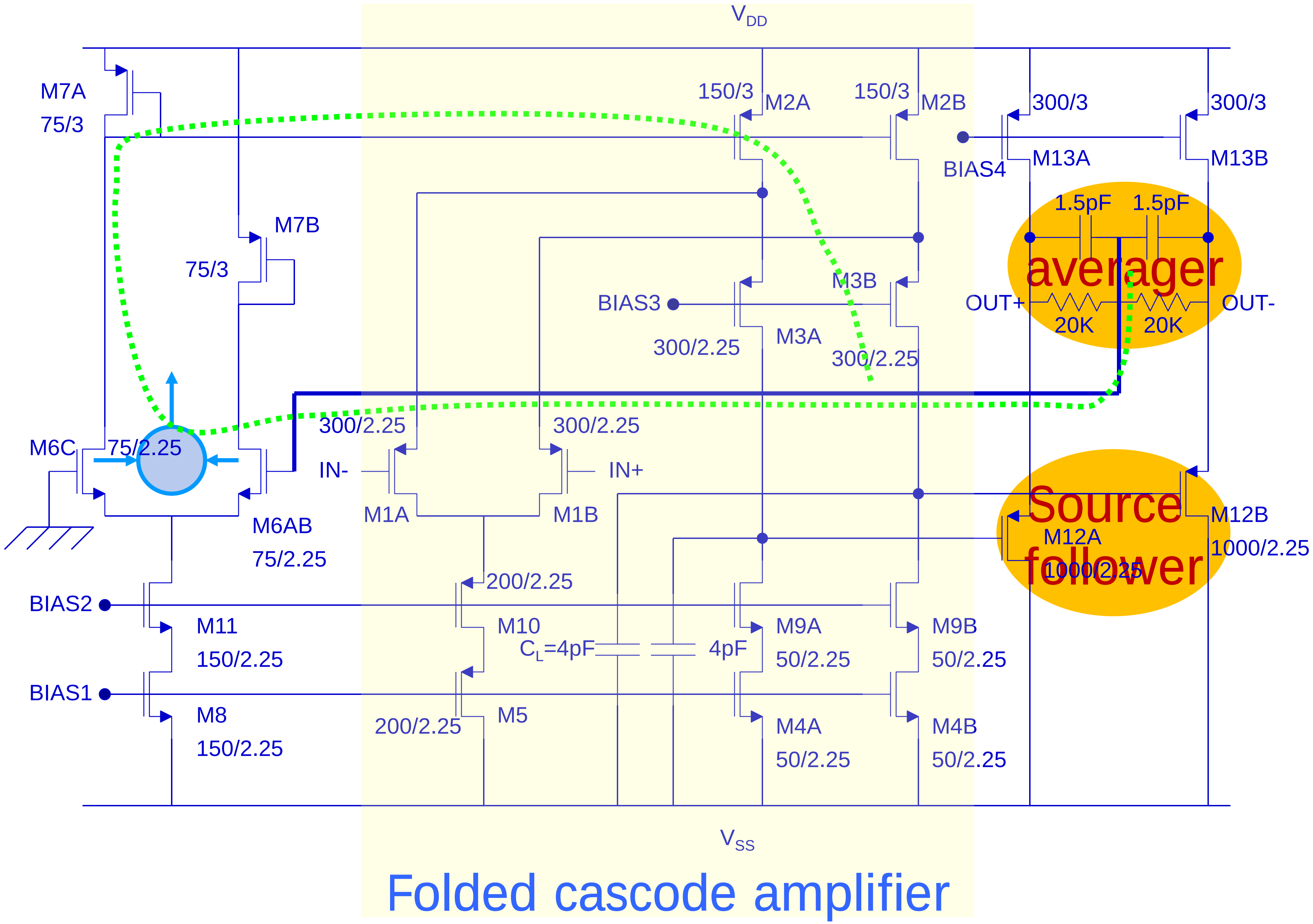
AC diff short

* Initial voltage on cap. Is unknown

Use buffer to isolate V_o node:

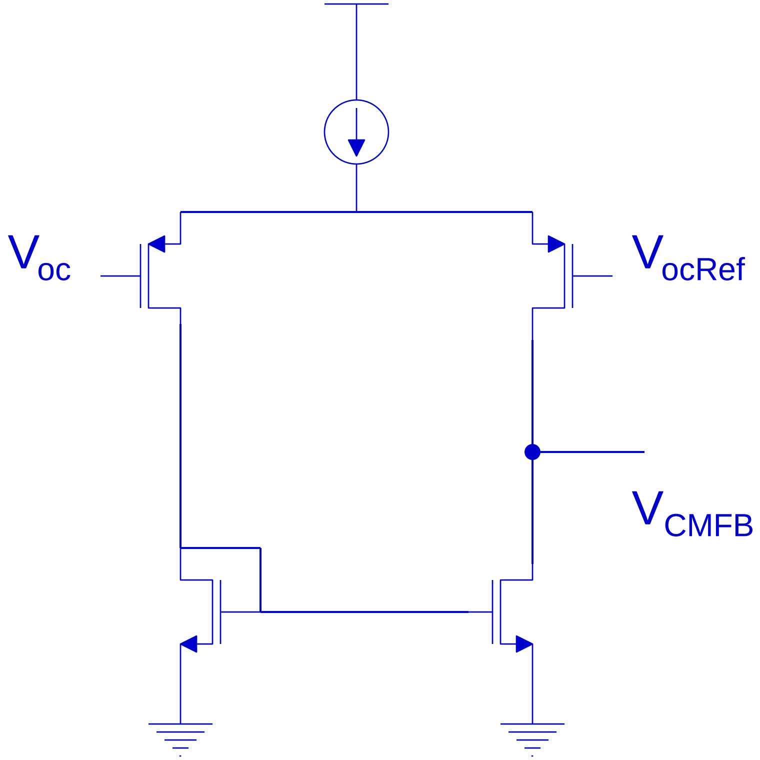


Practical: Combine resistor, capacitor, and buffering



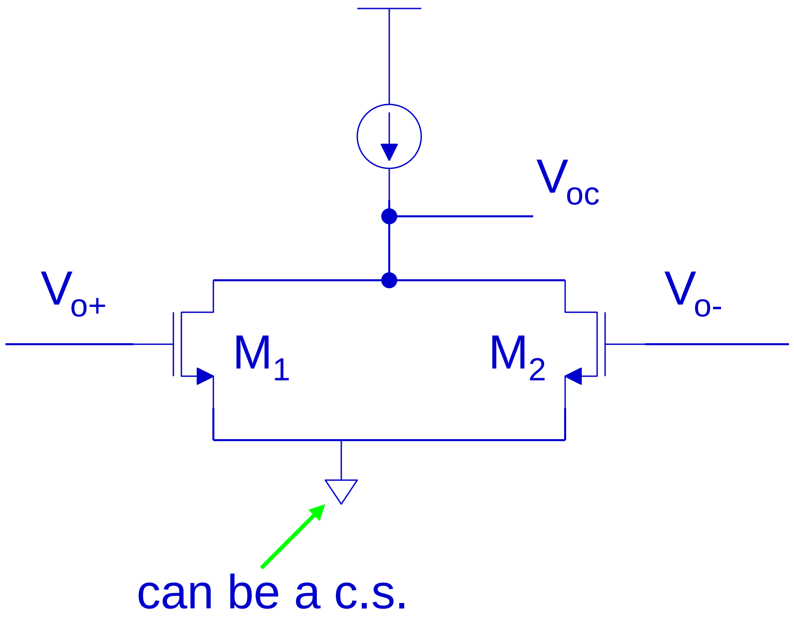
To increase or decrease the C.M. loop gain:

e.g.



Another implementation

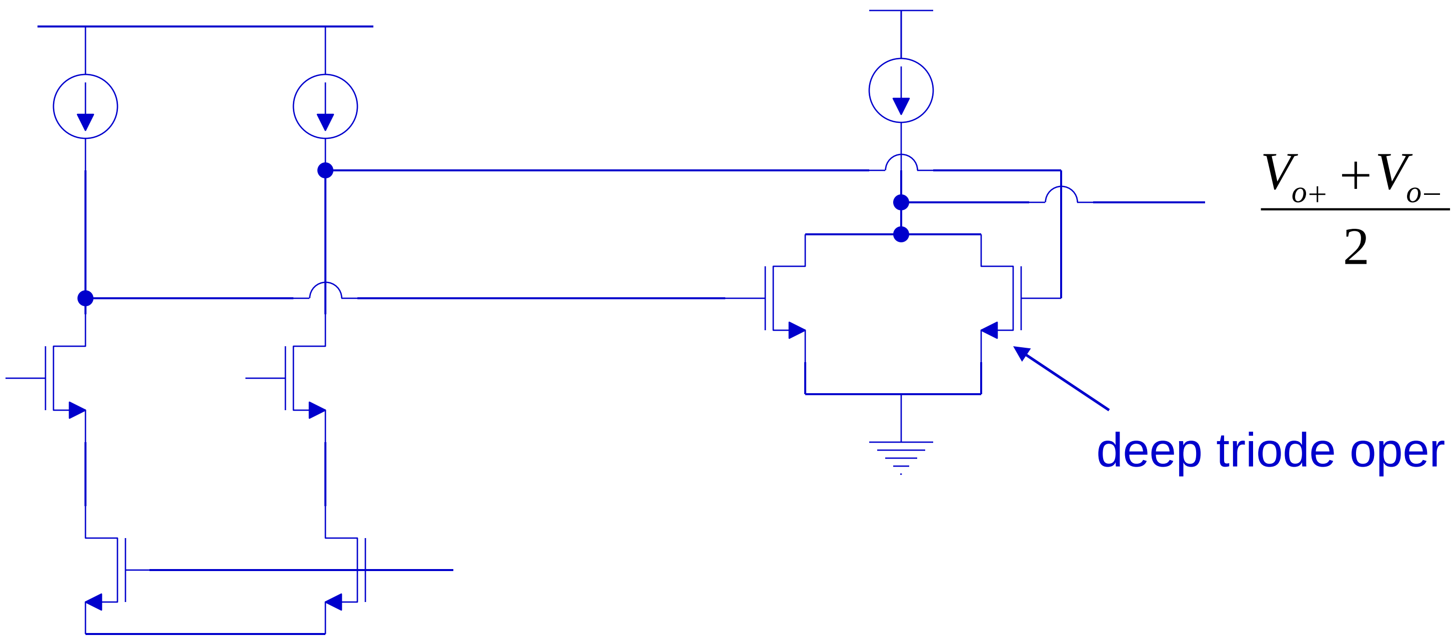
- Use triode transistors to provide isolation & z(s) simultaneously.



M_1, M_2 in deep triode.

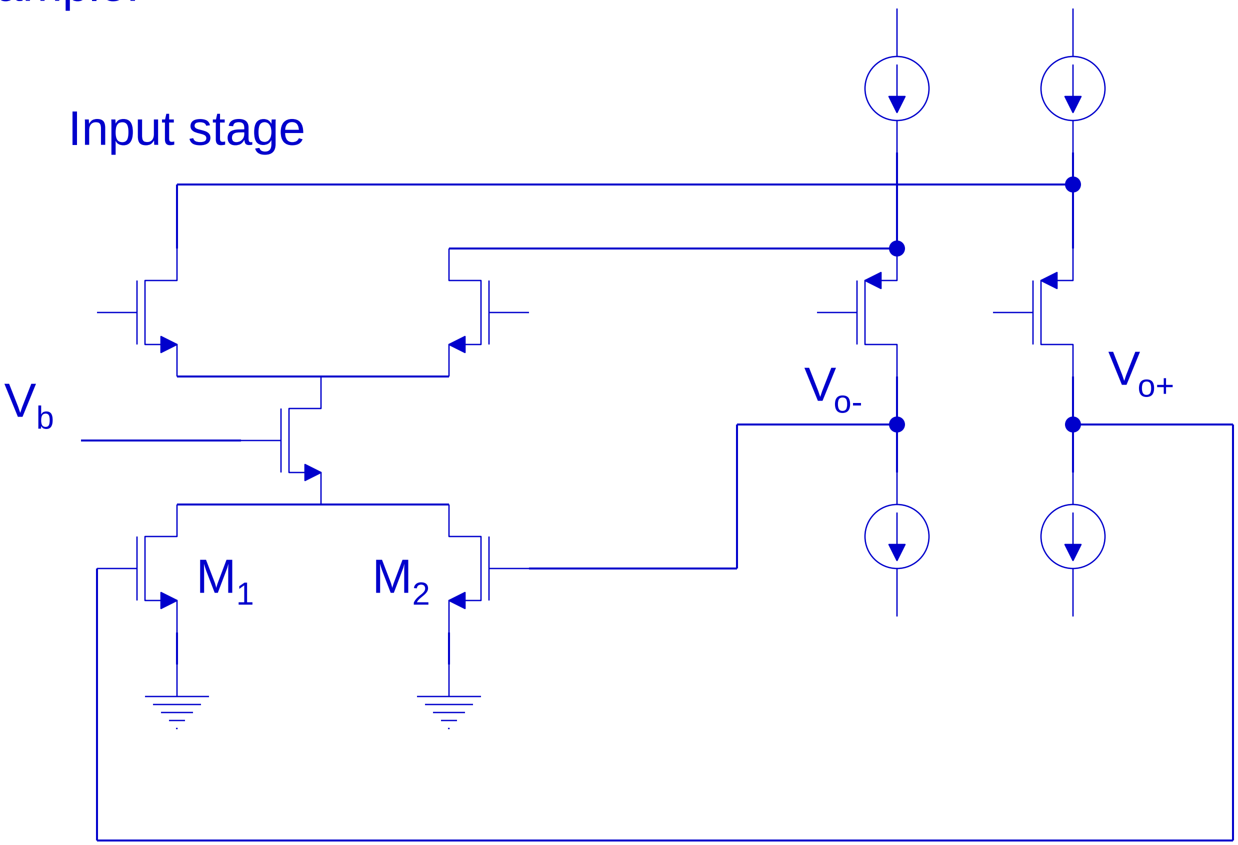
V_{GS1}, $V_{GS2} >> V_T$

In that case, circuit above M_1, M_2 needs to ensure that M_1, M_2 are in triode.



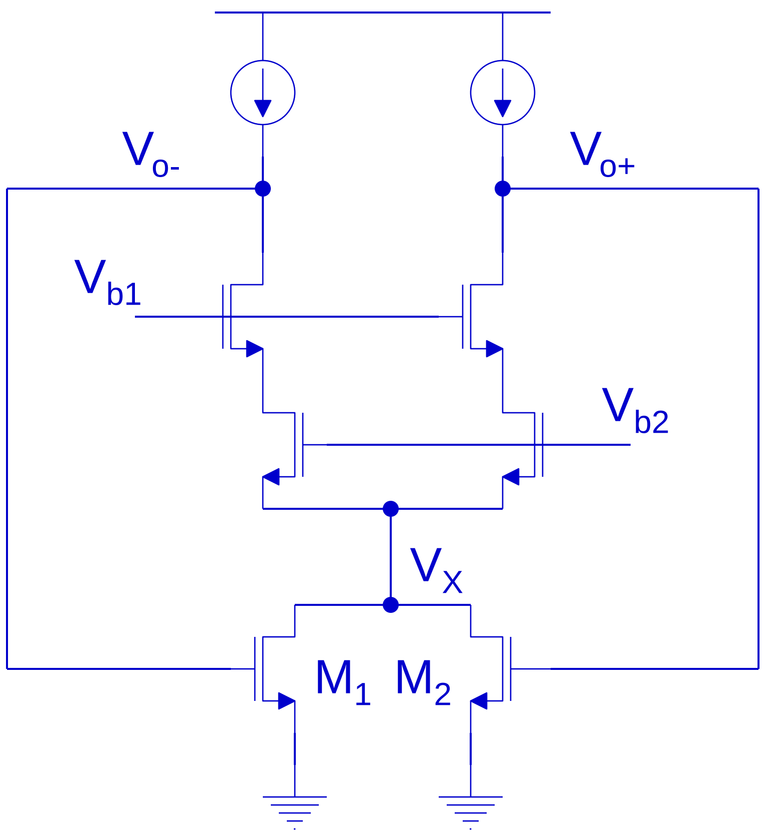
$\frac{V_{o+} + V_{o-}}{2}$
deep triode oper

Example:



e.g. V_{o+}, $V_{o-}\approx 2V$ at Q & $V_b \approx 1V$,

Then $M_{1\&2}$ will be in deep triode.



If $V_{o+}, V_{o-} \uparrow$

$\Rightarrow V_{oc} \uparrow$

$\Rightarrow V_{G1}, V_{G2} \uparrow$

$\Rightarrow R_{M1}, R_{M2} \downarrow$

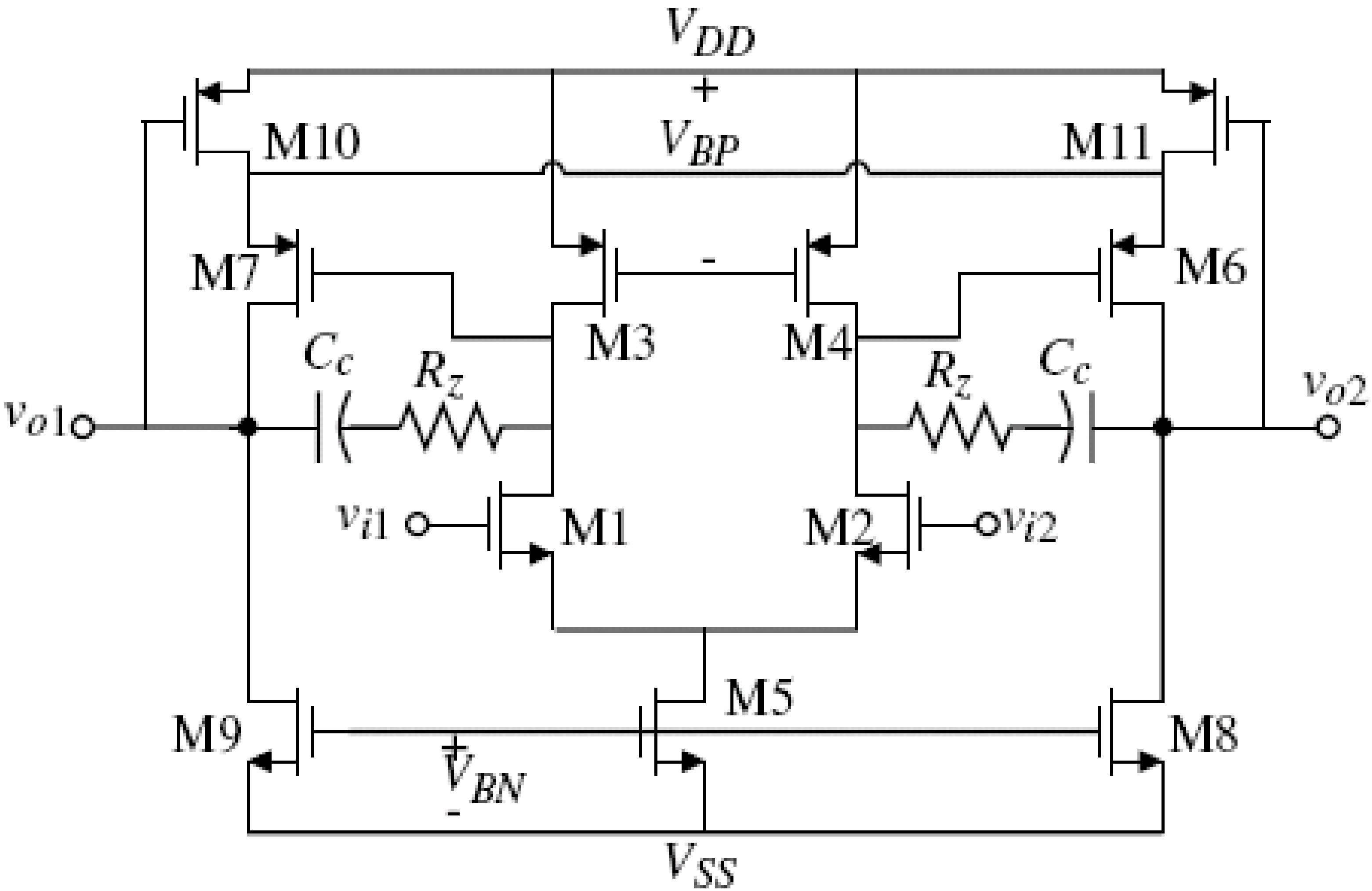
$\Rightarrow V_X \downarrow (I \approx \text{const})$

but V_X to V_{o+}, V_{o-}

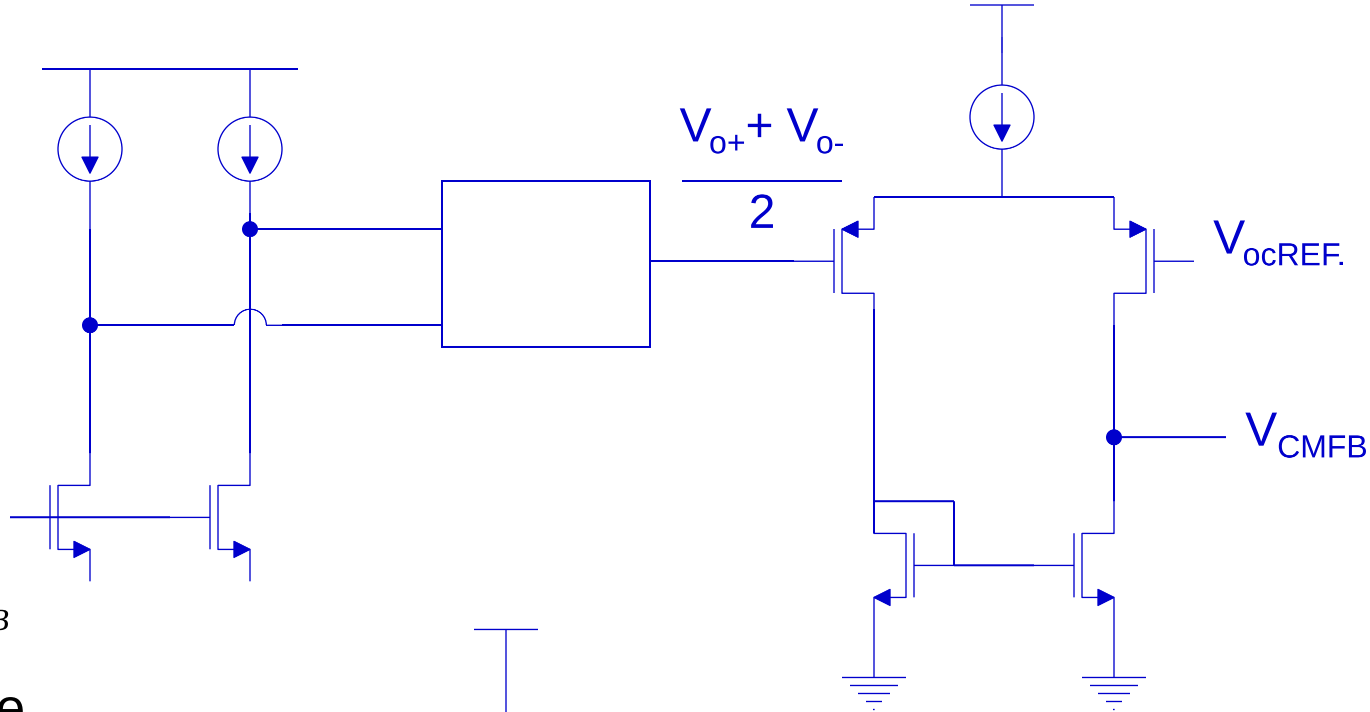
is cascoded C.G.

$\Rightarrow V_{o+}, V_{o-} \downarrow$

Two-Stage, Miller, Differential-In, Differential-Out Op Amp

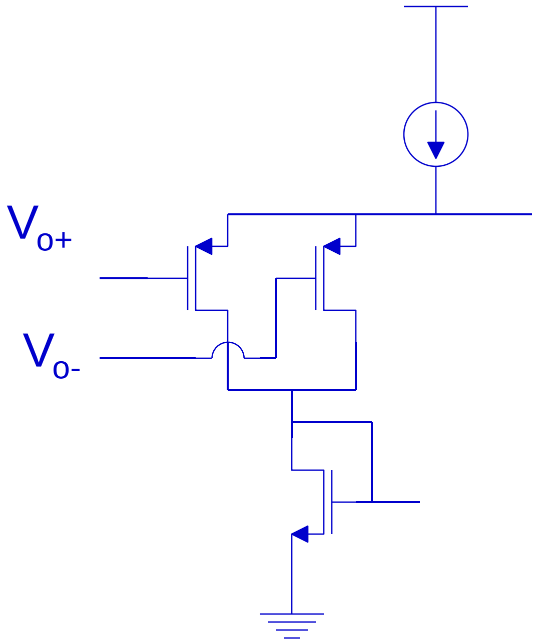


M10 and M11 are in deep triode



$$\frac{V_{o+}+V_{o-}}{2} \rightarrow V_{CMFB}$$

gain can be large

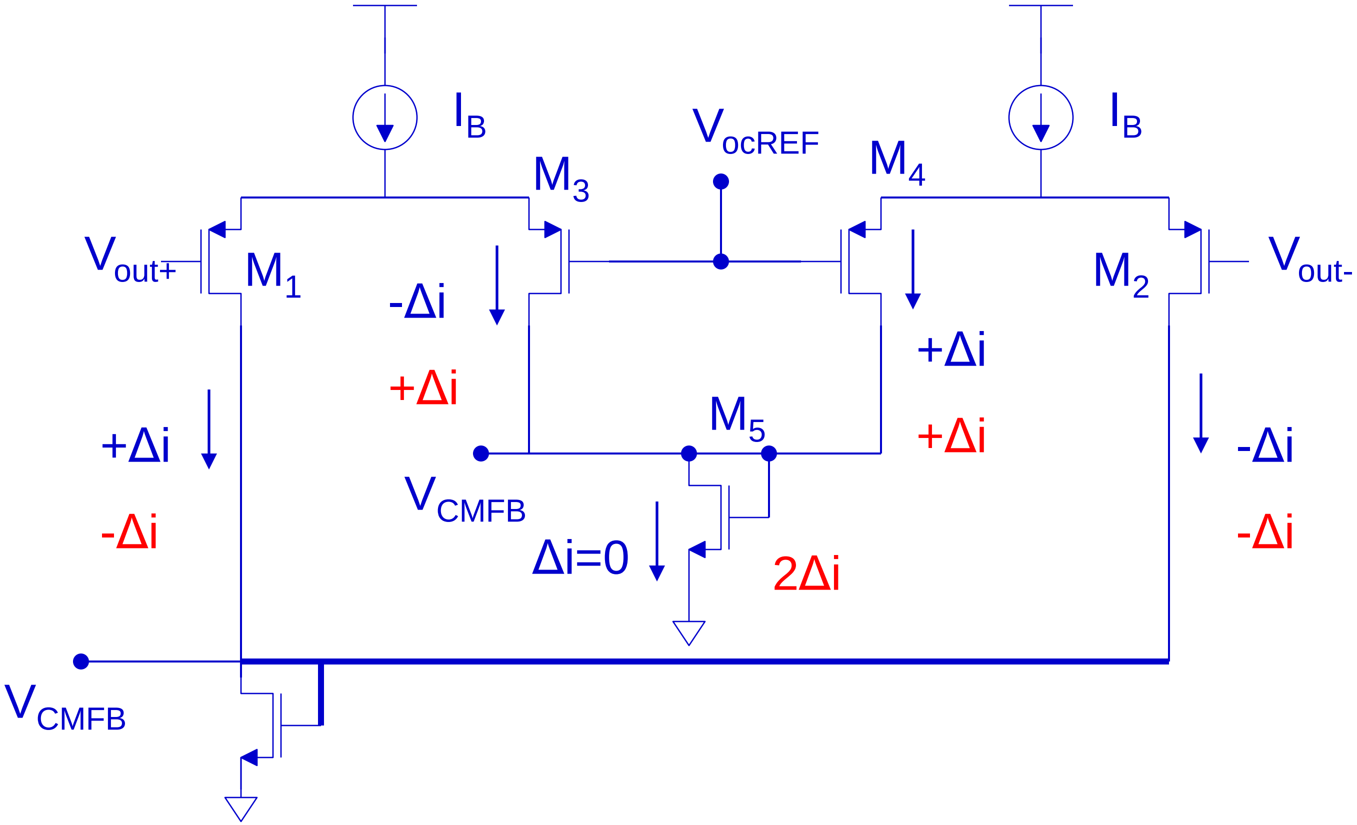


Note the difference from the book

accommodates much larger V_{oCM} range

Small signal analysis of CMFB

Example:



Differential signal

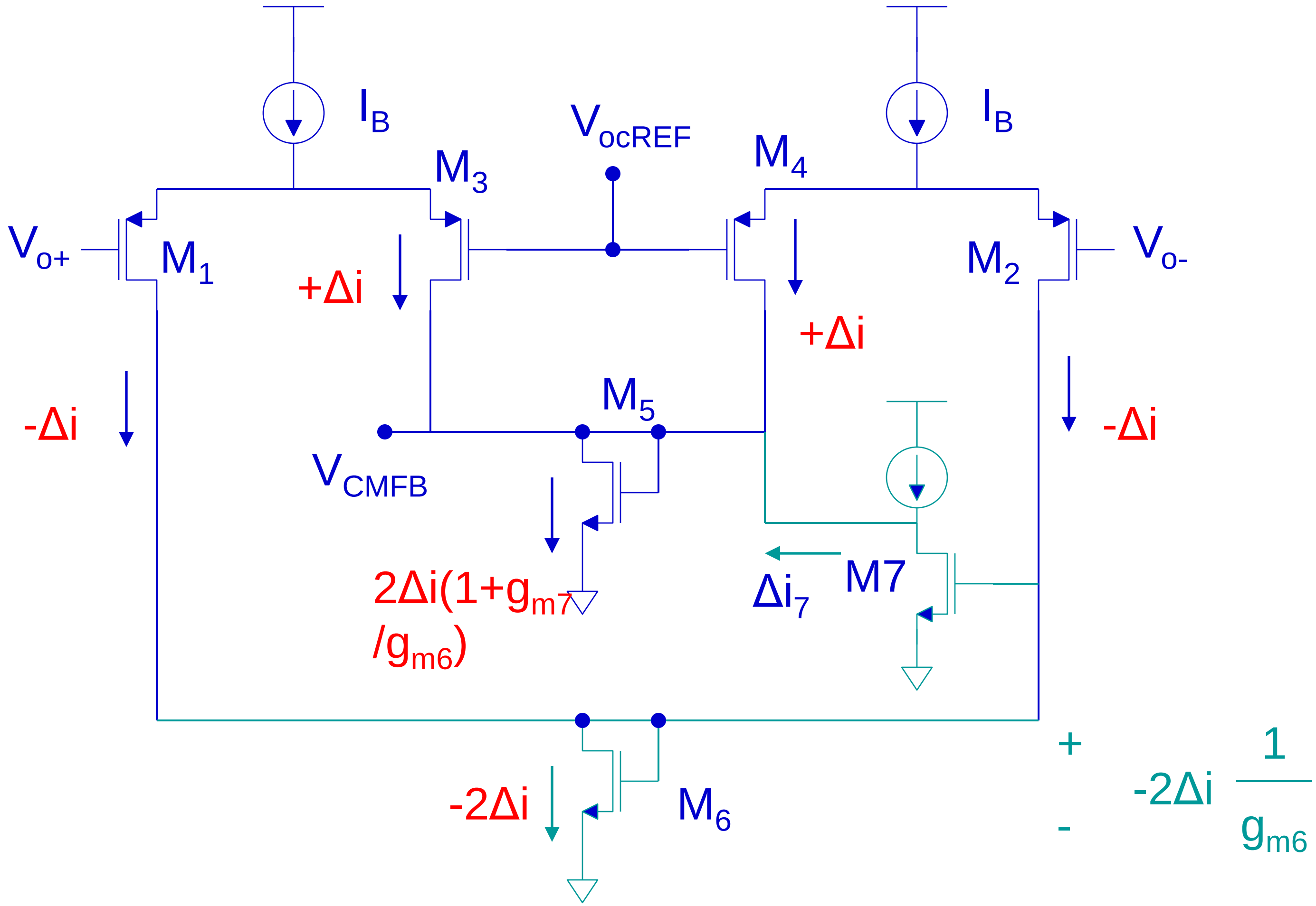
Common mode signal

- Differential V_o: $V_{o+}\downarrow$ by ΔV_o, $V_{o-}\uparrow$ by ΔV_o
- Common mode V_o: $V_{o+}\uparrow$ by ΔV_o, $V_{o-}\uparrow$ by ΔV_o

$$\Delta i = g_{m1} \frac{\Delta V_o}{2} \qquad \left(g_{m1} = g_{m2} = g_{m3} = g_{m4}\right)$$

$$\Delta V_{CMFB} = \frac{1}{g_{m5}} \cdot 2\Delta i \qquad \left(k = \frac{g_{m1}}{g_{m5}}\right)$$

$$= k \cdot \Delta V_o$$



I_B
I_B
V_ocREF
M_3
M_4
V_o+
M_1
M_2
V_o-
+Δi
+Δi
-Δi
-Δi
M_5
V_CMFB
2Δi(1+g_m7/g_m6)
Δi_7
M7
-2Δi
M_6
+
-
-2Δi 1/g_m6

To increase gain:

$$\Delta V_{G7} = -2\Delta i \frac{1}{g_{m6}}$$

$$\Delta i_7 = -\Delta V_{G7} g_{m7} = 2\Delta i \frac{g_{m7}}{g_{m6}}$$

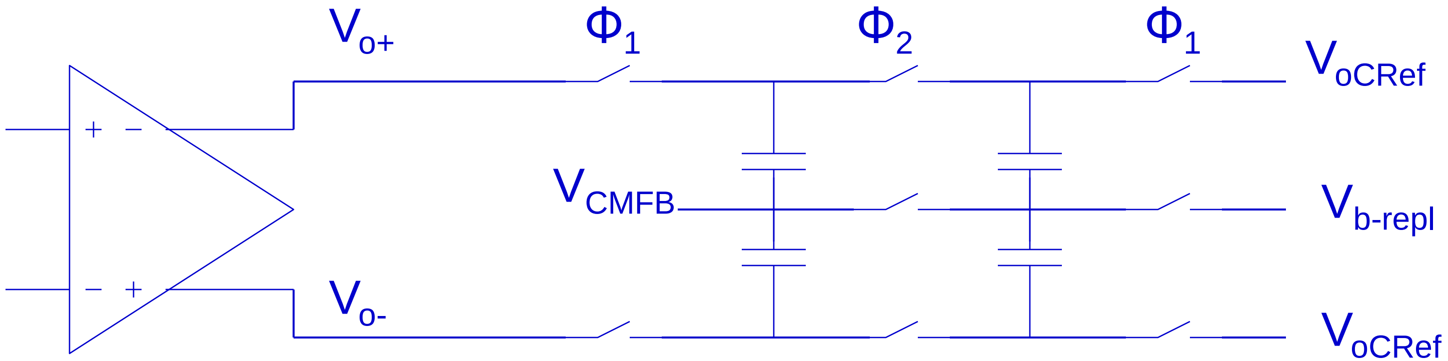
$$\therefore \Delta i_5 = 2\Delta i \left(1 + \frac{g_{m7}}{g_{m6}}\right)$$

$$\Delta V_{CMFB} = \frac{g_{m1}}{g_{m5}} \left(1 + \frac{g_{m7}}{g_{m6}}\right) \Delta V_o$$

* gain by geometric ratios $\Rightarrow$ can be made accurate

- With PMOS for M1-4, $V_{o+\max}$ is $V_{DD} - V_{DS}(sat) - V_{\mathrm{T}}$ and $V_{o+\min}$ is $V_{SS} + V_{DS}(sat)$
- Over this range, both M1 and M3 should be on.
- V_{ocREF} should be set in the middle of this range.
- Size M1,3 and tail current: $2\sqrt{2} * V_{od} \geq$ this range.
- The $V_{DS}(sat)$ of tail CS can be made ver small.
- With selected tail current, size M5,6 to achieve
- $\mathrm{V_{gs}}$ that matches desired $\mathrm{V_{CMFB}}$ at Vod = 0.
- Use M7 (one on each side) to increase CM gain.
- Split CMFB MOST to reduce CM gain.

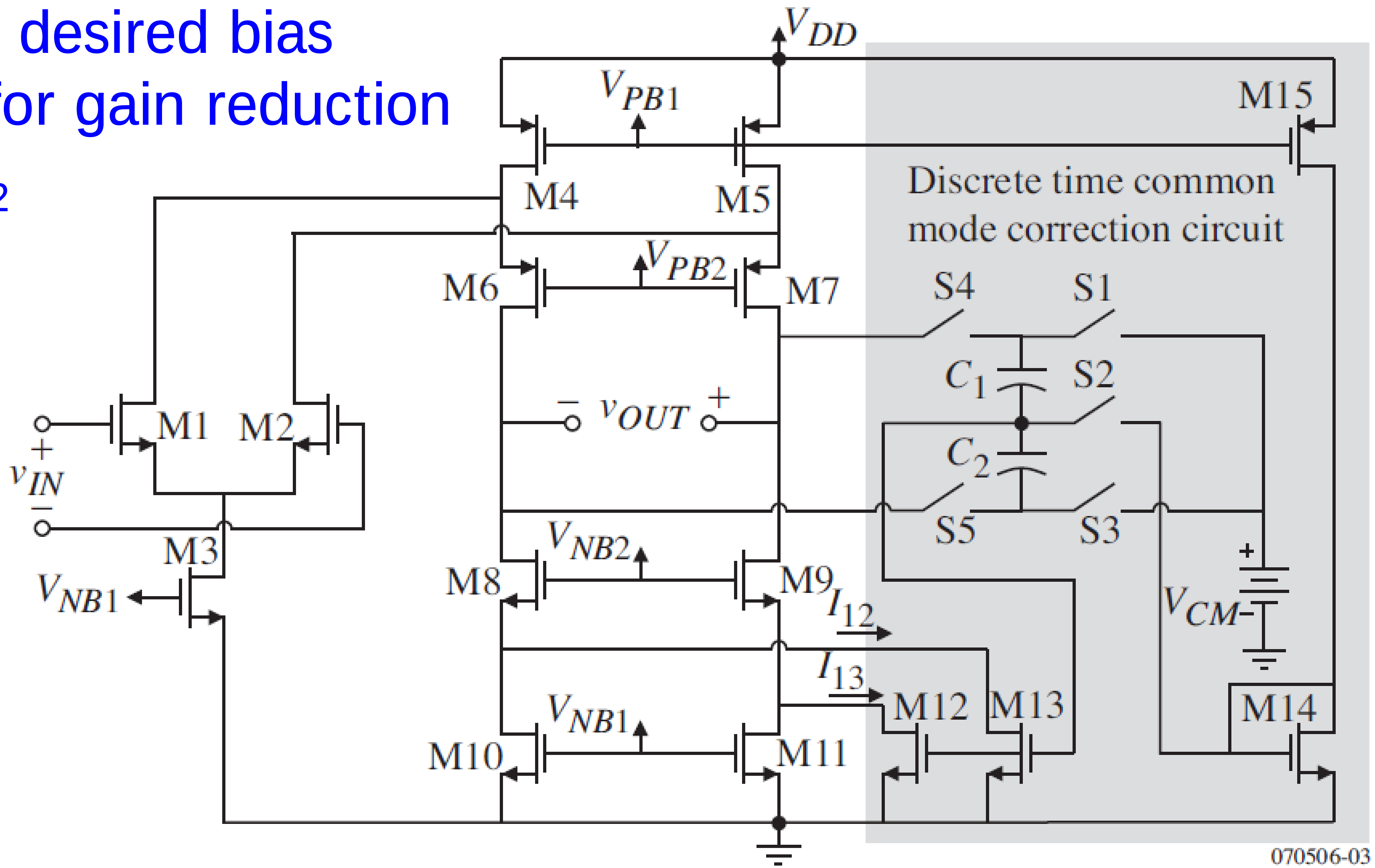
Switched cap CMFB supports full V_o swing: V_{SS} to V_{DD}



During phi_1, the left cap are charged by the op amp output, and the right caps are charged by the reference and nominal bias voltage.
During phi_2, the charges are averaged.

One simplified implementation

V_{CM}: desired Voc
V_{GS14}: desired bias
Split for gain reduction
$C_1 = C_2$



Points to consider

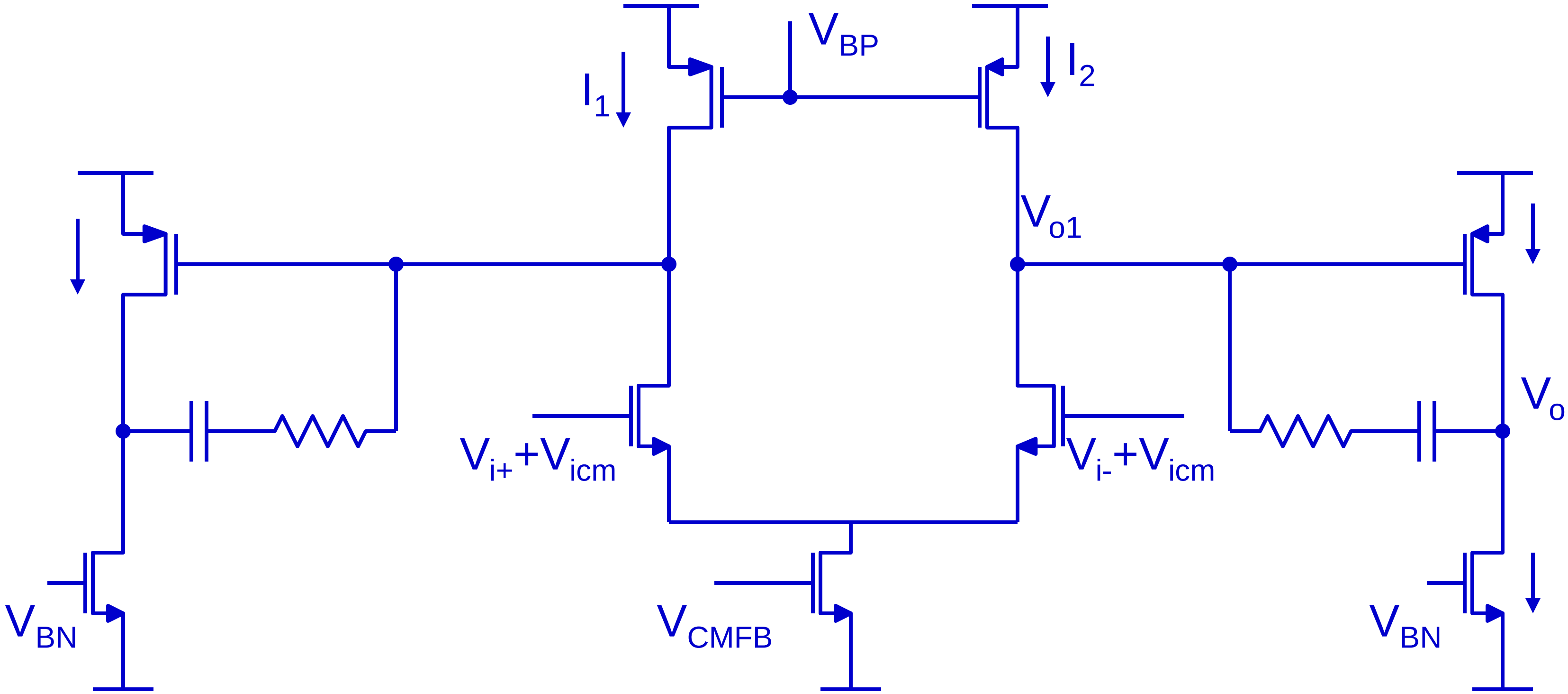
- If supply is high:
  - S2 can be NMOS
  - S1 and S3 can be either NMOS or PMOS or transmission gates
  - S4 an S5 must be transmission gates
- If supply is very low:
  - May need to use charge pump to boost the switch gate voltages
- Error due to charge injection from switches
  - Intentionally offset VCM and VGS14
  - Use simulation to determine the right values

Bandwidth of CMFB loop

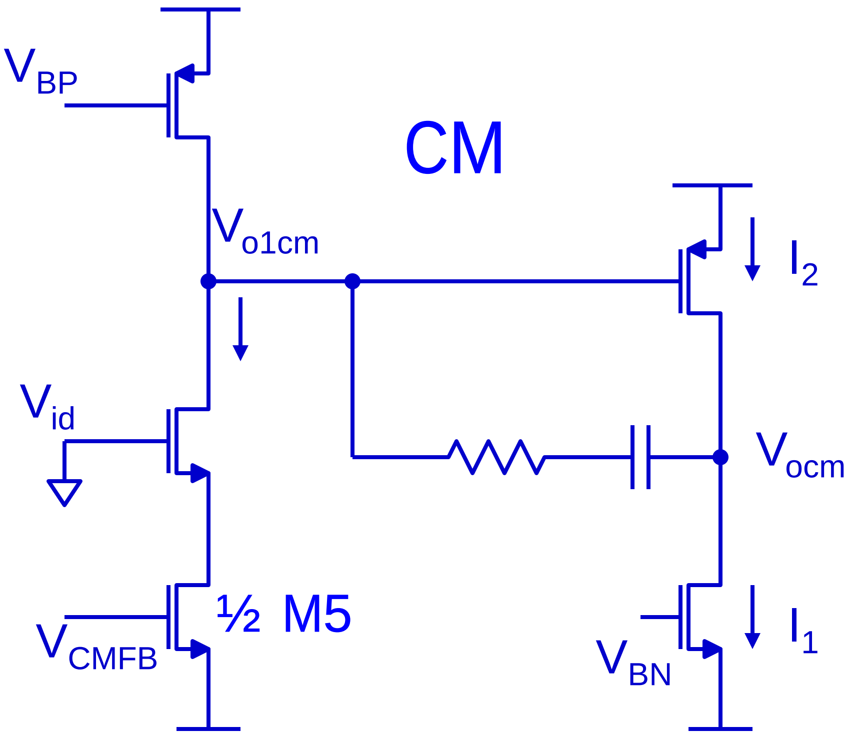
- Ideally, if CM and DM are fully decoupled, CM only needs to stabilize operating points. ➔ CM bandwidth only needs to be wide enough to handle disturbances affecting operating points.
- Practically, there is CM←→DM conversion. ➔CM loop needs to handle disturbances of bandwidth comparable to DM BW
- But CM loop shares most of DM poles and have additional poles, ➔ difficult to achieve similar bandwidth, ➔ make CM loop bandwidth a few times lower than DM

Here Bandwidth = unity loop gain frequency

Example

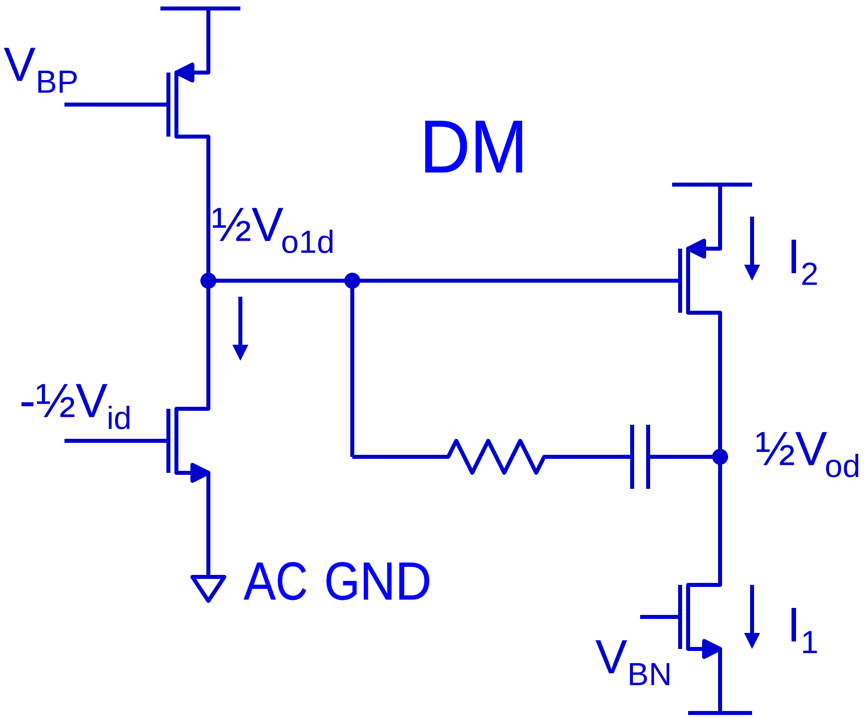


CM and DM equivalent circuit Comparison



$r_{o1} = r_{dsp} || r_{cascode} \approx r_{dsp}$

$g_m = \frac{1}{2} g_{m5}$



$r_{o1} = r_{dsp} || r_{dsn} \approx \frac{1}{2} r_{dsp}$

$g_m = g_{m1}$

- ➢Low frequency pole p1 is about 2X lower in CM;
- ➢DC gain is change by $2 * \frac{1}{2} g_{m5}/g_{m1}$,
- ➢unity gain frequency g_m/C_C is changed by $\frac{1}{2} g_{m5}/g_{m1}$,
- ➢high frequency poles and zeros of DM remain in CM,
- ➢CM has one additional node at D5

➔similar or worse PM at unity gain fre

To ensure sufficient CMFB loop stability

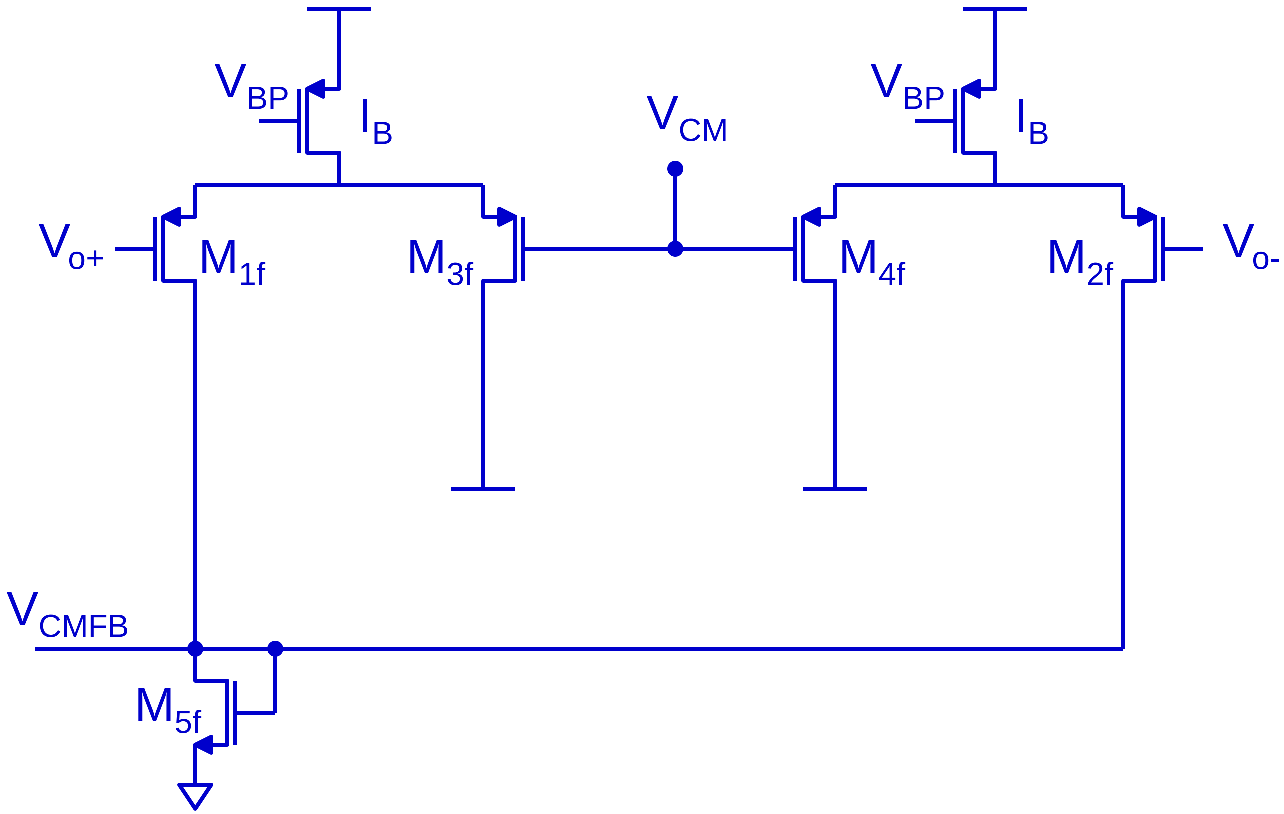
- CMFB loop gain = CM gain from VCMFB to Voc * gain of CMFB circuit
- To ensure sufficient PM for CMFB loop
  - Make the DC gain of CMFB circuit to be a few time less than one
  - That makes the CMFB loop UGF to be a few times lower than CM gain's UGF
  - Make sure the additional pole in the CM gain and any additional poles from the CMFB circuit to be at higher frequency than DM UGF

CM gain's additional pole at D5 is given by: ~ $-g_{m1}/(C_{gs1}+½C_{db5})$

This is close to f_T of M1. So at very high fre.

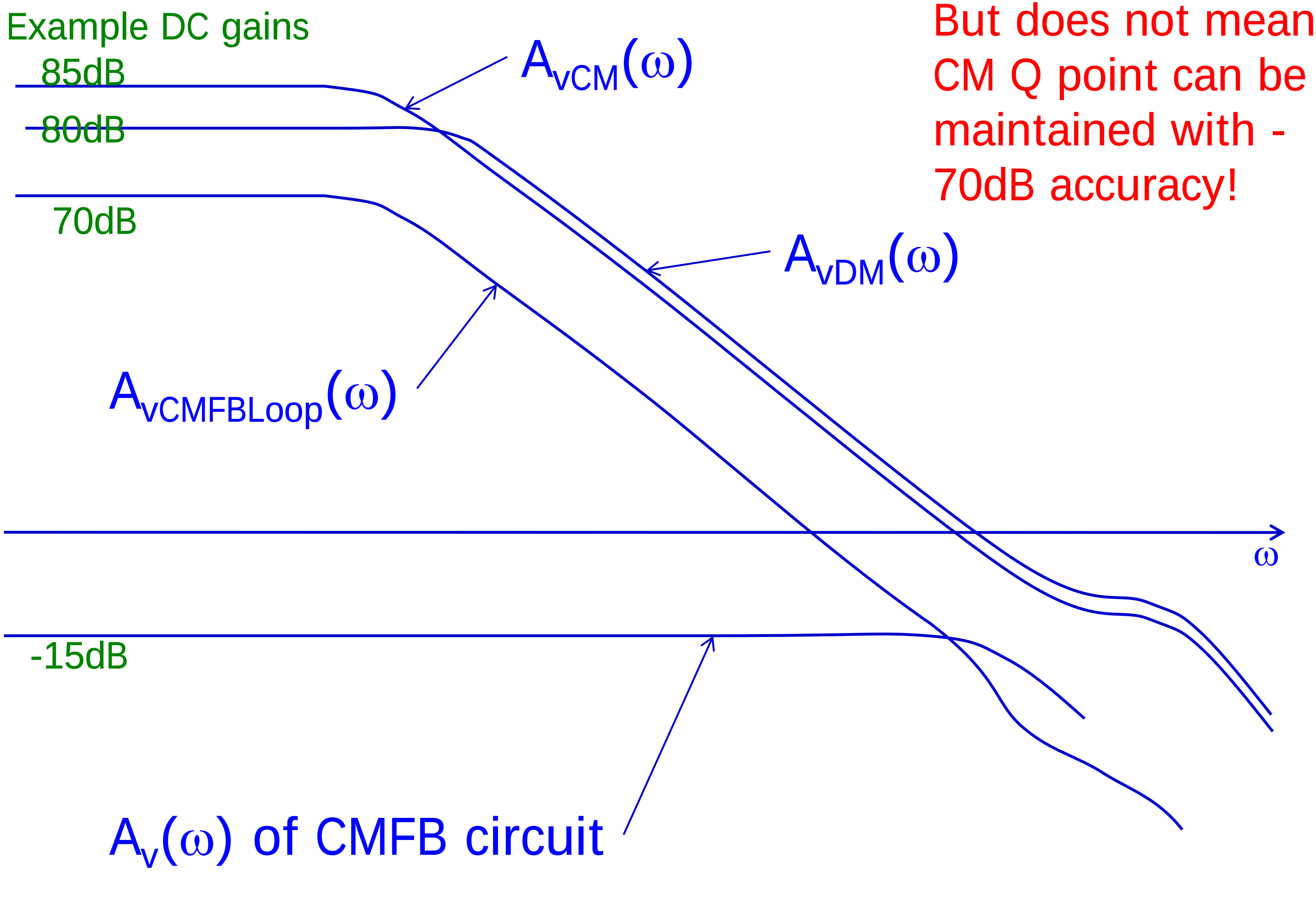
If the CMFB circuit below is to be used, then the following needs to be true:

1. I_B and M_5 sized to give desired V_{CMFB} when Vo+=Vo-=desired
2. CMFB circuit DC gain $A_{CMFB}=2g_{m1f}/g_{m5f}$ is small.
3. Pole of CMFB – $g_{m5f}/(C_{gs5}+C_{gs5f}+C_{db5f}+C_{db1,2f})$ >> A_{CMFB}*UGF of DM



Also, W/L of $M_{1\text{-}4f}$ should be small, so that their V_{EB} is large to accommodate V_{o+}, V_{o-} swing.

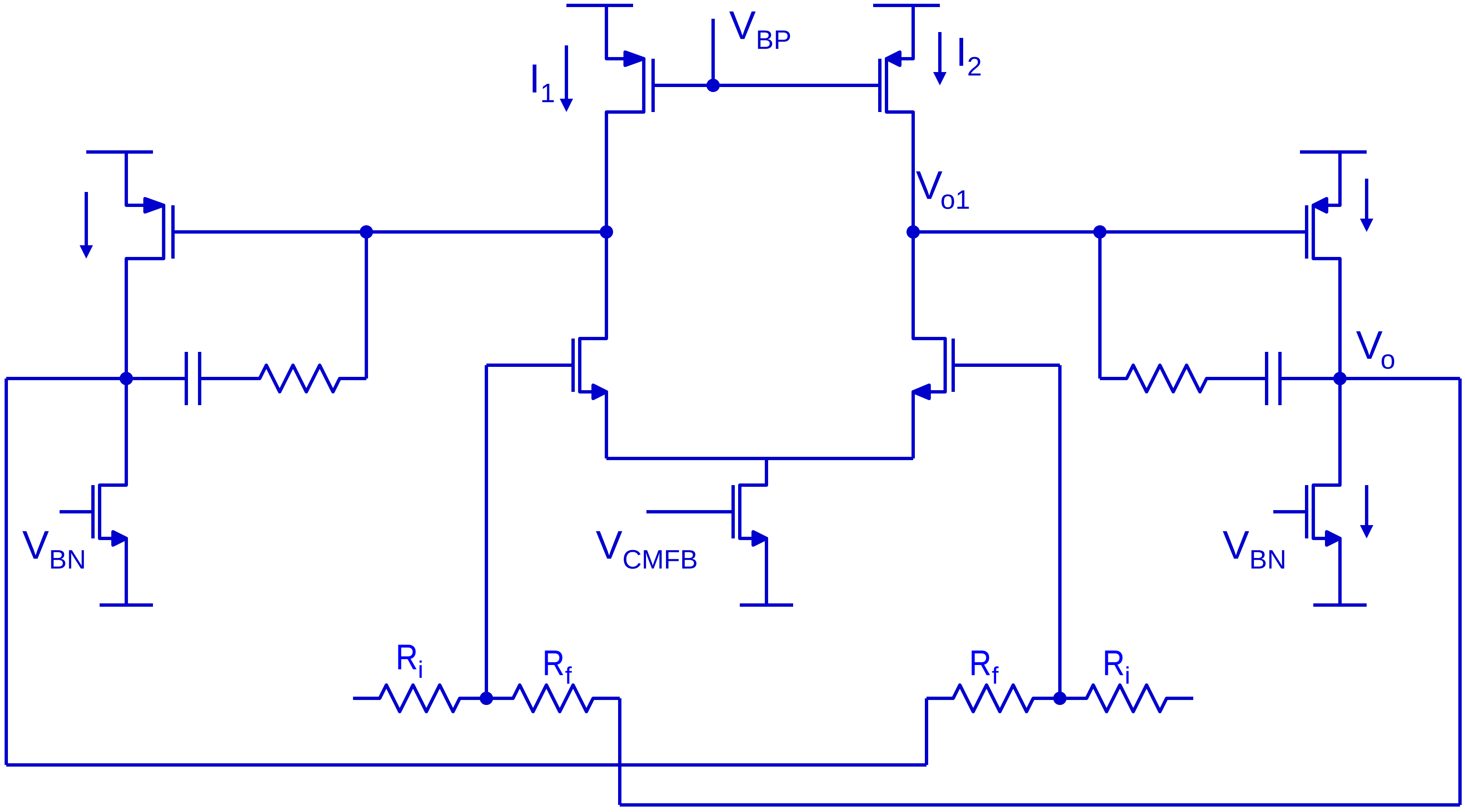
This is consistent with (1.) above

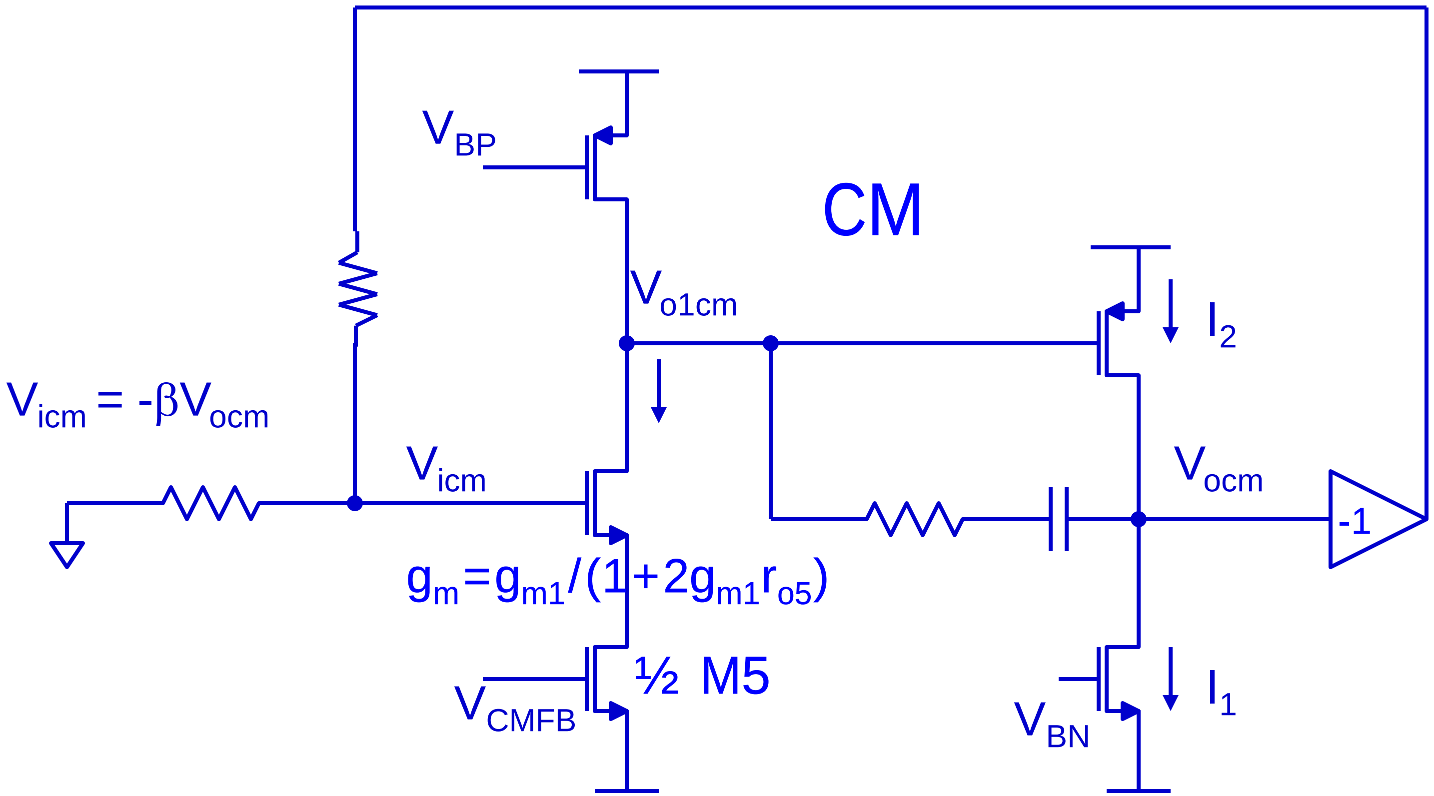


But does not mean CM Q point can be maintained with -70dB accuracy!

Why?

Because op amp is always used in feedback configuration.
DM feedback also kills CM gain, since DM and CM share the same path from vo1 to vo.

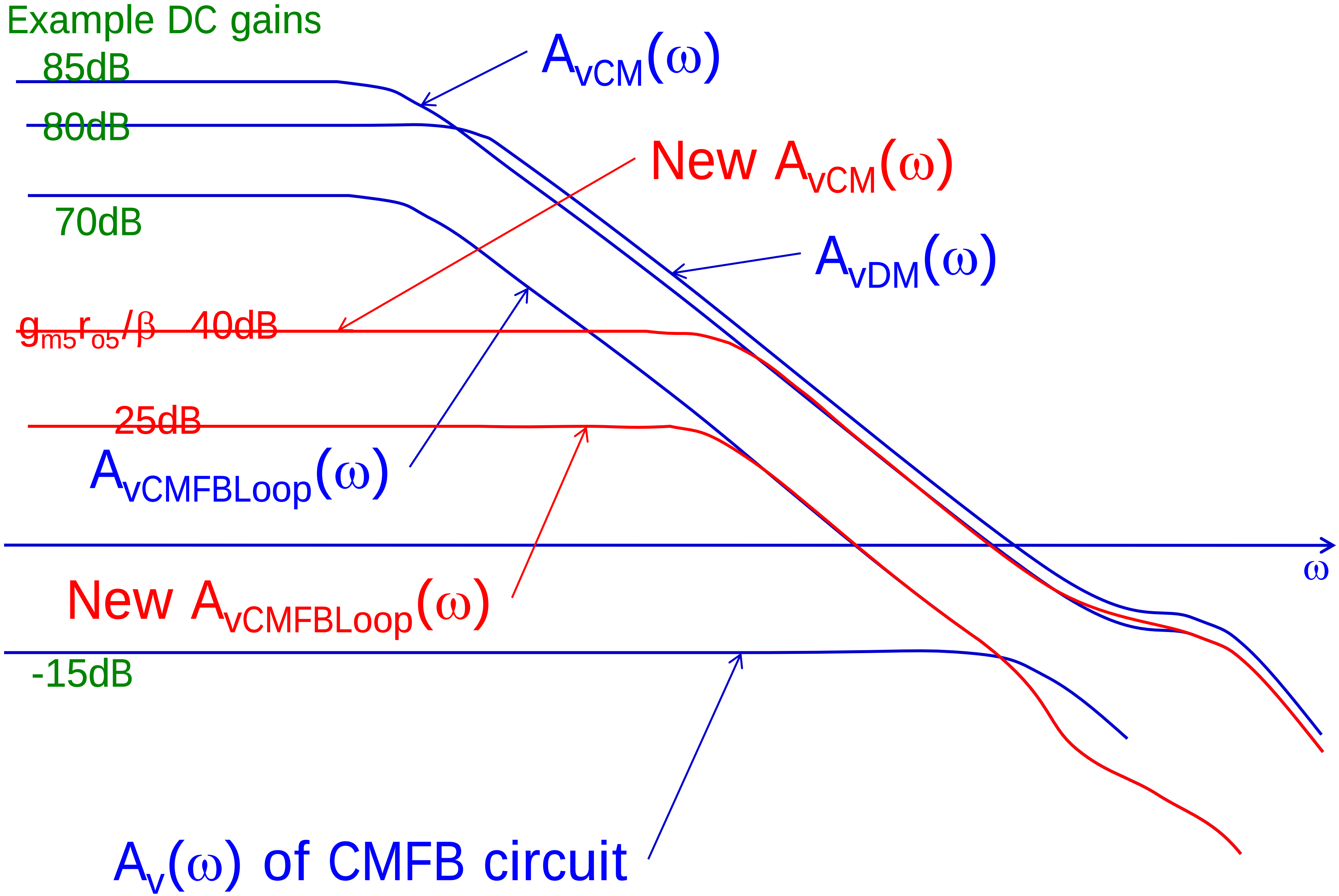




$$V_{ocm} = A_{vCM}(\omega)V_{CMFB} + A_{ViCM}(\omega)V_{iCM} = A_{vCM}(\omega)V_{CMFB} + \frac{\dfrac{g_{m1}}{1+2g_{m1}r_{o5}}}{\dfrac{1}{2}g_{m5}} A_{vCM}(\omega)(-\beta V_{ocm})$$

$$V_{ocm} = \frac{g_{m5}r_{o5}A_{vCM}(\omega)}{g_{m5}r_{o5} + \beta A_{vCM}(\omega)} V_{CMFB}$$

$$\frac{V_{ocm}}{V_{CMFB}} = \begin{cases} \dfrac{g_{m5}r_{o5}}{\beta} & \text{when } A_{vCM} \text{ large} \\ A_{vCM}(\omega) & \text{when } A_{vCM} \text{ small} \end{cases}$$



Example DC gains
85dB
80dB
70dB
$g_{m5}r_{o5}/\beta$ 40dB
25dB
-15dB
$A_{vCM}(\omega)$
New $A_{vCM}(\omega)$
$A_{vDM}(\omega)$
$A_{vCMFBLoop}(\omega)$
New $A_{vCMFBLoop}(\omega)$
ω
$A_v(\omega)$ of CMFB circuit

Is it good enough to stabilize the CM Q points to -25 dB accuracy level?

If not, what can be done?

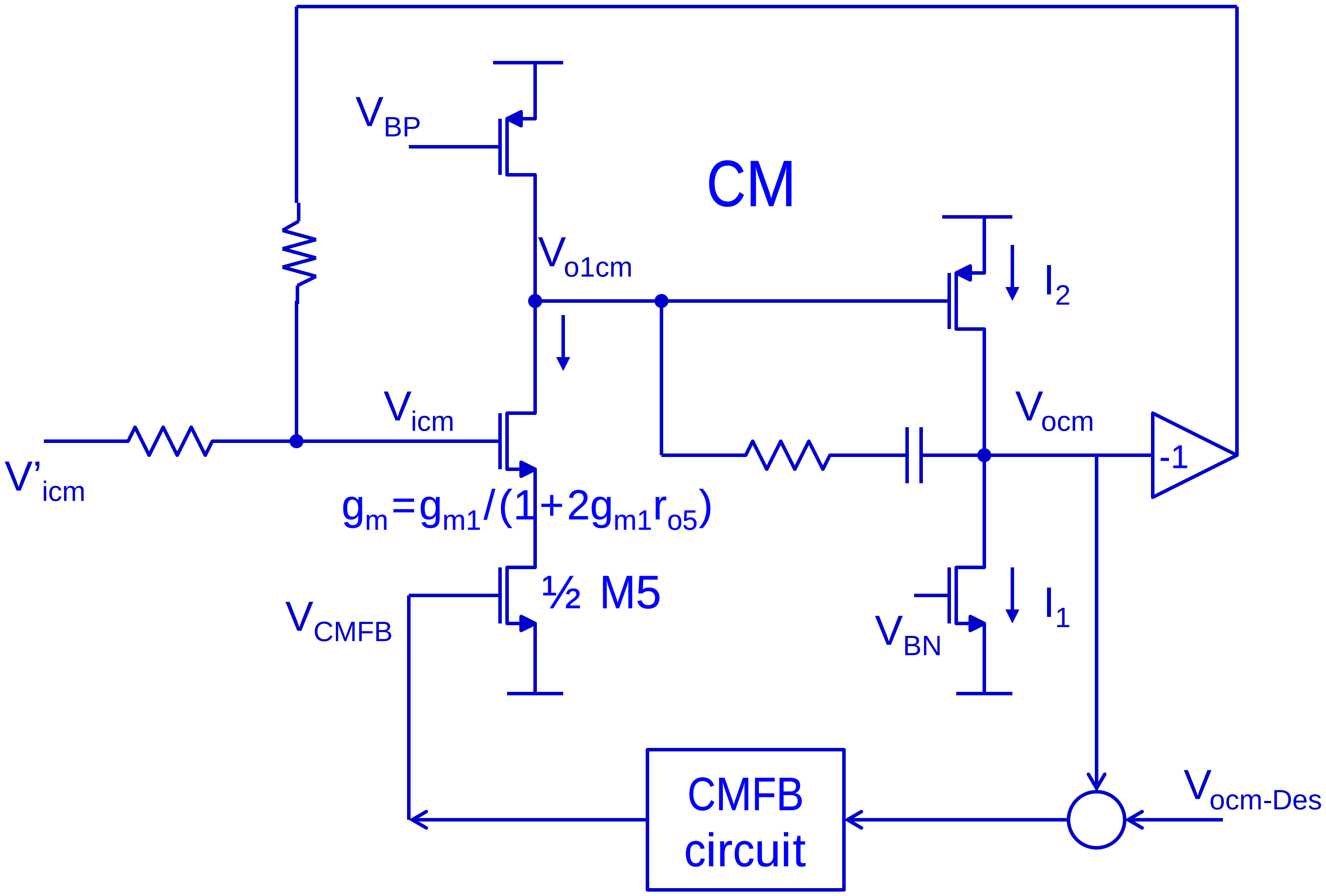
➔ Increase the effective $g_{m5}r_{o5}$!
That is: use cascode tail current source.

This will improve the CMFB loop gain under DM feedback by about 30 to 35 dB.

➔ Or, increase the gain of CMFB circuit.
In doing so, avoid introducing high impedance node, avoid introducing poles near or lower than DM GB.

Voc variation range

- Voc variation comes from two sources
  - Input common mode
  - Common mode PVT variations
- Vicm induced Voc variation
  - Find closed-loop Vicm range
  - Find closed-loop gain from Vicm to Voc
  - Find contribution to Voc variation
- PVT induced Voc variation
  - Refer all PVT variations to V_{BP} variation
  - Find gain closed-loop from V_{BP} to Voc
  - Find contribution to Voc variation



$$V_{ocm} = A_{vCM}(\omega)V_{CMFB} + A_{ViCM}(\omega)V_{iCM} + A_{VBP}(\omega)V_{BP}$$

$$V_{CMFB} = A_{VCMFBCircuit}(\omega)\left(V_{ocm-des} - V_{ocm}\right)$$

$$V_{iCM} = V'_{iCM} - \beta(\omega)(V_{ocm} + V'_{iCM})$$