ECEN474/704: (Analog) VLSI Circuit Design
Spring 2018

Lecture 15: Fully Differential Amplifiers & CMFB

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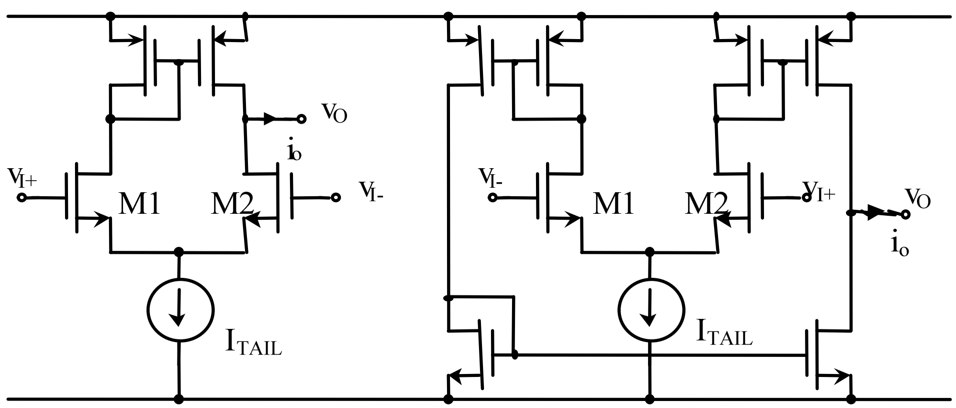
Announcements

- Project Report Due May 1
  - Email it to me by 5PM
- Exam 3 is on May 3
  - 3PM-5PM

Agenda

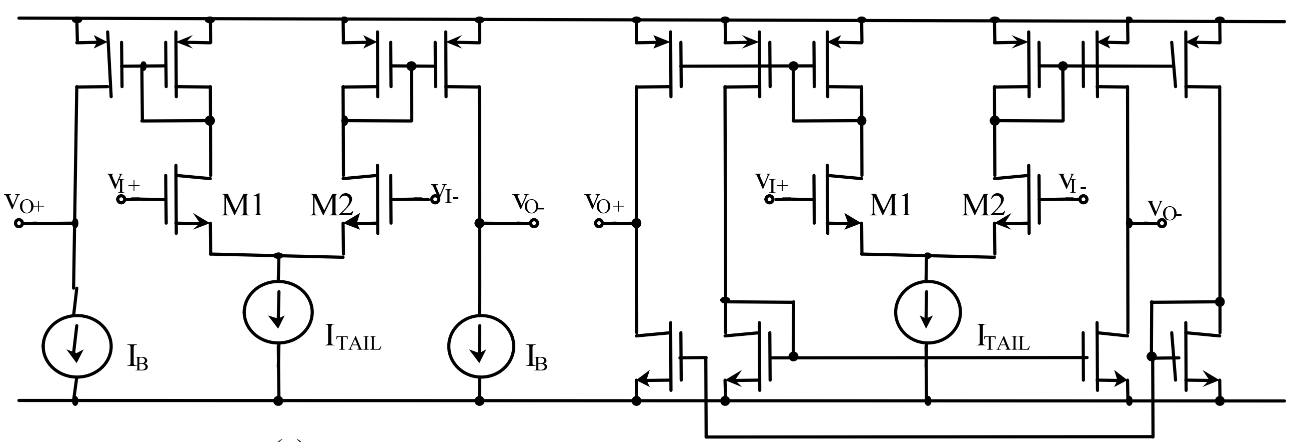
- Fully differential circuits
- Common-mode feedback circuits
- Multi-OTA stages CMFB
- OTA-C filter w/ CMFB example

Basic Operational Transconductance Amplifier Topologies



(a) (b)

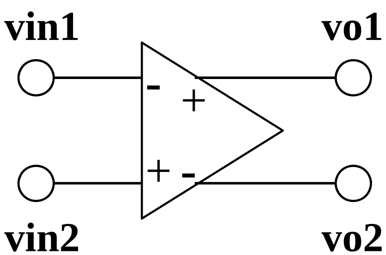
SINGLE-ENDED



(c) (d)

FULLY-DIFFERENTIAL

Fully-Differential Circuits



In general:

$$v_{o1} = \frac{v_{o1} - v_{o2}}{2} + \frac{v_{o1} + v_{o2}}{2} = \frac{v_{od}}{2} + v_{oc}$$

$$v_{o2} = \frac{v_{o2} - v_{o1}}{2} + \frac{v_{o1} + v_{o2}}{2} = -\frac{v_{od}}{2} + v_{oc}$$

- Hence

$$\begin{bmatrix} v_{od} \\ v_{oc} \end{bmatrix} = \begin{bmatrix} A_{dd} & A_{dc} \\ A_{cd} & A_{cc} \end{bmatrix} \begin{bmatrix} v_{id} \\ v_{ic} \end{bmatrix}$$

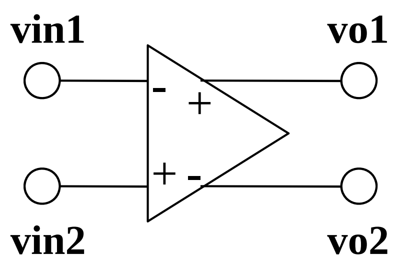
Differential-mode output

$$A_{dd} = \left.\frac{v_{od}}{v_{id}}\right|_{Vic=0} \qquad A_{dc} = \left.\frac{v_{od}}{v_{ic}}\right|_{Vid=0}$$

Common-mode output

$$A_{cd} = \left.\frac{v_{oc}}{v_{id}}\right|_{Vic=0} \qquad A_{cc} = \left.\frac{v_{oc}}{v_{ic}}\right|_{Vid=0}$$

Fully-Differential Filters: Effects of current source inpedance and mismatches

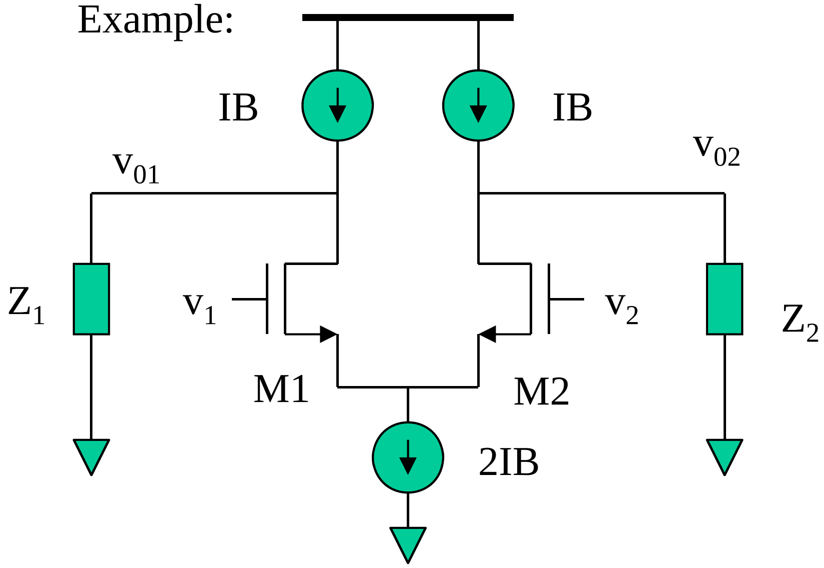


A very important parameter:

$$\text{CMRR} = \frac{A_{dd}}{A_{dc}}$$

w/ $v_{id} = v_{i2} - v_{i1}$ **and** $v_{ic} = \dfrac{v_{i2} + v_{i1}}{2}$

Example:



Solving the circuit:

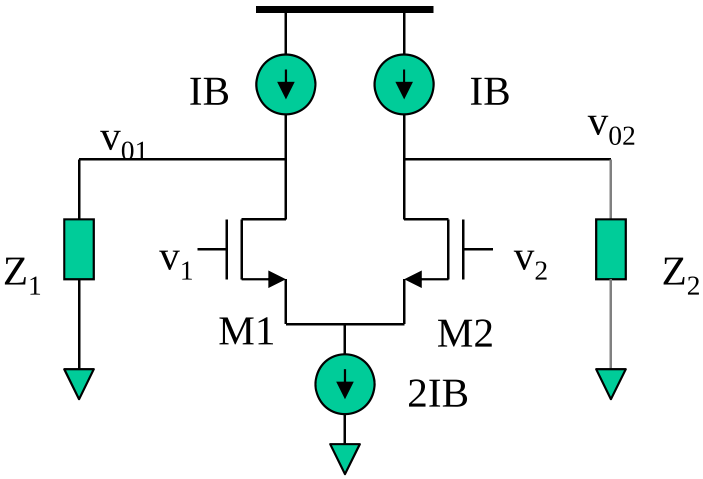
$$v_{01} = \frac{g_{m1} g_{m2} Z_1}{g_{m1} + g_{m2} + Y_s} \left[\left(1 + \frac{Y_s}{2 g_{m2}}\right) v_{id} - \left(\frac{Y_s}{g_{m2}}\right) v_{ic} \right]$$

$$v_{02} = \frac{g_{m1} g_{m2} Z_2}{g_{m1} + g_{m2} + Y_s} \left[-\left(1 + \frac{Y_s}{2 g_{m1}}\right) v_{id} - \left(\frac{Y_s}{g_{m1}}\right) v_{ic} \right]$$

Y_s is the admittance associated with the current source 2IB

Fully-Differential Filters: Non-idealities

Voltage gain: Note the effects of the mismatches, especially in A_{dc} and A_{cd}



$$A_{dd}=\left.\frac{v_{o1}-v_{o2}}{v_{i2}-v_{i1}}\right|_{v_{ic}=0}=\frac{g_{m1}g_{m2}}{g_{m1}+g_{m2}+Y_s}\left[Z_1+Z_2+\frac{Y_s}{2}\left(\frac{Z_1}{g_{m2}}+\frac{Z_2}{g_{m1}}\right)\right]$$

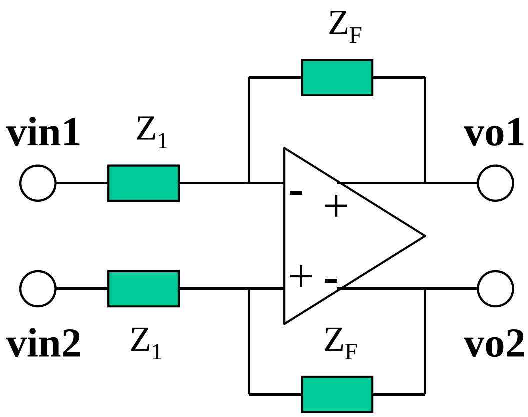
$$A_{dc}=\left.\frac{v_{o1}-v_{o2}}{(v_{i2}+v_{i1})/2}\right|_{v_{id}=0}=\frac{g_{m1}g_{m2}}{g_{m1}+g_{m2}+Y_s}\left[Y_s\left(\frac{Z_2}{g_{m1}}-\frac{Z_1}{g_{m2}}\right)\right]$$

$$A_{cd}=\left.\frac{(v_{o2}+v_{o1})/2}{v_{i2}-v_{i1}}\right|_{v_{ic}=0}=\frac{g_{m1}g_{m2}}{g_{m1}+g_{m2}+Y_s}\left(\frac{1}{2}\right)\left[Z_1-Z_2+\frac{Y_s}{2}\left(\frac{Z_1}{g_{m2}}-\frac{Z_2}{g_{m1}}\right)\right]$$

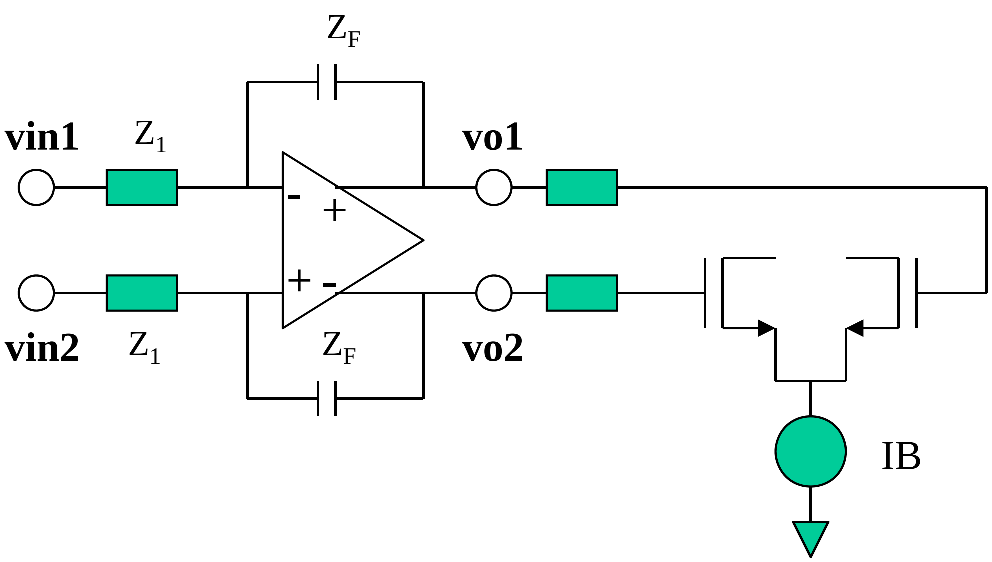
$$CMRR=\frac{A_{dd}}{A_{dc}}\cong\frac{g_{m1}\left(1+\frac{Z_1}{Z_2}\right)}{Y_s\left(1-\frac{g_{m1}Z_1}{g_{m2}Z_2}\right)}$$

$$A_{cc}=\left.\frac{(v_{o2}+v_{o1})/2}{(v_{i2}+v_{i1})/2}\right|_{v_{id}=0}=-\frac{g_{m1}g_{m2}}{g_{m1}+g_{m2}+Y_s}\left(\frac{1}{2}\right)\left[Y_s\left(\frac{Z_2}{g_{m1}}+\frac{Z_1}{g_{m2}}\right)\right]$$

Fully-Differential Circuits



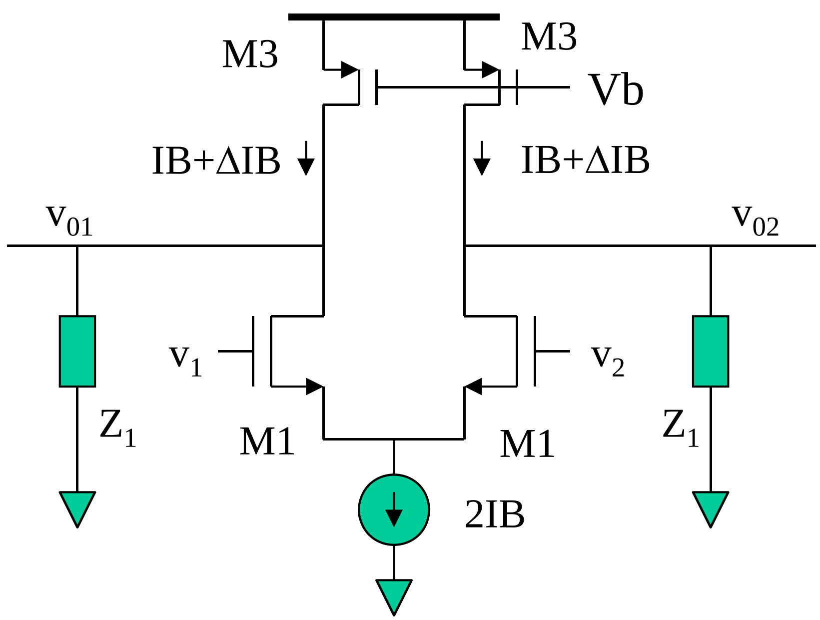
- Ideal voltage gain $A_{dd} = \dfrac{v_{01} - v_{02}}{v_{in2} - v_{in1}} = \dfrac{Z_f}{Z_1}$
- Ideally even-order distortions are cancelled
- Ideally common-mode signals are rejected
- What sets the output common-mode of these circuits?
  - Function of the amplifier output resistance



Common-mode offsets can impact the performance of the following stages

- **Can exceed the common-mode input range of preceeding stages**
- **With finite A_{cc} can accumulate in a multi-stage amplifier circuit**

Fully-Differential Amplifiers: COMMON-MODE DC offset



✓**If ΔIB is positive transistors M3 eventually will be biased in triode region (small resistance)**

✓**dc gain reduces drastically**

✓**Linear range is further minimized**

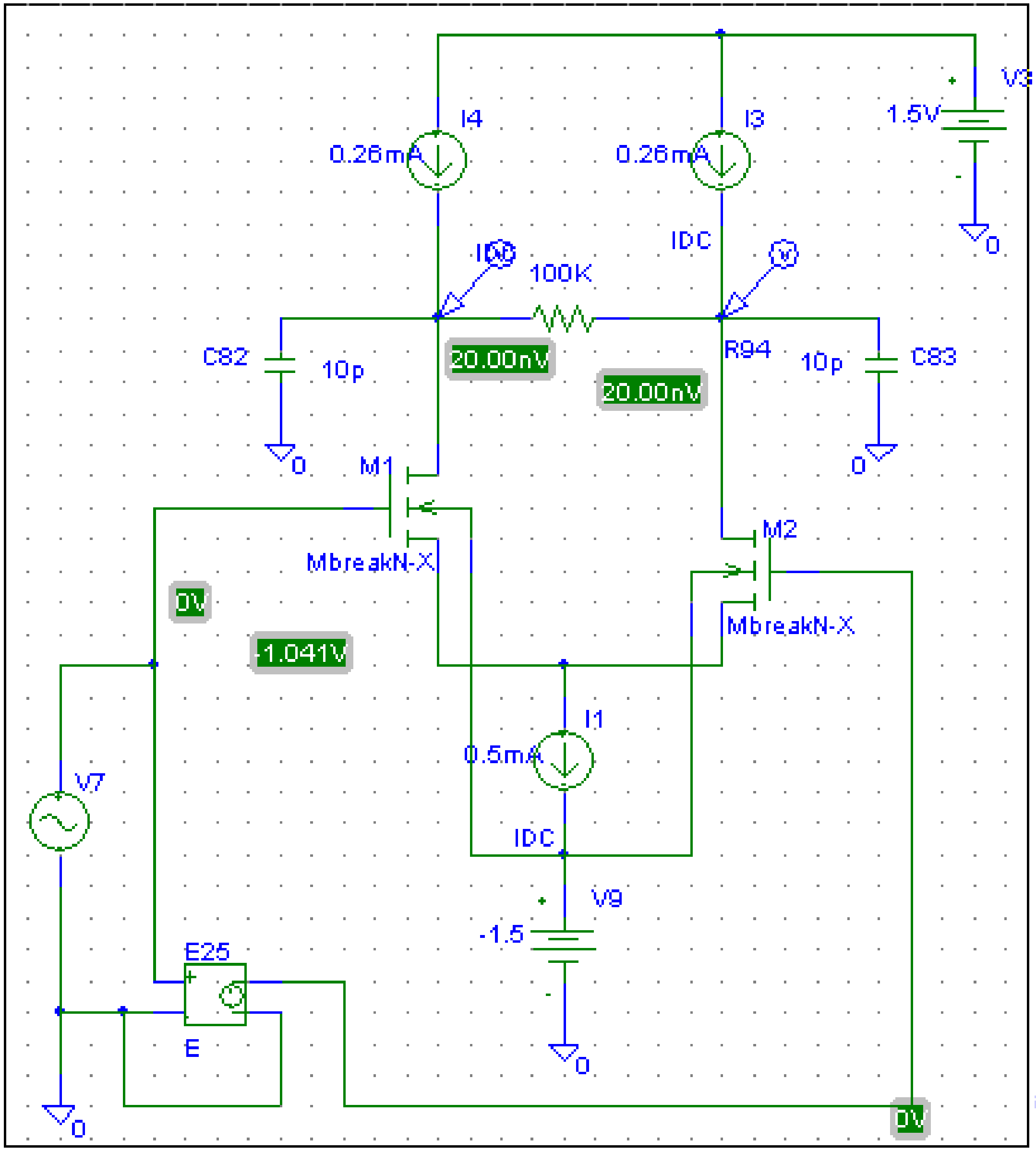
✓**THD increases**

✓**The common-mode output impedance is the parallel of the equivalent output resistance (M1 and M3) and the parasitic capacitors.**

✓**For large dc gain, the output impedance at nodes v01 and v02 are further increased and ΔIB produces a dc offset = $R_{out}\Delta IB$. Large common-mode offsets!**

✓**How can this issue be fixed?**

Fully-Differential Amplifiers: Characterization

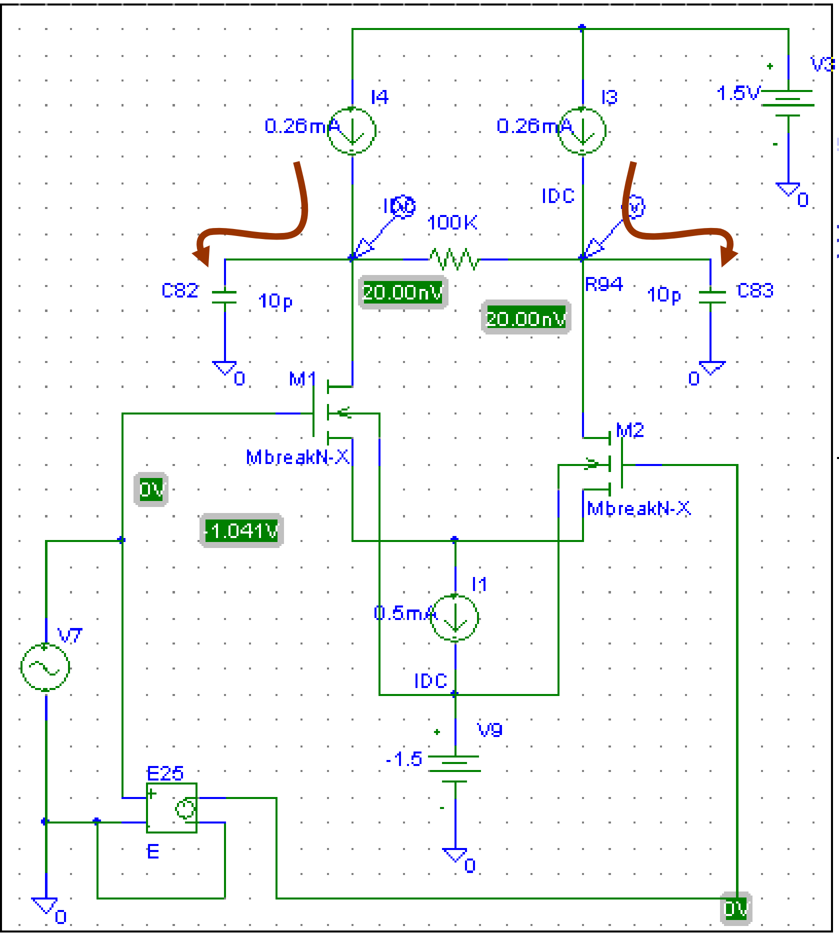


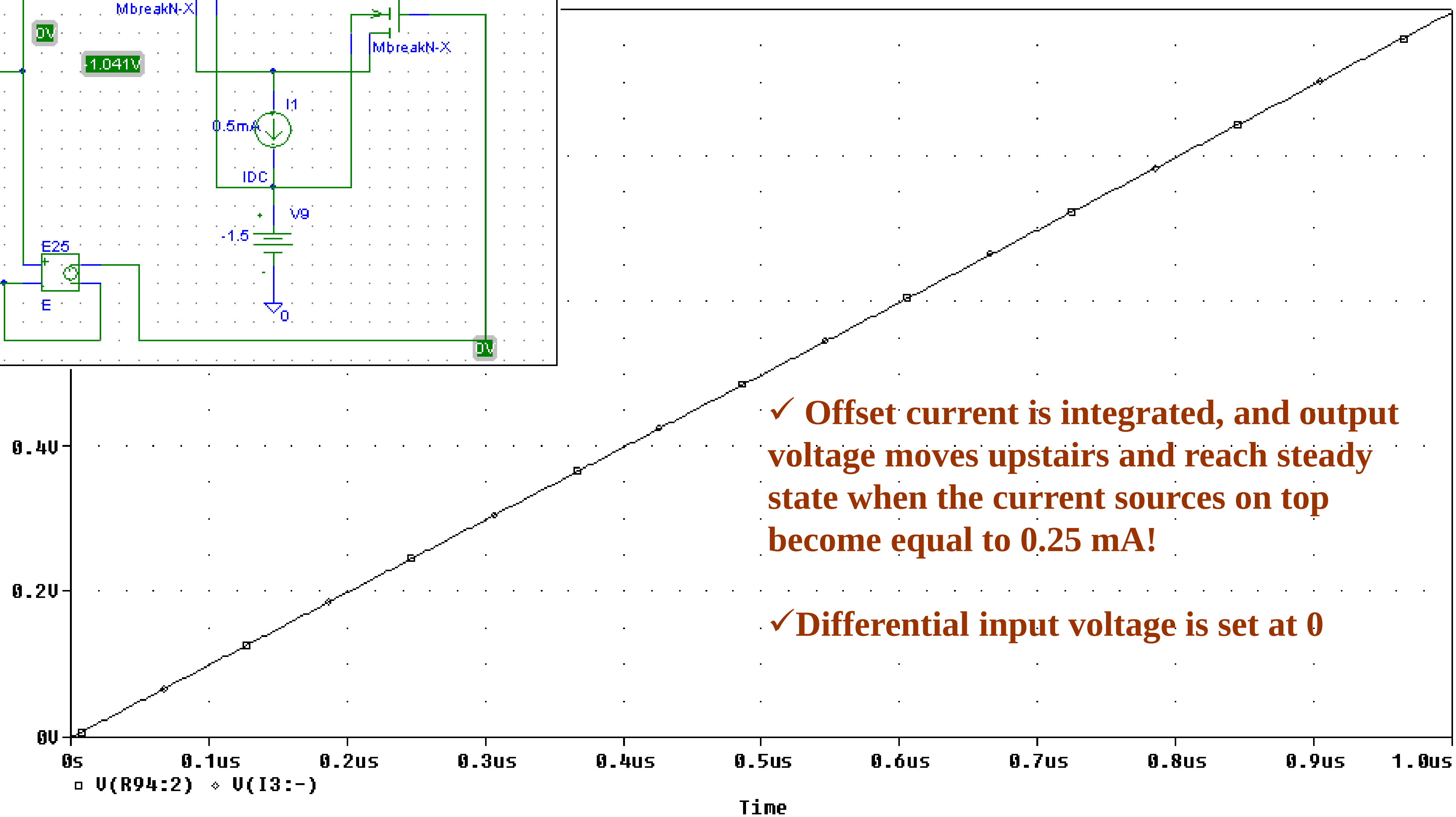
✓Common-mode current offset of 0.01 mA per side is added on purpose

Tail current is 0.5 mA while the current sources on top are 0.26 mA!

✓**Differential input voltage is set at 0**

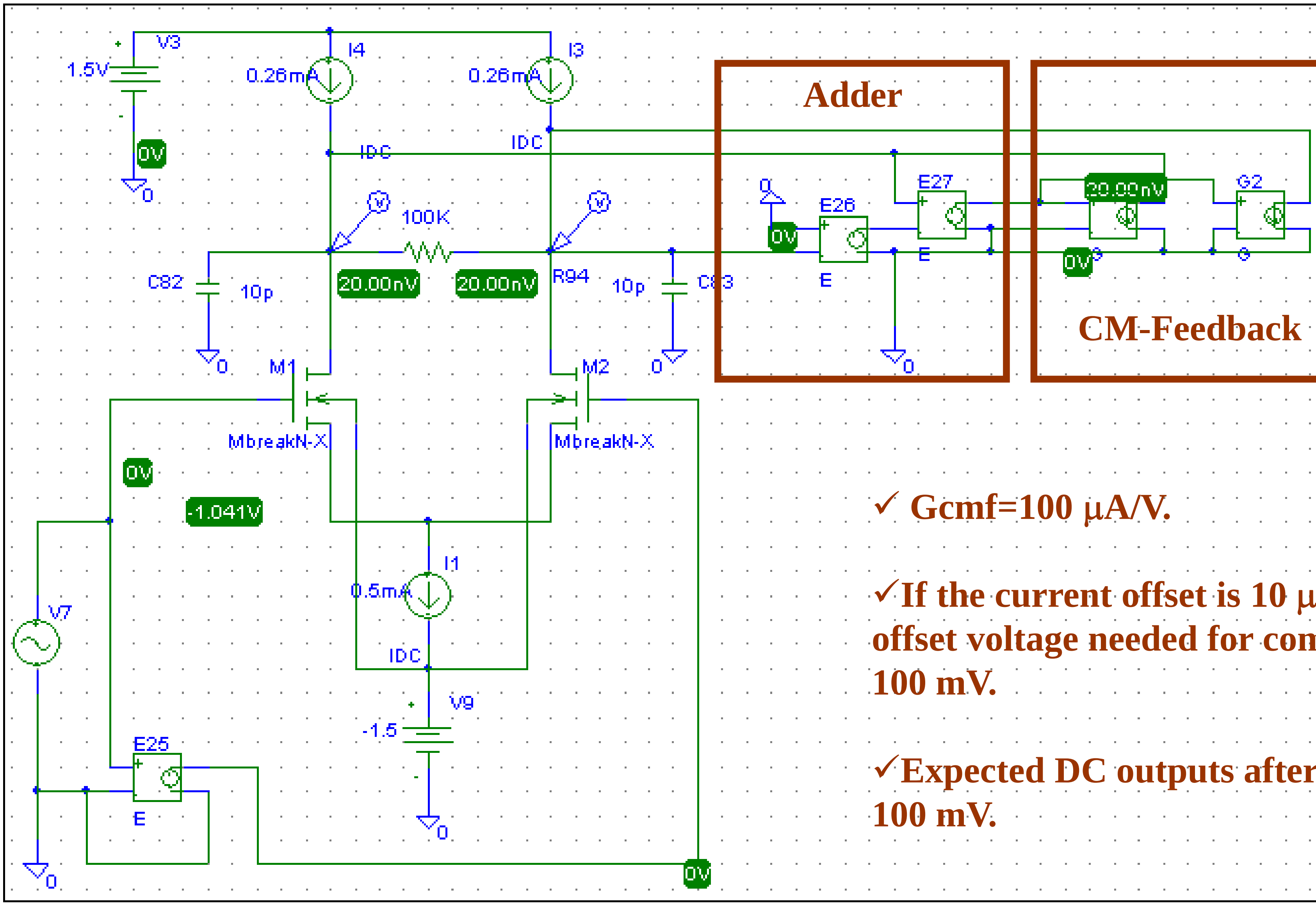
al Amplifiers: Characterization





- ✓ Offset current is integrated, and output voltage moves upstairs and reach steady state when the current sources on top become equal to 0.25 mA!
- ✓Differential input voltage is set at 0

Fully-Differential Amplifiers: Common-mode Feedback

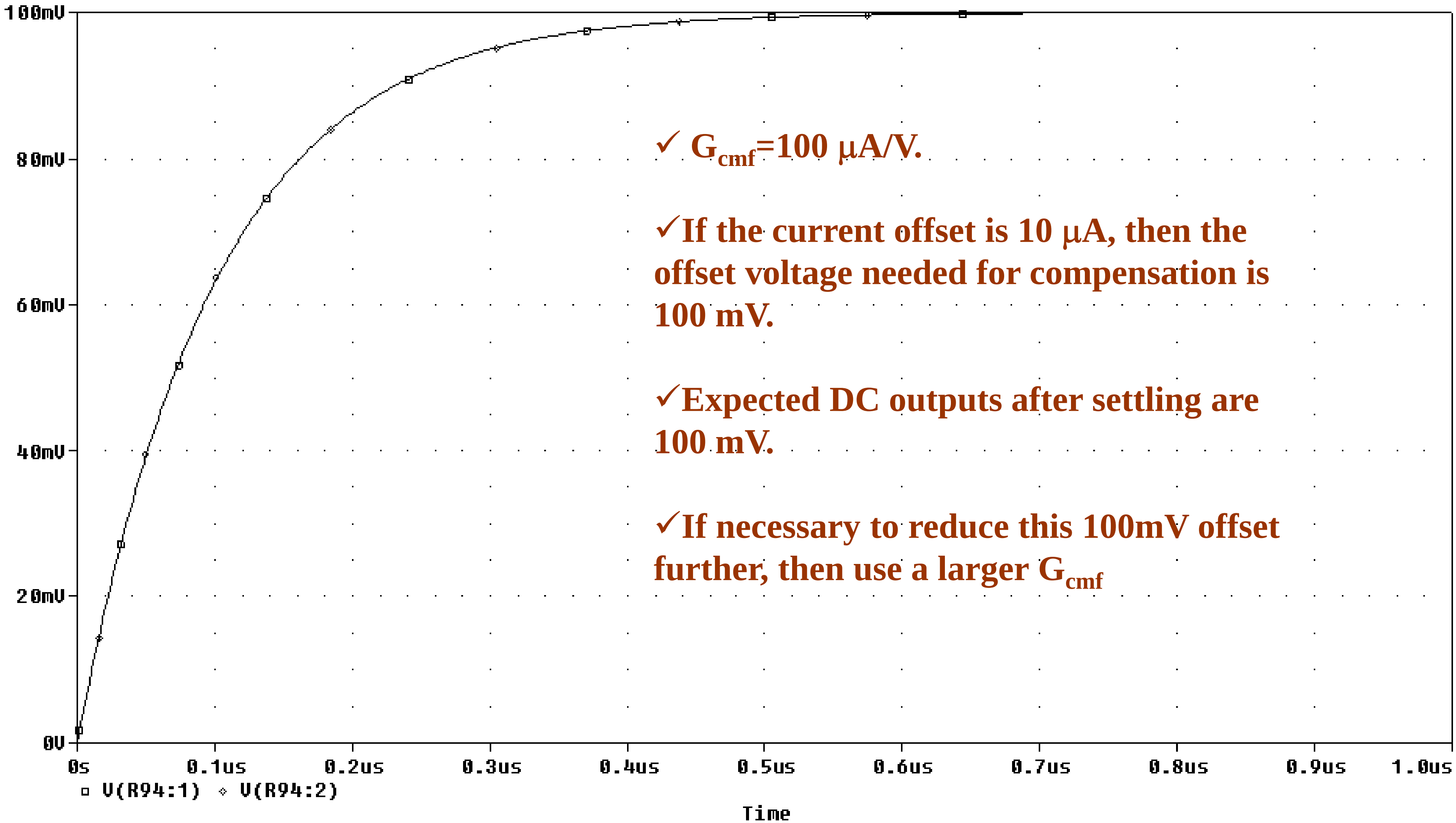


✓ Gcmf=100 µA/V.

✓If the current offset is 10 µA, then the offset voltage needed for compensation is 100 mV.

✓Expected DC outputs after settling are 100 mV.

Fully-Differential Amplifiers: Common-mode Feedback



- ✓ G_{cmf}=100 μA/V.
- ✓If the current offset is 10 μA, then the offset voltage needed for compensation is 100 mV.
- ✓Expected DC outputs after settling are 100 mV.
- ✓If necessary to reduce this 100mV offset further, then use a larger G_{cmf}

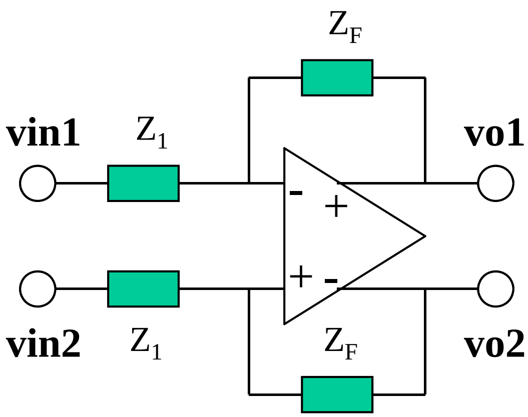
Agenda

- Fully differential circuits
- Common-mode feedback circuits
- Multi-OTA stages CMFB
- OTA-C filter w/ CMFB example

What is a common-mode feed-back correction circuit ?

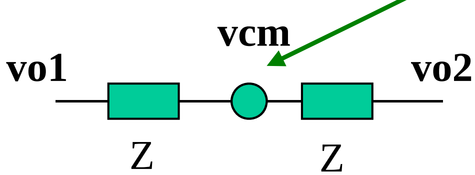
A common mode feed-back circuit is a circuit <u>sensing the common-mode voltage</u>, <u>comparing it with a proper reference</u>, and feeding back the correcting common-mode signal (both nodes of the fully-differential circuit) with the purpose <u>to cancel the output common-mode current component, and to fix the dc outputs to the desired level.</u>

Fully-Differential Amplifiers: CMFB Principle



- **A common-mode feedback loop must be used: Circuit must operate on the common-mode signals only!**
- **BASIC IDEA: CMFB is a circuit with very small impedance for the common-mode signals but transparent for the differential signals.**
- **Use a common-mode detector (eliminates the effect of differential signals and detect common-mode signals)**

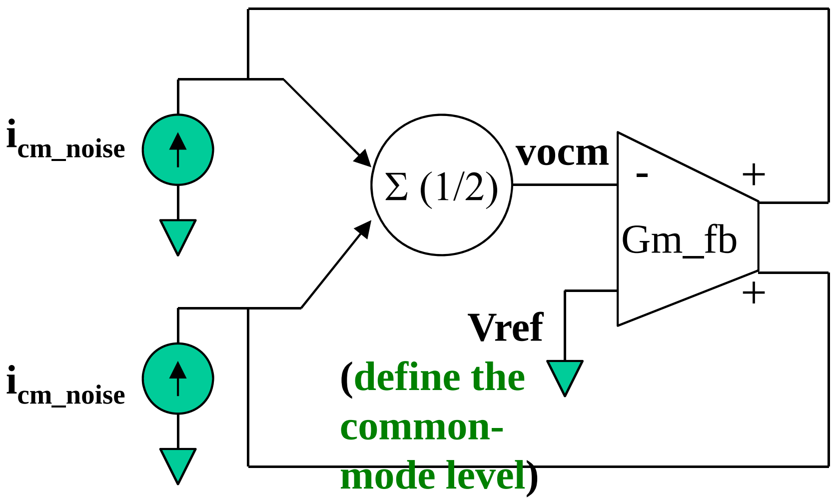
Simplest common-mode detector



$$v_{cm} = \frac{v_{01} + v_{02}}{2}$$

- **Analyze the common-mode feedback loop: Large transconductance gain and enough phase margin**
- **Minimum power consumption**

CMFB Principles: Analysis of the loop for common-mode signals only



➢Analysis for common-mode noise; for instance noise due to power supplies:

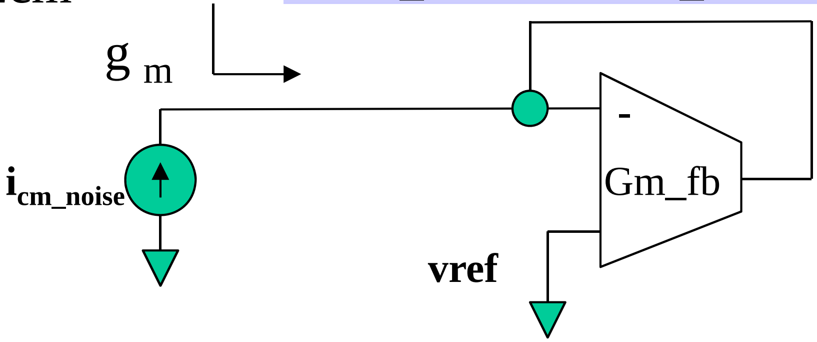
➢io1=io2=icm_noise

➢**The two outputs can be connected together for the analysis of the CMFB loop!**

Effect of common-mode noise:

$$Zcm = \frac{1}{g_m}$$

$$v_{cm\_noise} = i_{cm\_noise}/G_{m\text{-}fb}$$



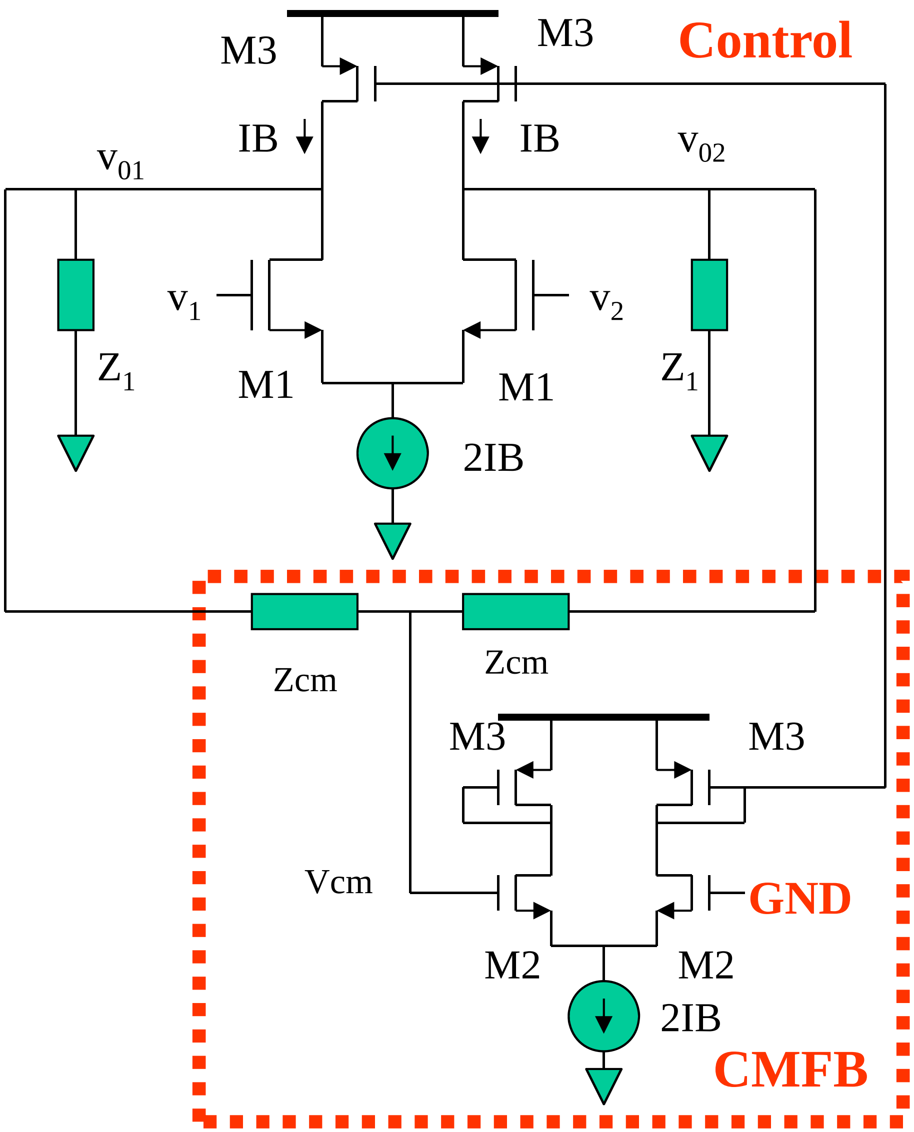
➢**BASIC CONCEPTS:**

➢The common-mode input noise is converted into a common-mode voltage (common-mode voltage noise) by the common-mode transconductance of the CMFB =1/Gm_fb.

➢**common-mode voltage variations $v_{cm\_noise}=i_{cm\_noise}/G_{m\_fb}$!!**

➢**The larger Gm_fb the smaller the effects of the common-mode noise!**

Fully-Differential Amplifiers: CMFB



➢**CMFB Characteristics:**

➢Transconductance gain=$g_{m2}/2$ (no PMOS mirror in CMFB OTA)

➢dominant pole at the output

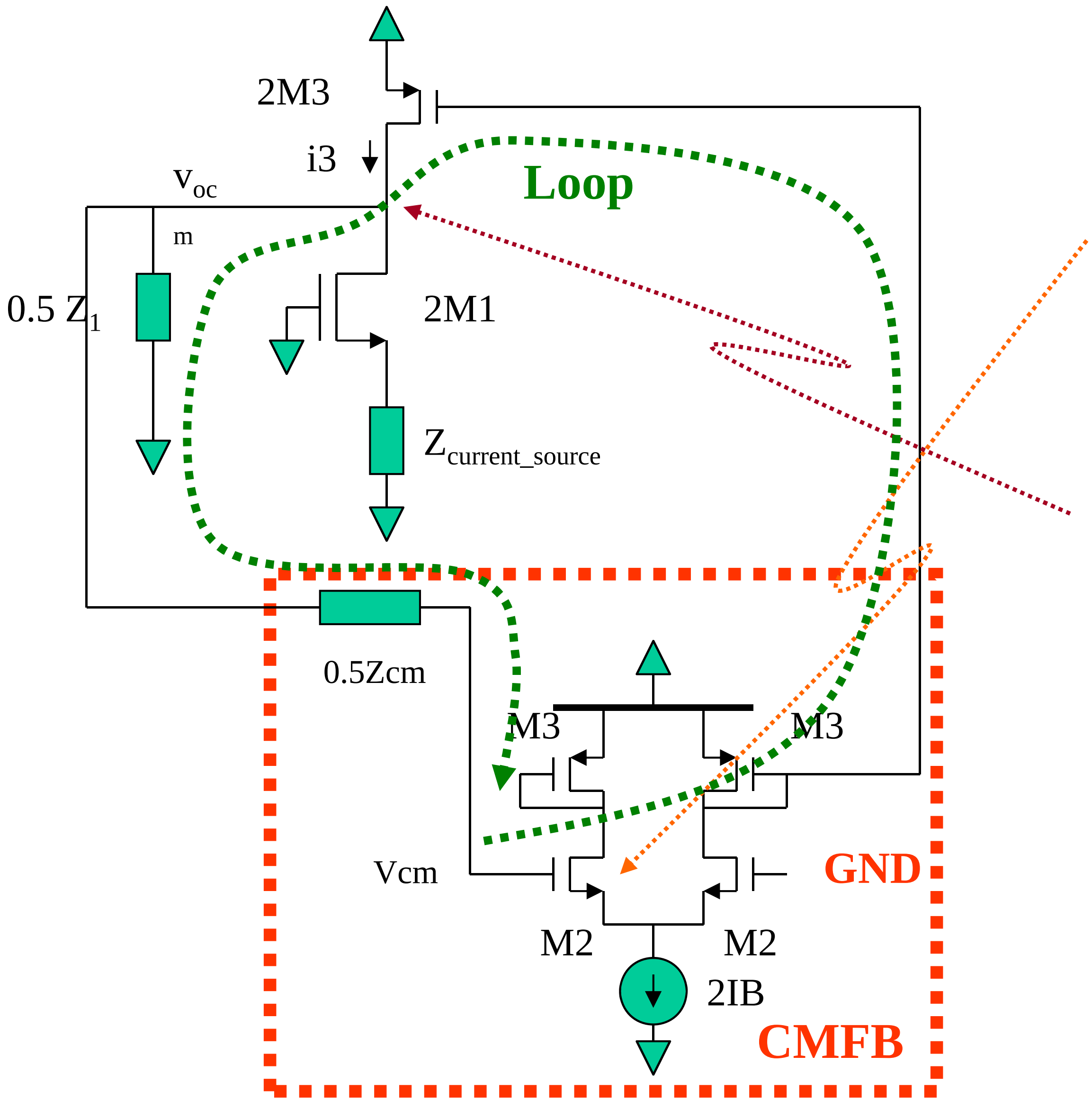
➢3 additional poles in the loop

➢Zcm reduces the OTA dc gain, affecting the differential gain

➢NOTE THAT Vcm IS FORCED TO BE AROUND THE GROUND LEVEL.

➢**DC OFFSET VOLTAGE IS AROUND 2*Ioff/gm2**

Fully-Differential Amplifiers: CMFB



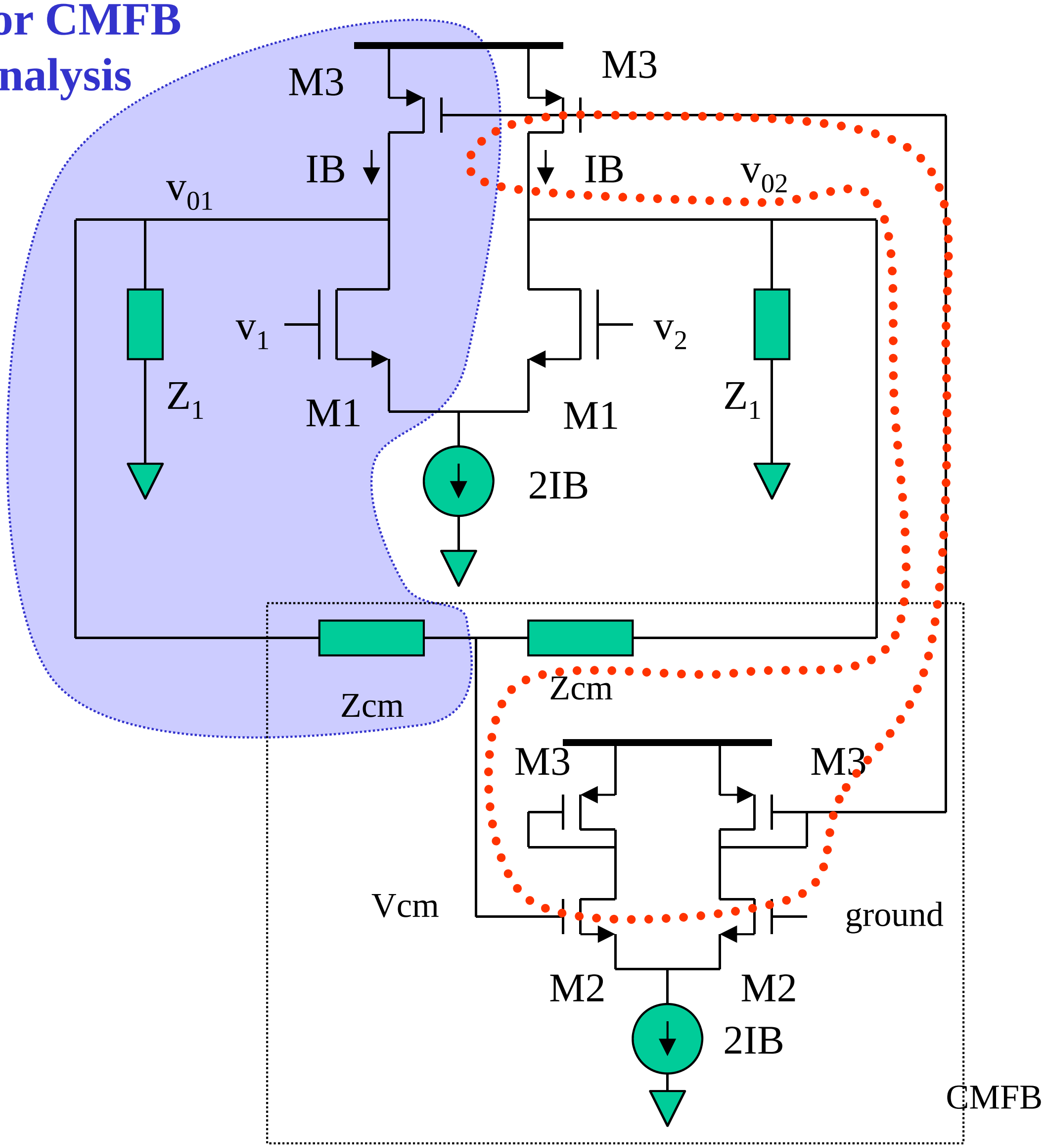
- **CMFB Characteristics:**
- DC Transconductance gain=$g_{m2}/2$
- Loop gain (ignoring poles)

$$\approx \left(\frac{g_{m2}}{2}\right)\left(\frac{1}{g_{m3}}\right)(-2g_{m3})\left(\frac{Z_1}{2}\right) = -\frac{g_{m2}Z_1}{2}$$

- dominant pole at the output
- 3 additional poles in the loop
- **DC OFFSET IS AROUND 2Ioff/gm2**

Fully-Differential Amplifiers: CMFB Principles

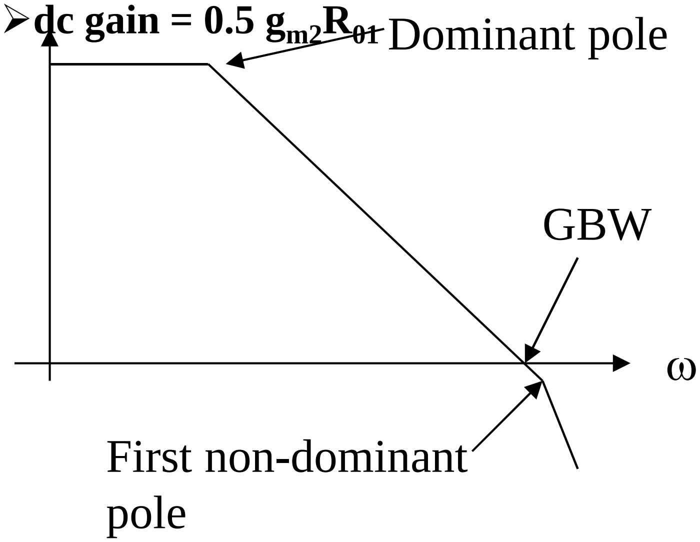
Can be removed for CMFB analysis



- **Common-mode stability: DC gain and most relevant poles**

- 1 pole at vcm (1/RC)
- 1 pole at M2 source ($2g_{m2}/C_2$)
- 1 pole at gate of M3 (g_{m3}/C_{P3})
- 1 pole at the output (g_{01}/C_1)

- **dc gain = 0.5 $g_{m2}R_{01}$**



Be sure phase margin > 45º

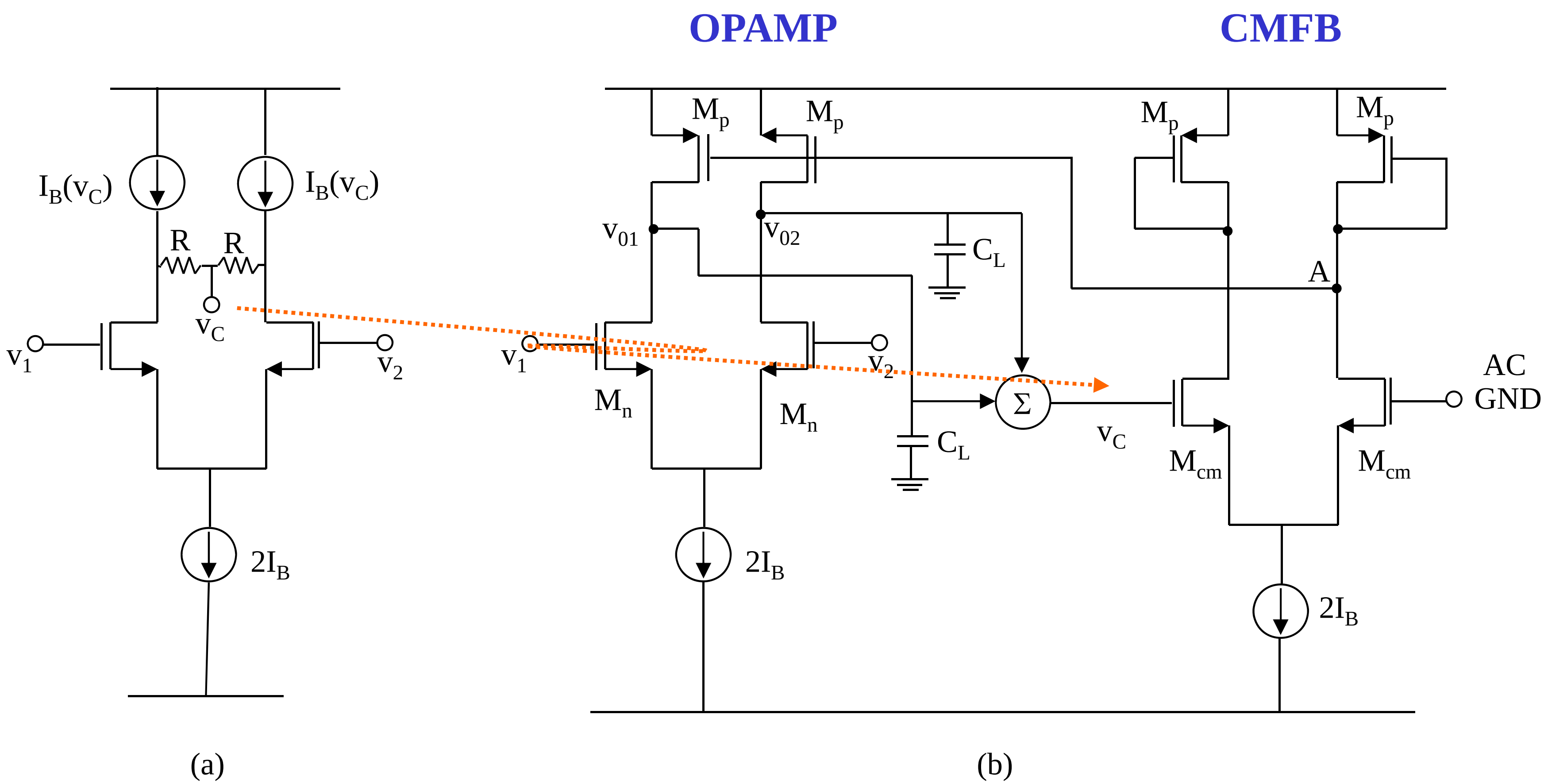
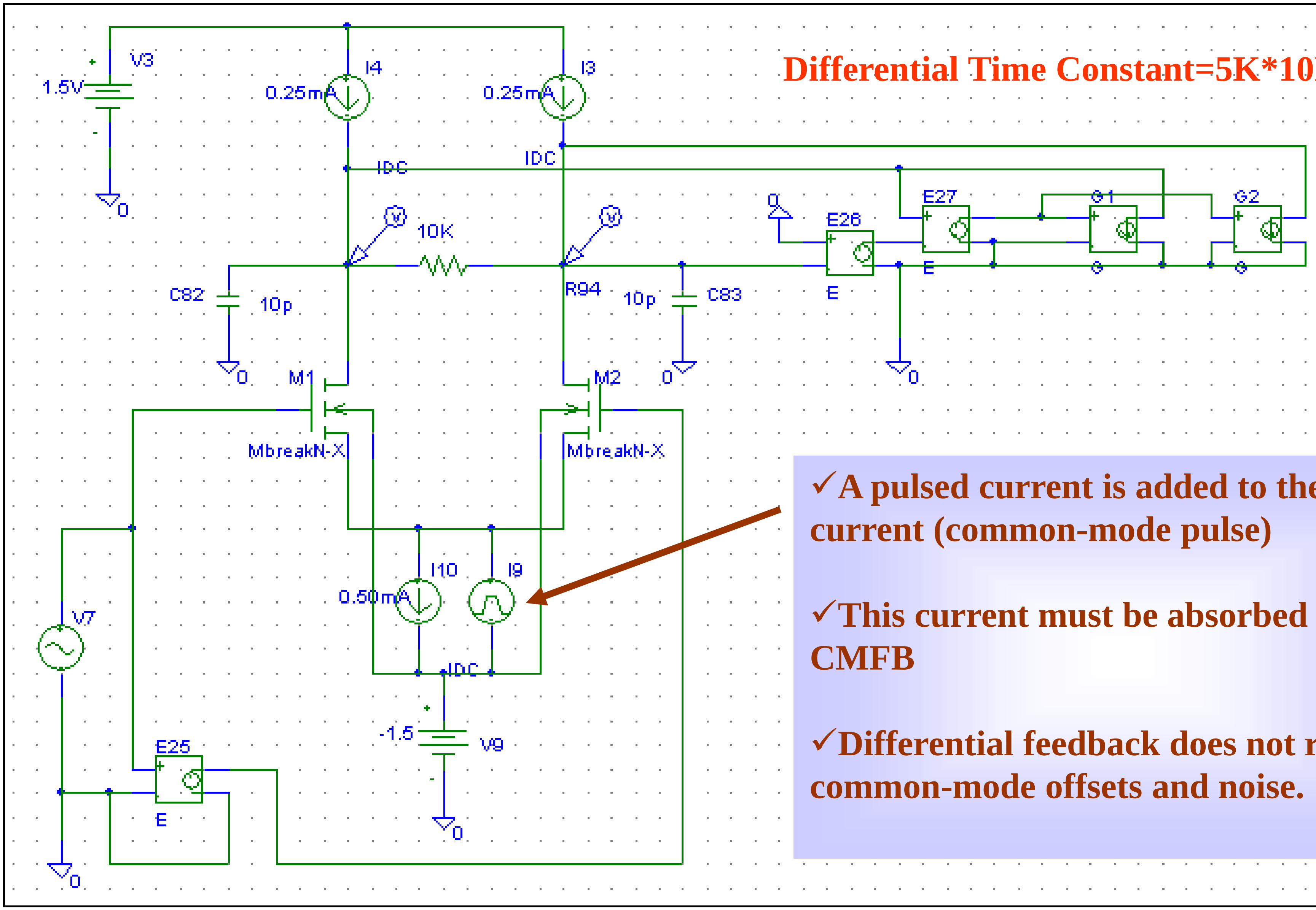


Fig. 3 Common-mode feedback basic circuit concept. (a) Basic common-mode detector, (b) A CMOS CMFB Implementation.

Notice that the resistors R reduce the differential gain!

Fully-Differential Amplifiers: Common-mode pulse



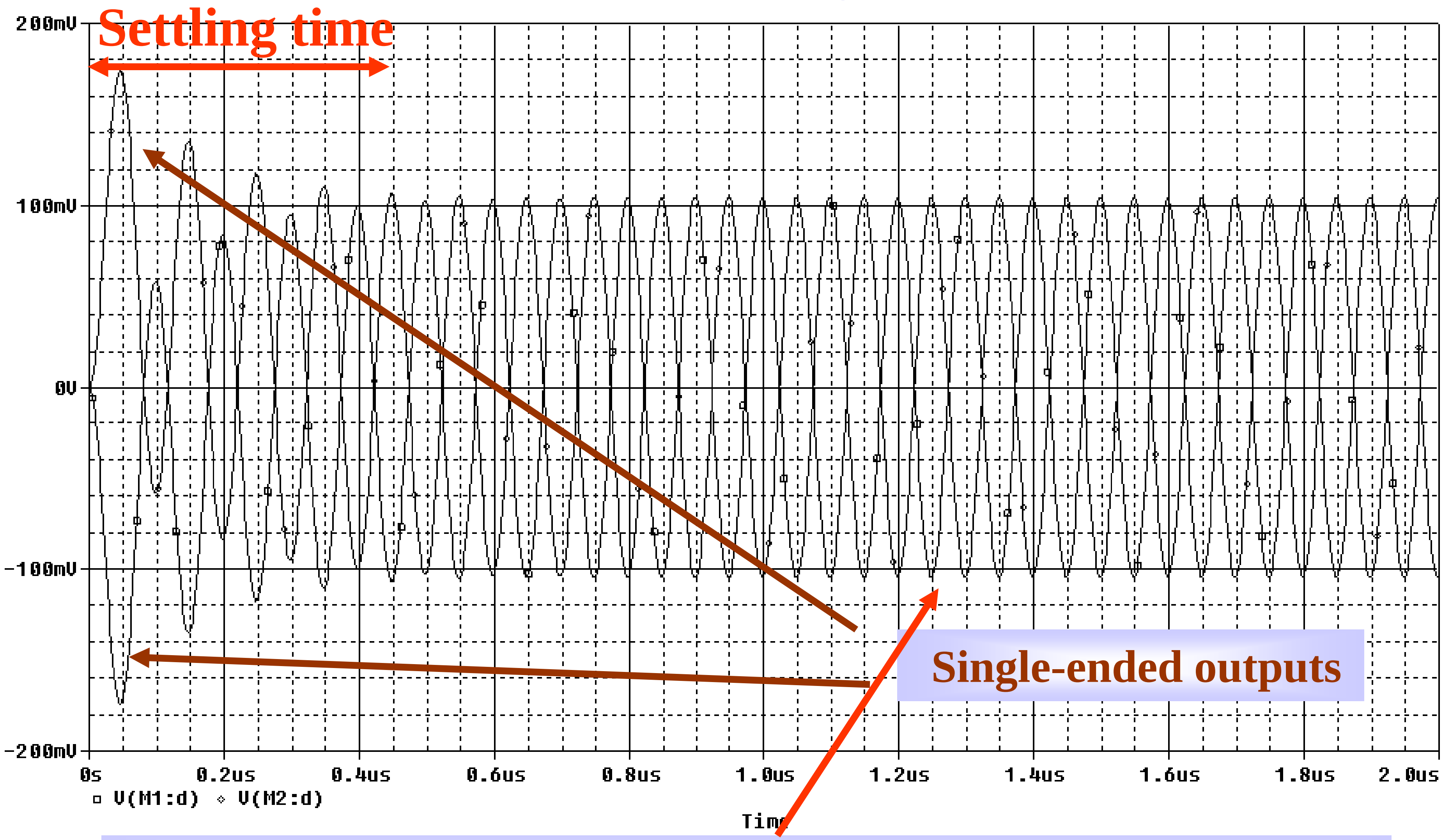
Differential Time Constant=5K*10P=50nsecs

✓**A pulsed current is added to the tail current (common-mode pulse)**

✓**This current must be absorbed by the CMFB**

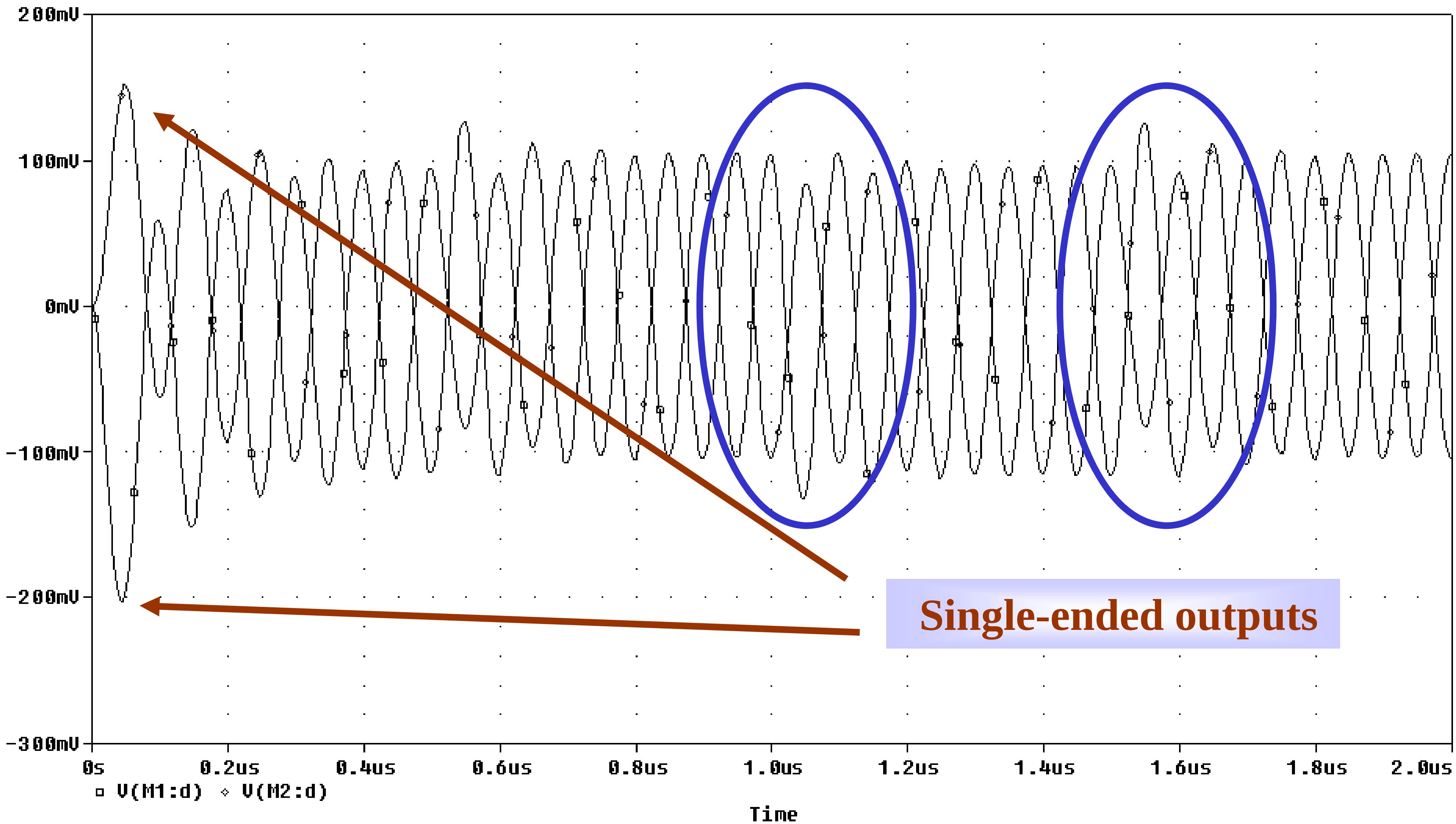
✓**Differential feedback does not reduce common-mode offsets and noise.**

Fully-Differential Amplifiers with CMFB
Differential input signals only



Seems to be that the system is working fine, isn't it?

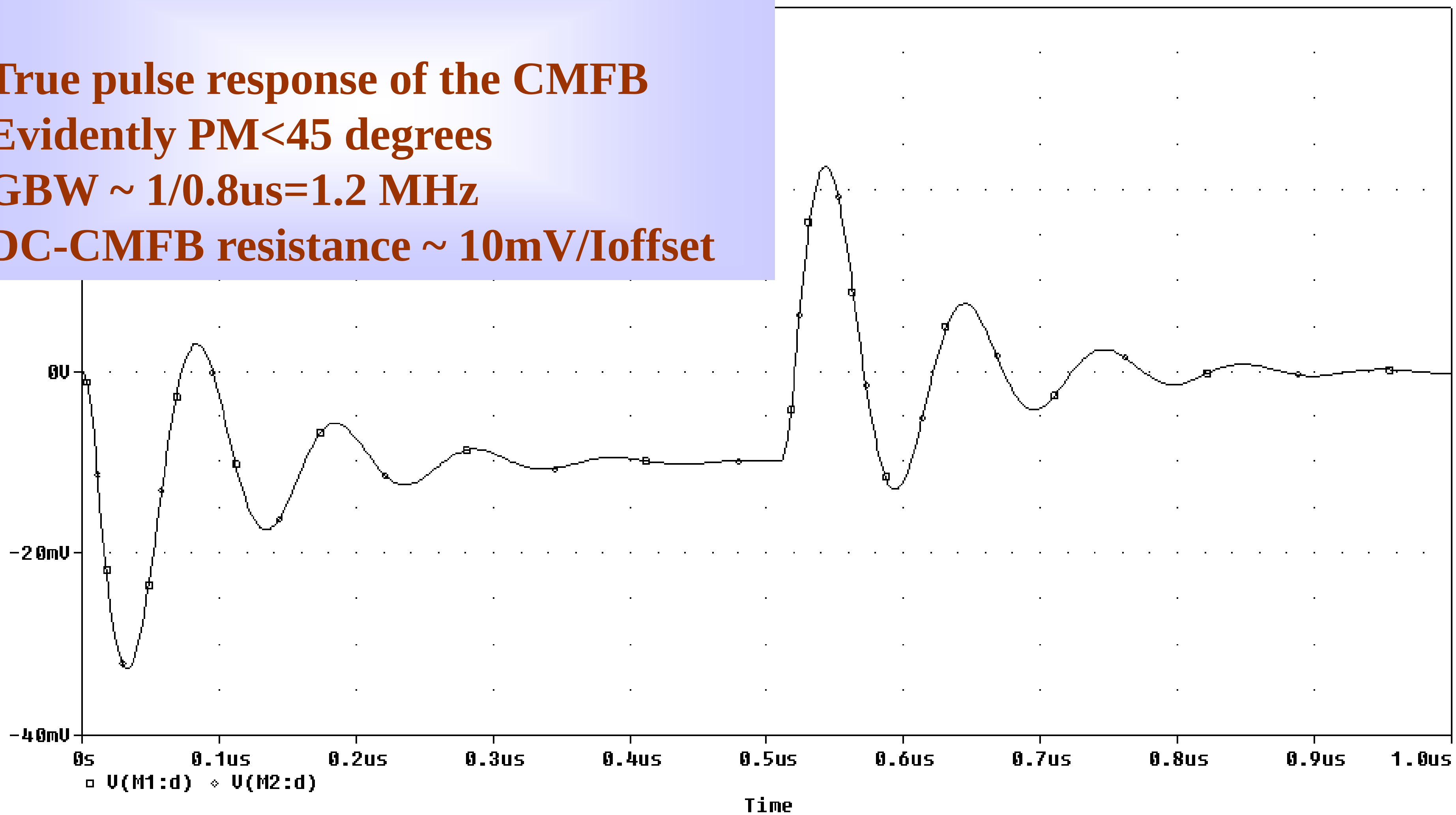
Fully-Differential Amplifiers with CMFB
Differential input signals + common-mode pulses



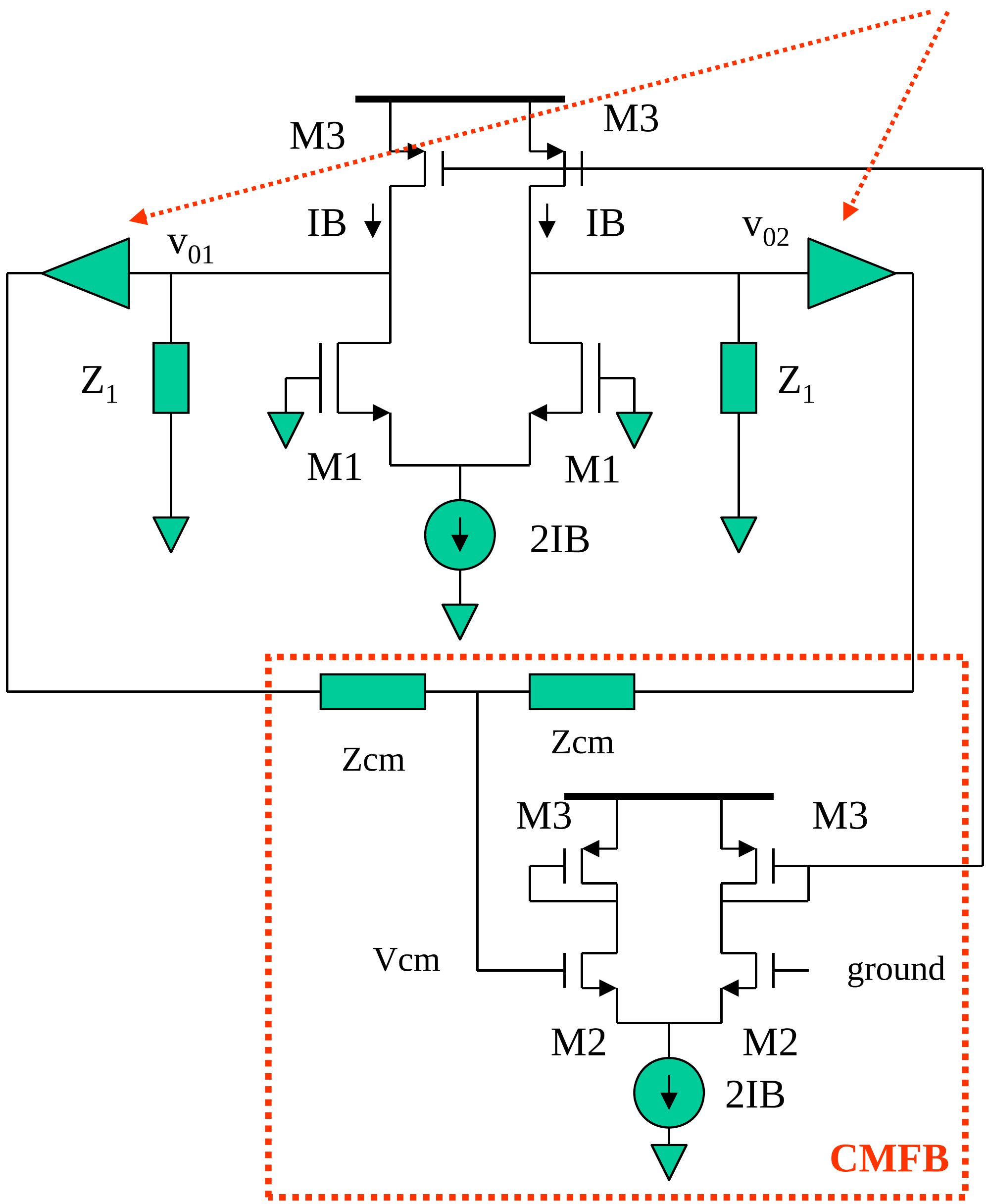
Fully-Differential Amplifiers with CMFB
Differential input signals + common-mode pulses

Common-mode output

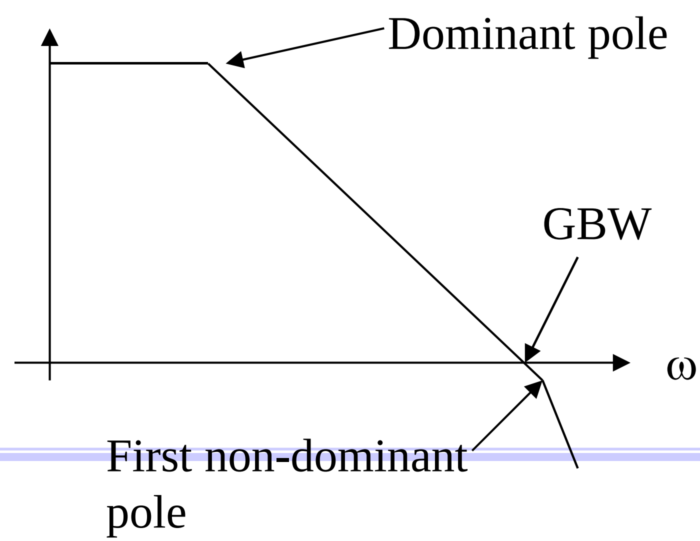
True pulse response of the CMFB
Evidently PM<45 degrees
GBW ~ 1/0.8us=1.2 MHz
DC-CMFB resistance ~ 10mV/Ioffset



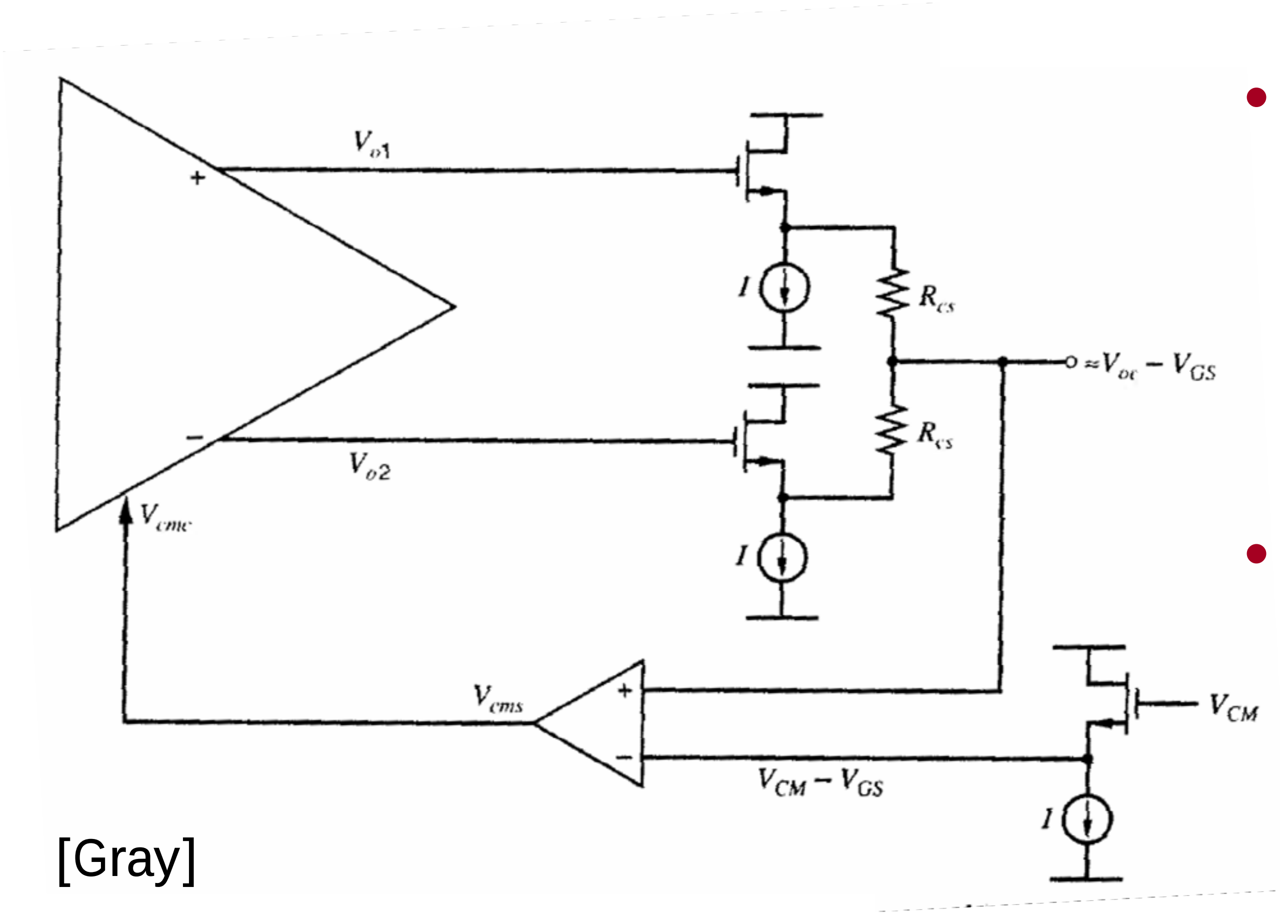
Fully-Differential Filters: Adding buffers to handle the resistive CM-detector



- **The stability conditions are exactly the same for OTA's and OPAMP's:**
- 1 pole at vcm (1/RC)
- 1 pole at M2 source ($2g_{m2}/C_2$)
- 1 pole at gate of M3 (g_{m3}/C_{P3})
- 1 pole at the output (g_{01}/C_1)
- 1 pole at buffer output
- **In OPAMP's you can use resistors as common-mode detector due to the presence of the output buffers**
- dc gain = $0.5g_{m2}R_{01}$



Isolated Common-Mode Sensing



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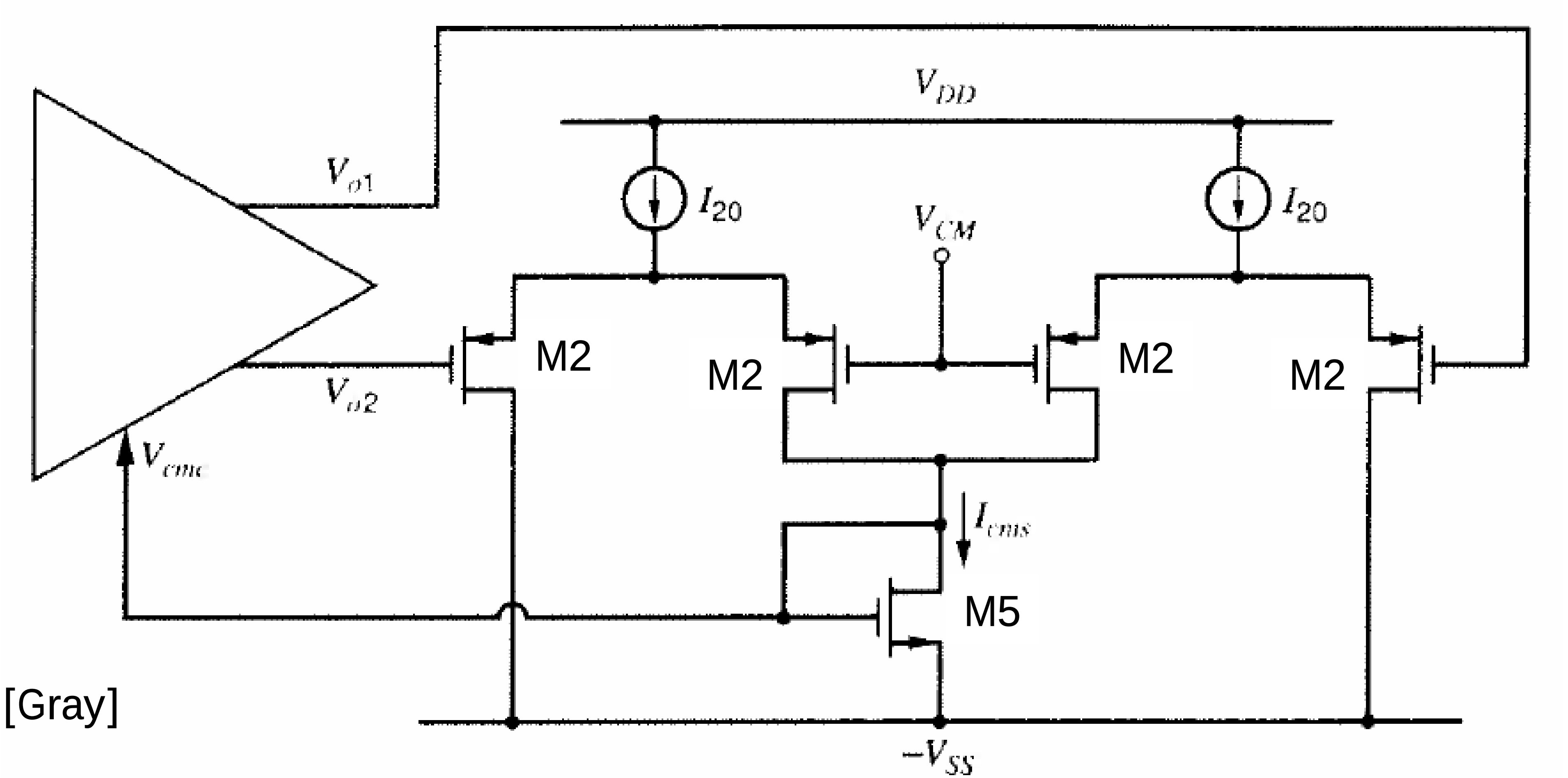
- Source-Followers isolate the loading of the common-mode sensor resistors
- Need to have a replica source follower to set the appropriate reference level for the CMFB amplifier

Two Differential Pair CM Sensor



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$$I_{cms} = I_{CM,DC} + I_{CM,AC} = I_{20} + g_{m2}(V_{oc} - V_{CM})$$

$$G_{cmf} = g_{m2}$$

$$V_{cmc} = V_{CM,DC} + \frac{g_{m2}}{g_{m5}}(V_{oc} - V_{CM})$$

Agenda

- Fully differential circuits
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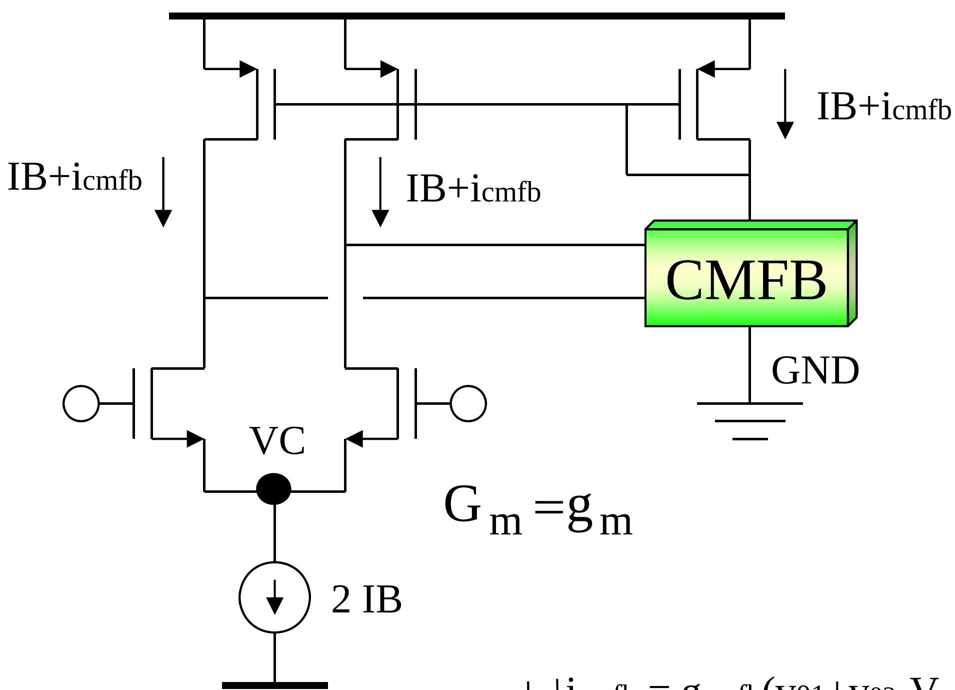
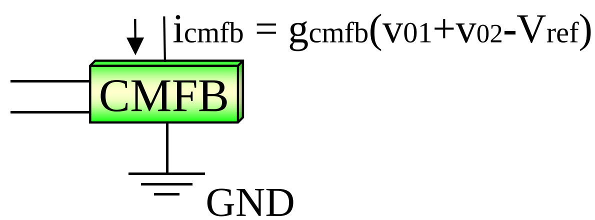
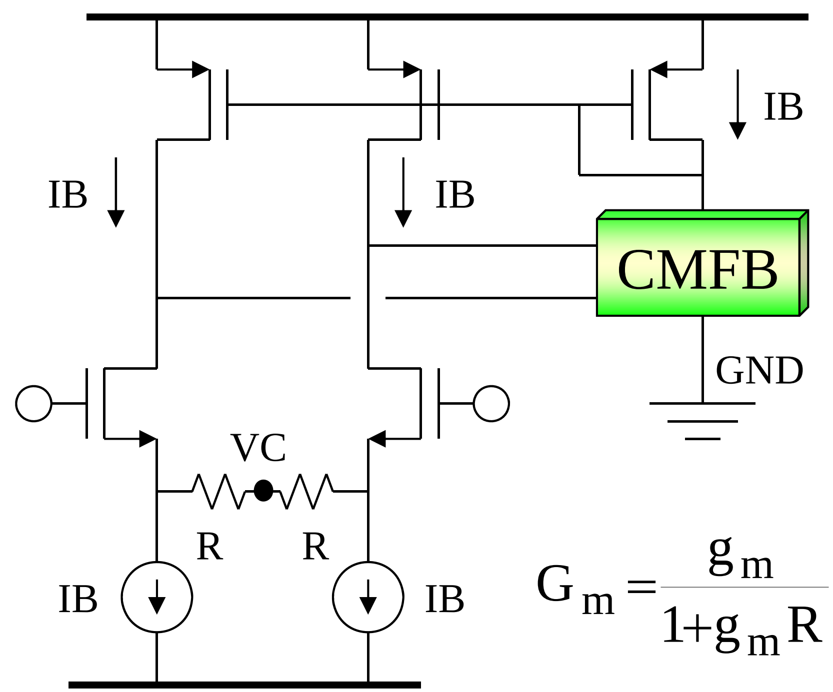
CMFB is required for Differential Structures

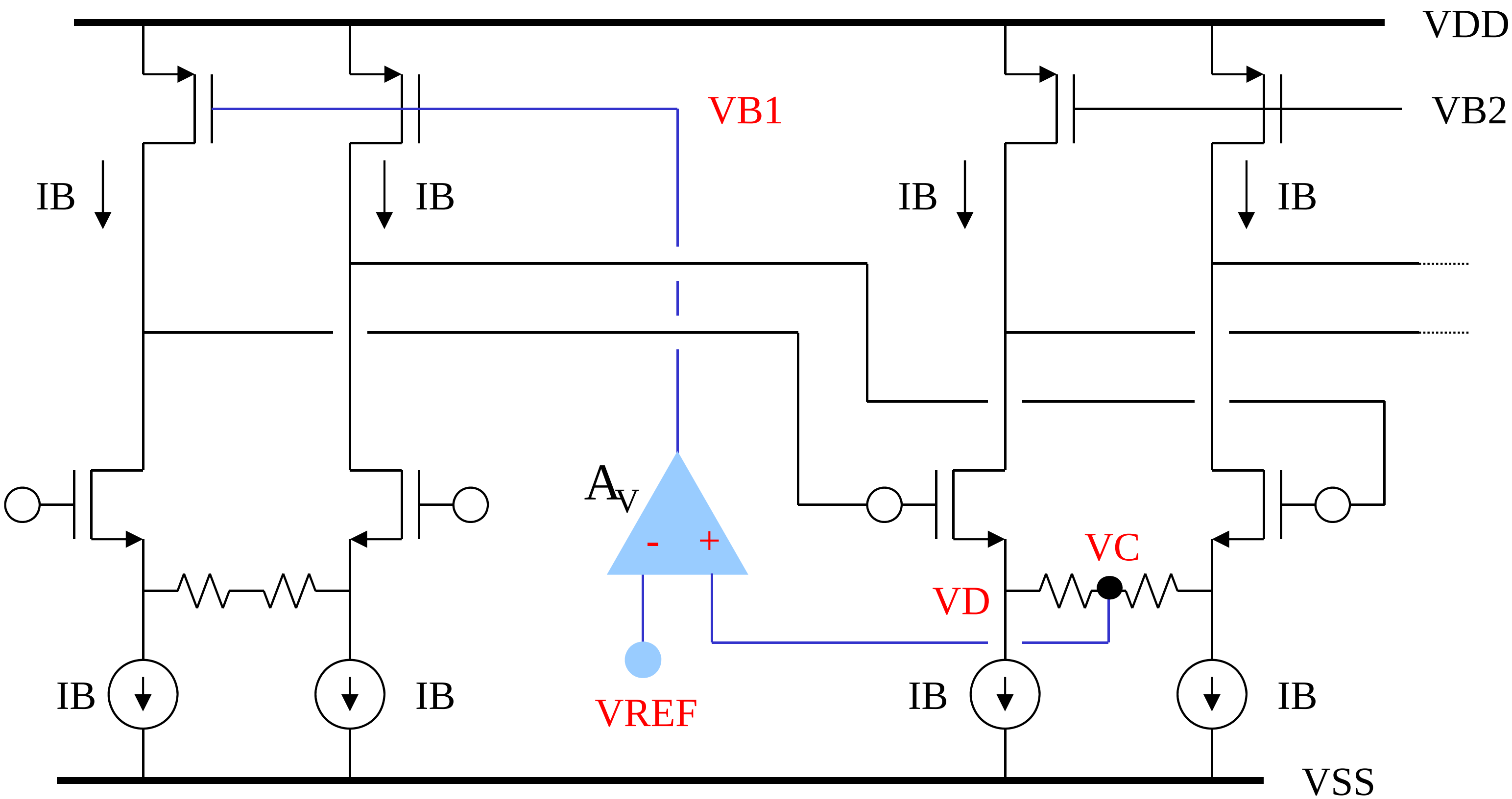
CMFB Requirements: Fixes the OTA output (low offset) ==> High dc loop gain
Reduction of common-mode noise==> Large Bandwidth





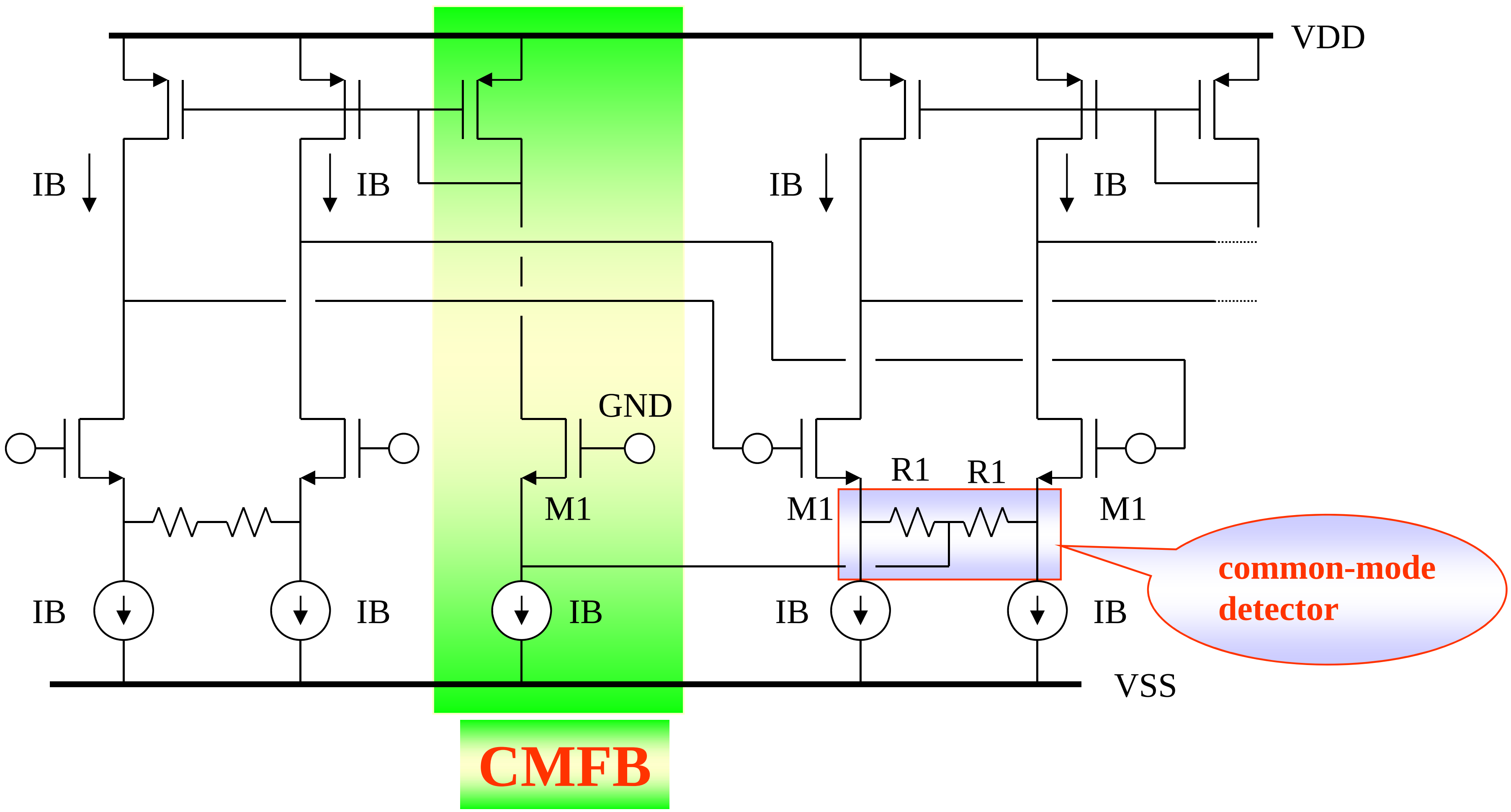


Efficient CMFB for Differential Pair Based OTAs



Common-mode loop gain = $A_V\, Gm_p\, R_L$
4 poles in the CMFB loop. Loop stability requires $A_V\, Gm_p / C_L < \omega_{p2}$ @ VC, ω_{p3} @ VB1, ω_{p4} @ VD

Efficient CMFB for Pseudo-Differential OTAs



Agenda

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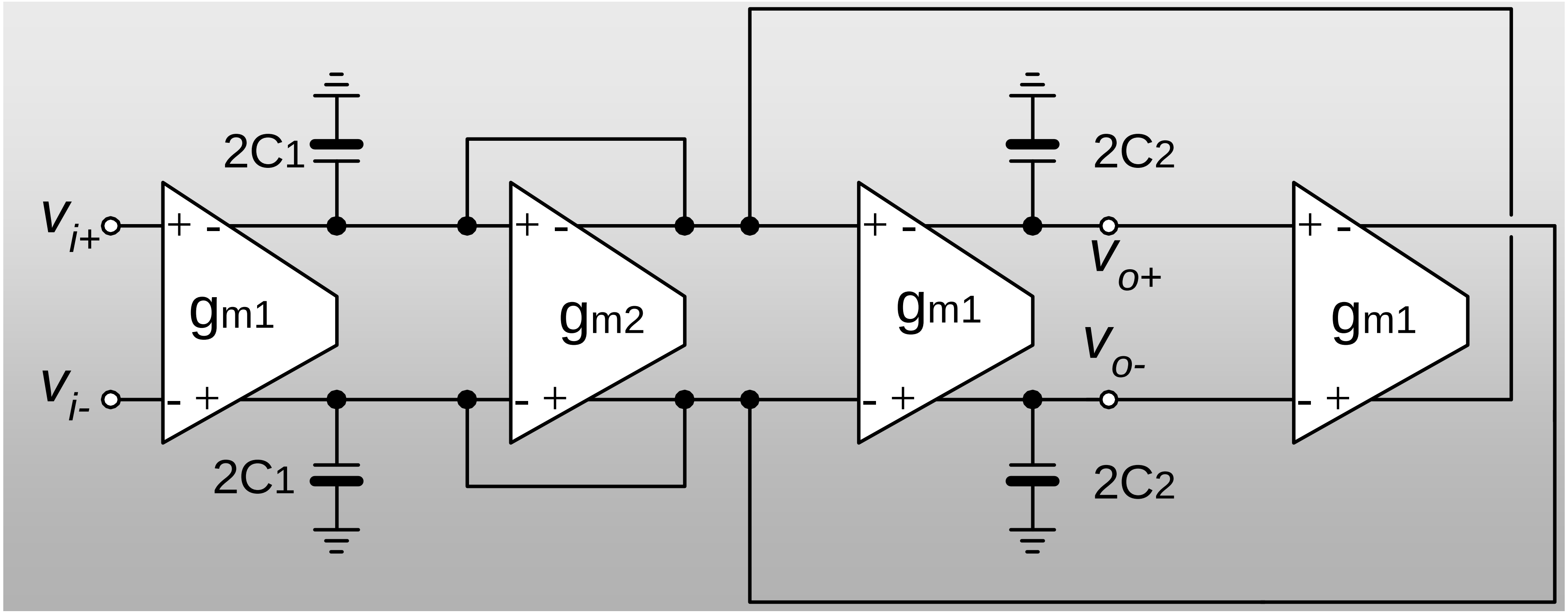
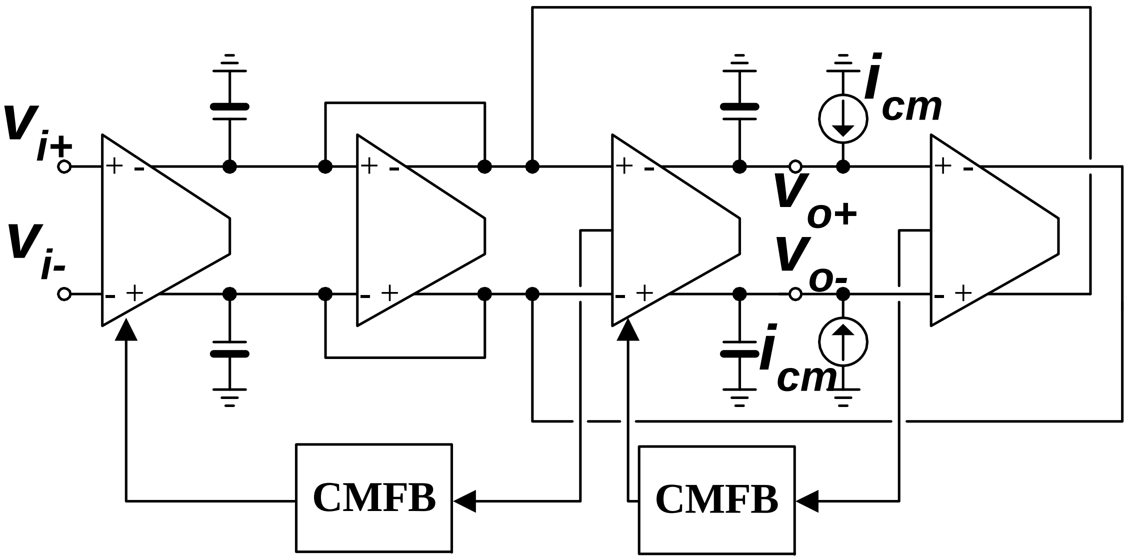
Filter is based on Biquadratic Cells:

Biquad Realization in Gm-C topology

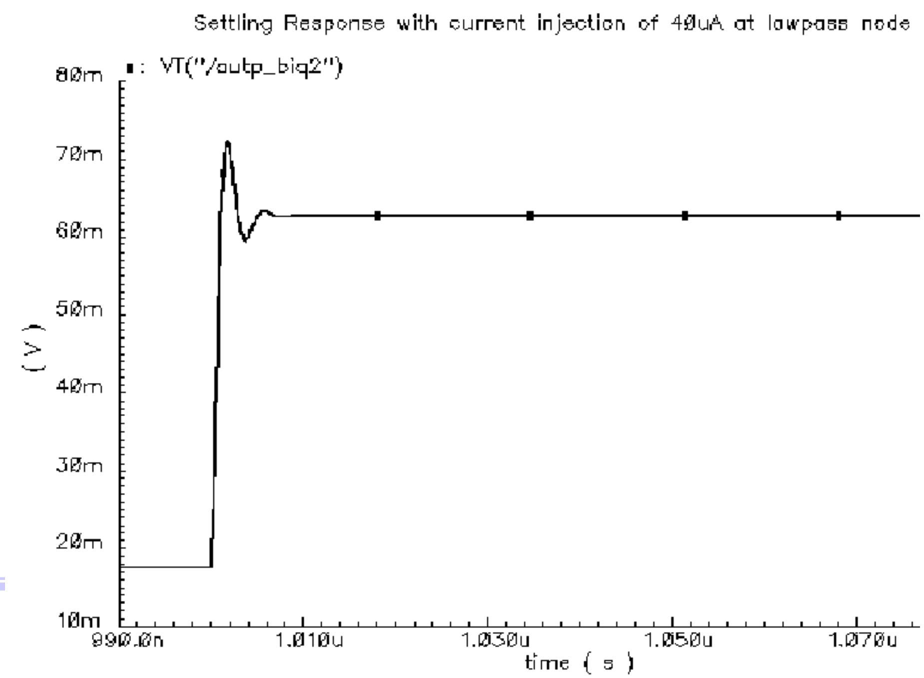


	f_0 (MHz)	G_{m1} (mA/V)	G_{m2} (mA/V)
Biquad 1	537.6	5.4	9.6
Biquad 2	793.2	5.4	5.07

Time Domain characterization of the CMFB

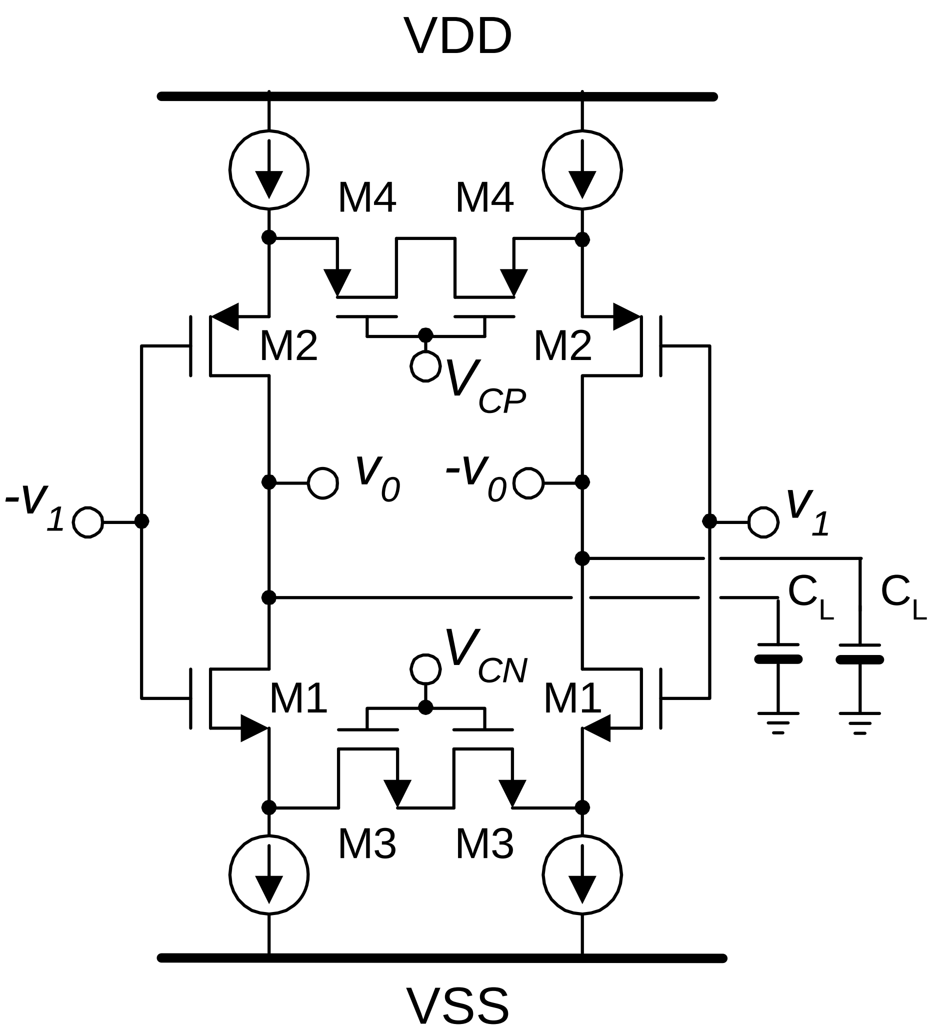


- Common-mode characterization using common-mode current pulses
- One CMFB circuit per pole



- Pulse response of the CMFB
- Phase margin is better than 45 degrees

OTA based on complementary differential pairs



- Efficient OTA based on linear complementary differential pairs

$$G_m = \frac{g_{m1}}{g_{m1}R_{M3}+1} + \frac{g_{m2}}{g_{m2}R_{M2}+1}$$

- Linear circuit due to source degeneration M3 and M4
- Suitable for fast applications

IEEE TRANSACTIONS ON CIRCUITS AND SYSTEMS—I: REGULAR PAPERS, VOL. 53, NO. 4, APRIL 2006 811

A CMOS 140-mW Fourth-Order Continuous-Time Low-Pass Filter Stabilized With a Class AB Common-Mode Feedback Operating at 550 MHz

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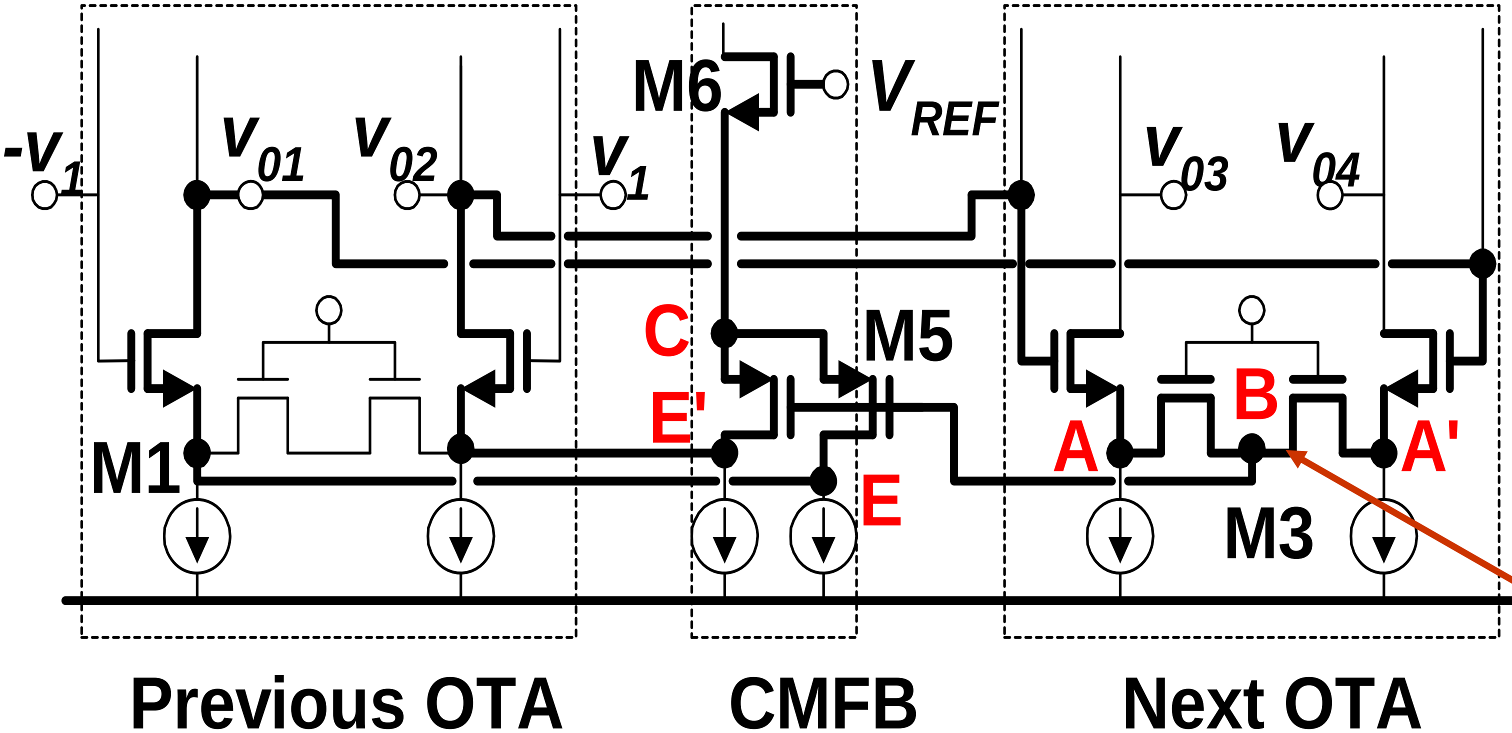
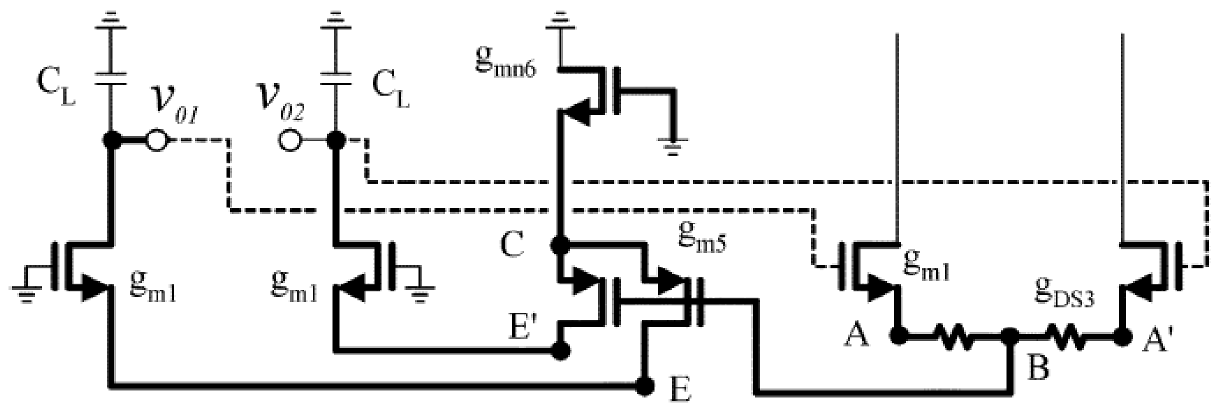
Optimized Class AB Common-mode Feedback



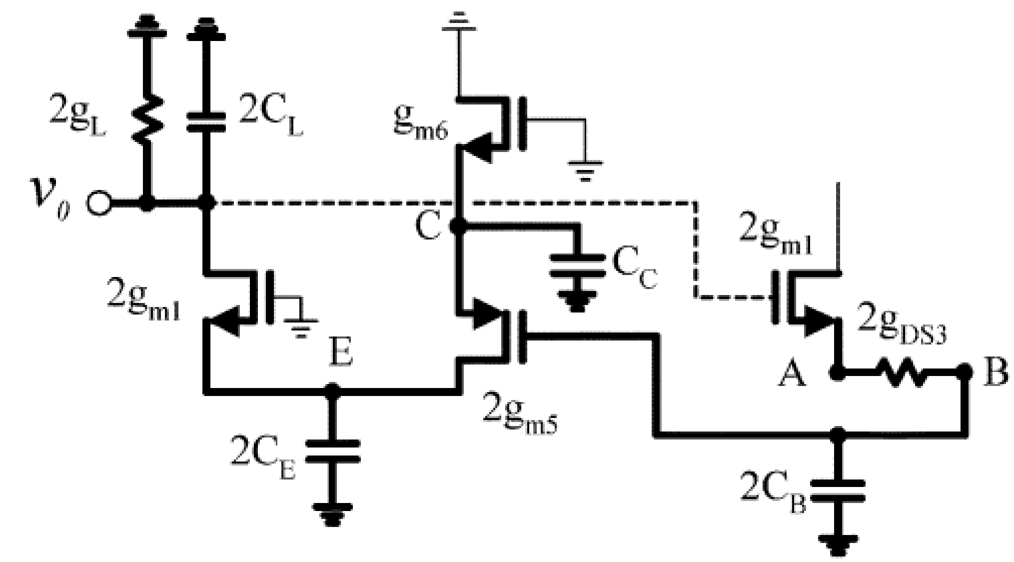
- Most important non-dominant pole at B

- Class AB error amplifier is used
- 4 non-dominant poles at A~E
- 2 LHP zeros at A and C (Helpful in BW extension)

Analysis of Class AB Common-mode Feedback

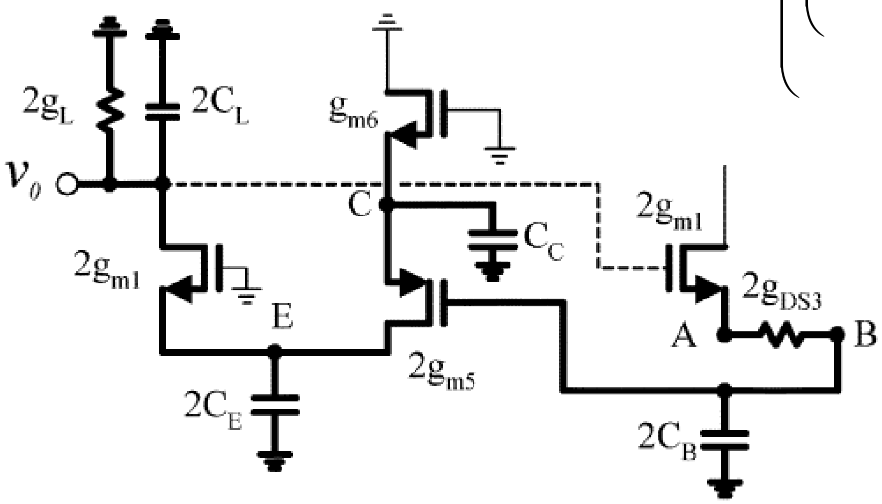


CMFB can be simplified taking advantage of circuit's symmetry



Class AB CMFB Analysis

$$A_{VCMFB} \cong \left(\frac{\dfrac{g_{m5}}{\left(1+\dfrac{2g_{m5}}{g_{m6}}\right)g_L}}{\left(1+\dfrac{sC_L}{g_L}\right)\left(1+\dfrac{sC_B}{g_{03}}\right)\left(1+\dfrac{sC_E}{g_{m1}}\right)} \right) \times \left(\frac{1+\dfrac{sC_{gs1}}{g_{m1}}}{1+\dfrac{sC_A}{g_{m1}}} \right) \left(\frac{1+\dfrac{sC_C}{g_{m6}}}{1+\dfrac{sC_C}{g_{m6}+2g_{m5}}} \right)$$



$$\cong \left(\frac{\dfrac{g_{m5}}{\left(1+\dfrac{2g_{m5}}{g_{m6}}\right)g_L}}{\left(1+\dfrac{sC_L}{g_L}\right)\left(1+\dfrac{sC_B}{g_{03}}\right)\left(1+\dfrac{sC_E}{g_{m1}}\right)} \right)$$

- 2 pole-zero pairs (A and C) are very close to each other
- Allows for stable CMFB

Remarks

- **DC operating points for high impedances are difficult to fix**

- **Fully differential amplifiers with high output impedance nodes must use common-mode feedback circuits .**

- **Common mode circuits can fix the DC operating points as well as minimize the common mode output components.**

- **Low voltage constraints impose optimal bias conditions at both the input and output ports of an amplifier.**

- **Common mode circuits for LV should be used both at the input and output**

Next Time

- Output Stages