ECEN474: (Analog) VLSI Circuit Design
Fall 2011

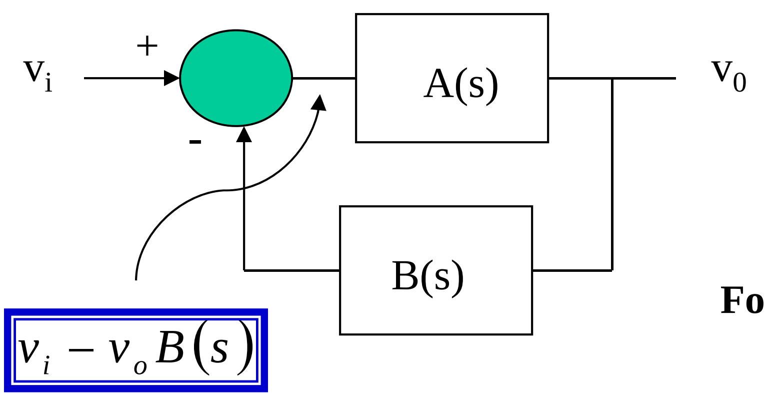
Lecture 19: Fully Differential Amplifiers & CMFB

Sebastian Hoyos
Analog & Mixed-Signal Center
Texas A&M University

Agenda

- Feedback amplifier examples
- Fully differential circuits
- Common-mode feedback introduction

Non-Inverting Amplifier Example



$$\boxed{v_i - v_o B(s)}$$

$$\frac{v_o}{v_i} = \frac{A(s)}{1-(-T(s))}$$

If $T(s) >> 1$, **then** $\frac{v_o}{v_i} \cong \frac{A(s)}{T(s)} = \frac{1}{B(s)}$

For Error, can write : $\frac{v_o}{v_i} = \frac{1}{B(s)}\left[\frac{T(s)}{1+T(s)}\right] = \frac{1}{B(s)}\left[\frac{1}{1+\frac{1}{T(s)}}\right]$

Error $\propto -\frac{1}{T(s)}$

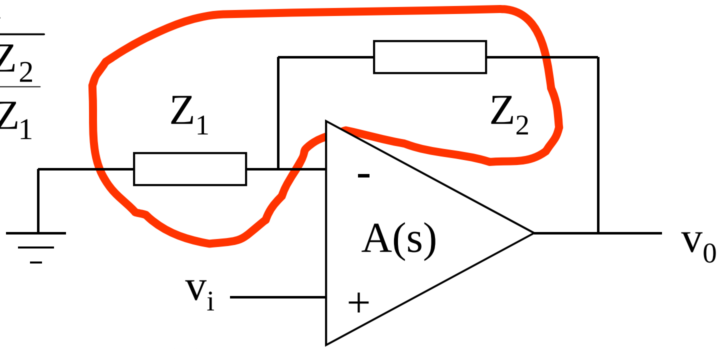
Key points:

If you want to amplify your signal: B(s) must be an attenuator (voltage divider!!)

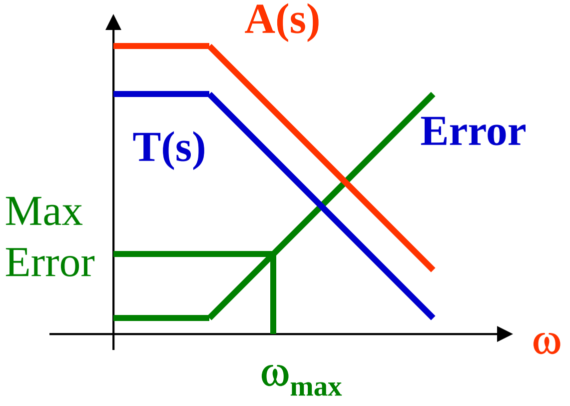
The error is determined by the overall loop gain: T(s)=A(s)B(s)

$$B(s) = \frac{Z_1}{Z_1+Z_2} = \frac{1}{1+\frac{Z_2}{Z_1}}$$

$$\boxed{\frac{v_o(s)}{v_i(s)} \cong 1+\frac{Z_2}{Z_1}}$$



$A(s)$ **is amplifier response only**

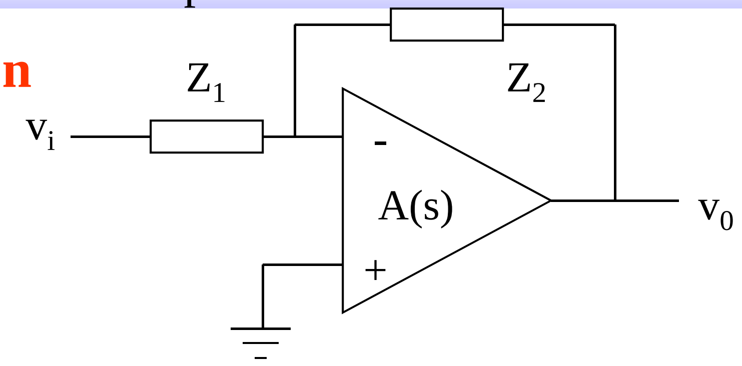


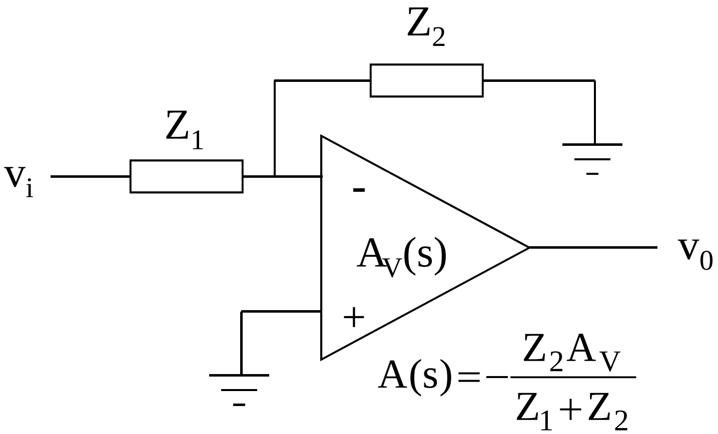
Inverting Amplifier Example

Inverting Amplifier: Apply superposition

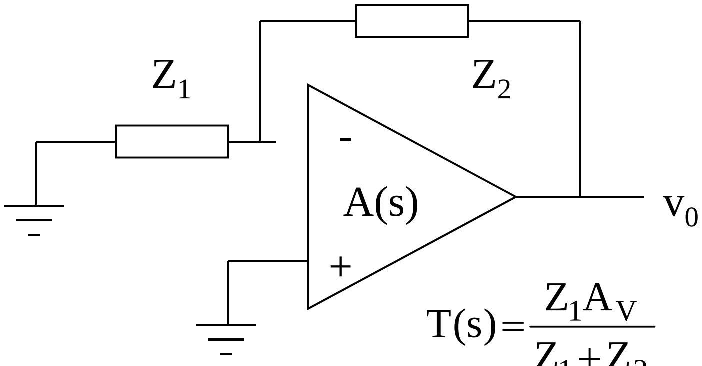
A(s) and B(s) are sharing some elements!!

A(s)= ? B(s) = ? T(s) = ?





$$A(s) = -\frac{Z_2 A_V}{Z_1 + Z_2}$$



$$T(s) = \frac{Z_1 A_V}{Z_1 + Z_2}$$

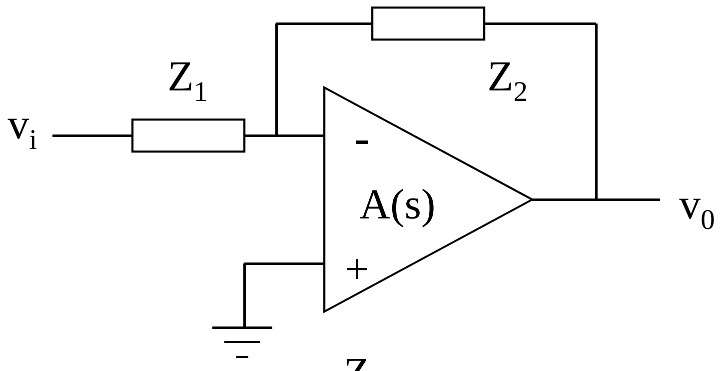
From $T(s) = A(s)B(s)$

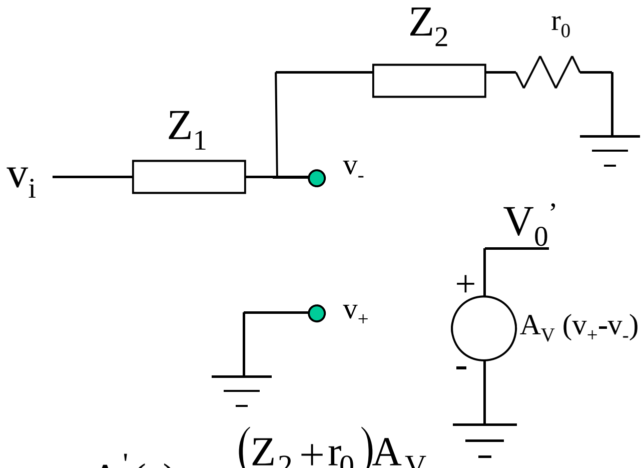
$$B(s) = \frac{T(s)}{A(s)} = -\frac{Z_1}{Z_2}$$

$$\boxed{\frac{v_o(s)}{v_i(s)} \cong \frac{1}{B(s)} = -\frac{Z_2}{Z_1}}$$

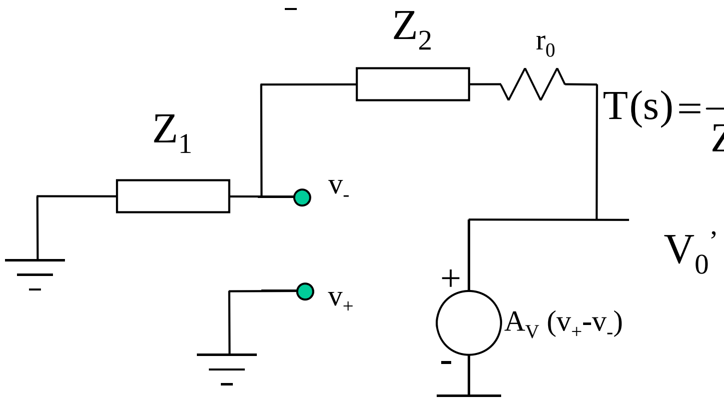
$$\frac{v_0}{v_i} = \frac{A(s)}{1+T(s)} = -\frac{\dfrac{Z_2 A_V}{Z_1 + Z_2}}{1 + \dfrac{Z_1 A_V}{Z_1 + Z_2}} = -\frac{Z_2}{Z_1}\left(\frac{1}{1 + \dfrac{1 + \dfrac{Z_2}{Z_1}}{A_V}}\right)$$

Inverting Amplifier: consider the non-zero output impedance!!





$$A'(s) = -\frac{(Z_2+r_0)A_V}{Z_1+Z_2+r_0}$$



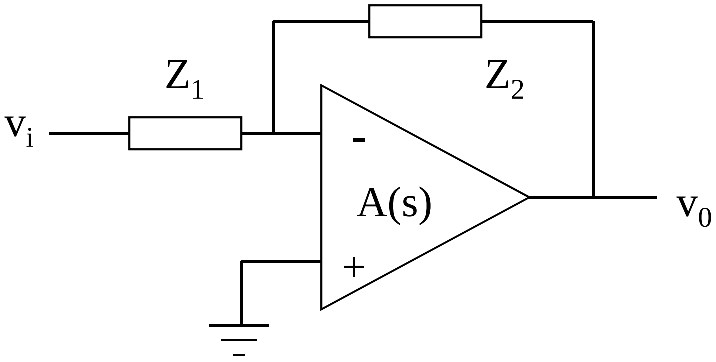
$$T(s) = \frac{Z_1 A_V}{Z_1+Z_2+r_0}$$

$$\frac{v_0'}{v_i}(s) = -\frac{\dfrac{(Z_2+r_0)A_V}{Z_1+Z_2+r_0}}{1+\dfrac{Z_1 A_V}{Z_1+Z_2+r_0}}$$

$$\boxed{\frac{v_o}{v_i}(s) = \left(\frac{v_o}{v_i}'\right)\frac{Z_1+Z_2}{Z_1+Z_2+r_0} = -\frac{Z_2}{Z_1}\left[\frac{1-\dfrac{r_0}{A_V Z_2}}{1+\dfrac{1+\dfrac{Z_2+r_0}{Z_1}}{A_V}}\right]}$$

Inverting Amplifier: consider the non-zero output impedance!!

$$\boxed{\frac{v_o}{v_i}(s) = -\frac{Z_2}{Z_1}\left[\frac{1-\dfrac{r_0}{A_V Z_2}}{1+\dfrac{1+\dfrac{Z_2+r_0}{Z_1}}{A_V}}\right]}$$



IDEAL GAIN

The error can be approximated as:

$$\text{Error} \cong -\frac{r_0}{A_V Z_2} - \frac{1+\dfrac{Z_2+r_0}{Z_1}}{A_V}$$

Determined by the OPAMP open-loop gain

Determined by the OPAMP output impedance

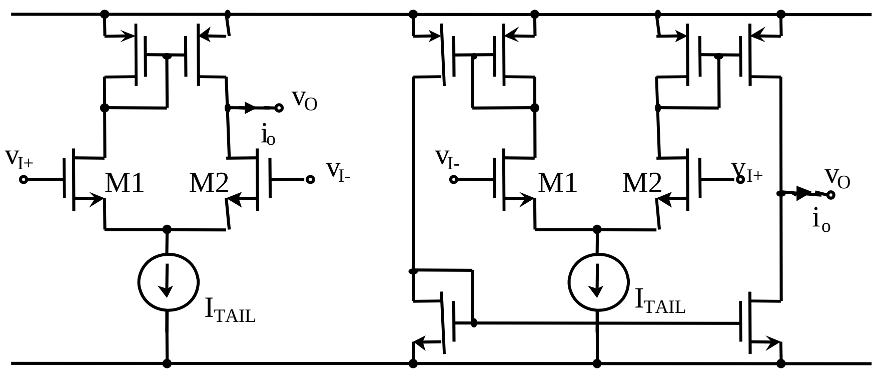
Common-Mode Feedback Techniques for Analog Circuits

Jose Silva-Martinez

Texas A&M University

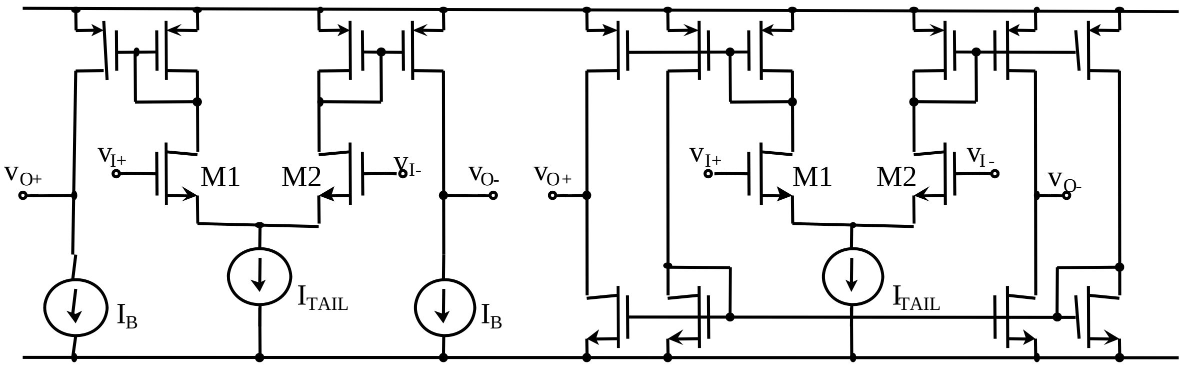
Department of Electrical and Computer Engineering

Basic Operational Transconductance Amplifier Topologies



(a) (b)

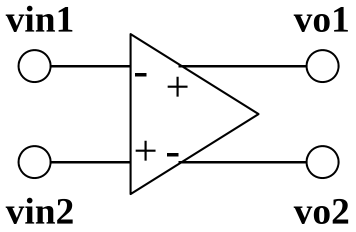
SINGLE-ENDED



(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

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

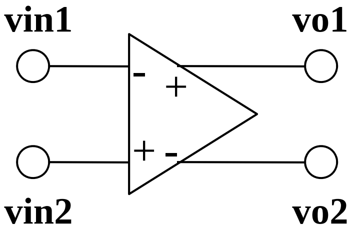
Differential-mode output

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

Common-mode output

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

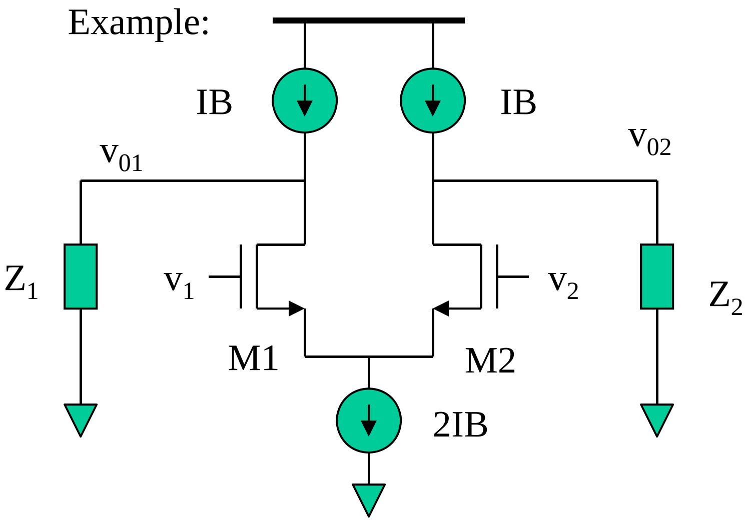
Fully-Differential Filters: Effects of current source inpedance and mismatches



A very important parameter:

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

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



Solving the circuit:

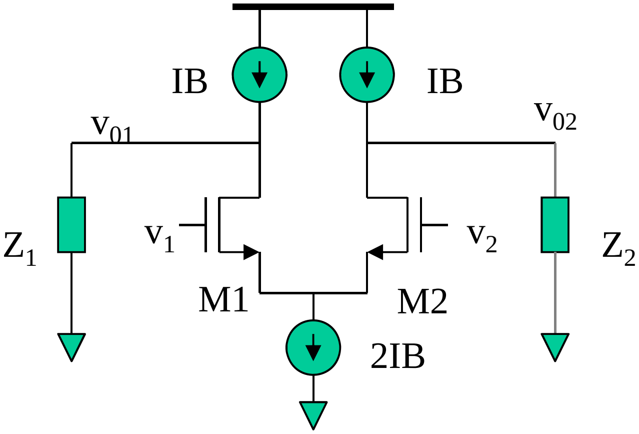
$$v_{01} = \frac{g_{m1} g_{m2} Z_1}{g_{m1} + g_{m2} + Y_s}\left[\left(1 + \frac{Y_s}{2 g_{m2}}\right) v_{id} - \left(\frac{Y_s}{g_{m2}}\right) v_{ic}\right]$$

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

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}



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

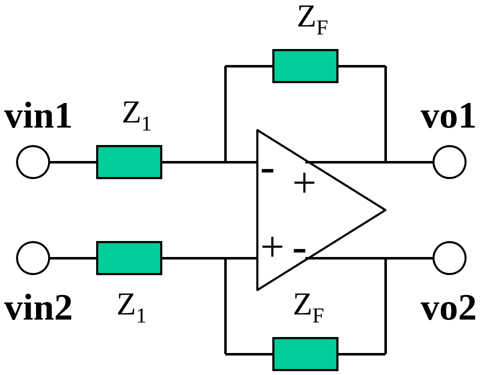
$$A_{dc}=\left.\frac{v_{o1}-v_{o2}}{(v_{i2}+v_{i1})/2}\right|_{v_{id}=0}=\frac{g_{m1}g_{m2}}{g_{m1}+g_{m2}+Y_s}\left[Y_s\left(\frac{Z_2}{g_{m1}}-\frac{Z_1}{g_{m2}}\right)\right]$$

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

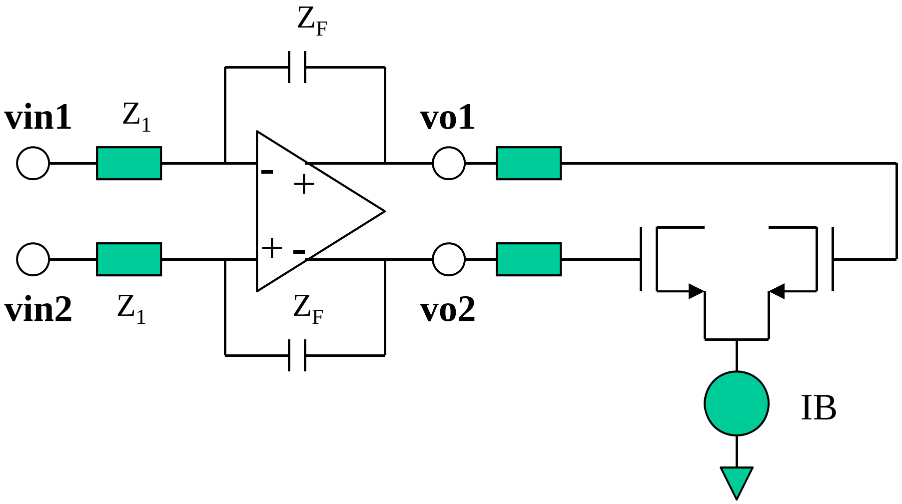
$$CMRR=\frac{A_{dd}}{A_{dc}}\cong\frac{g_{m1}\left(1+\frac{Z_1}{Z_2}\right)}{Y_s\left(1-\frac{g_{m1}Z_1}{g_{m2}Z_2}\right)}$$

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

Fully-Differential Circuits



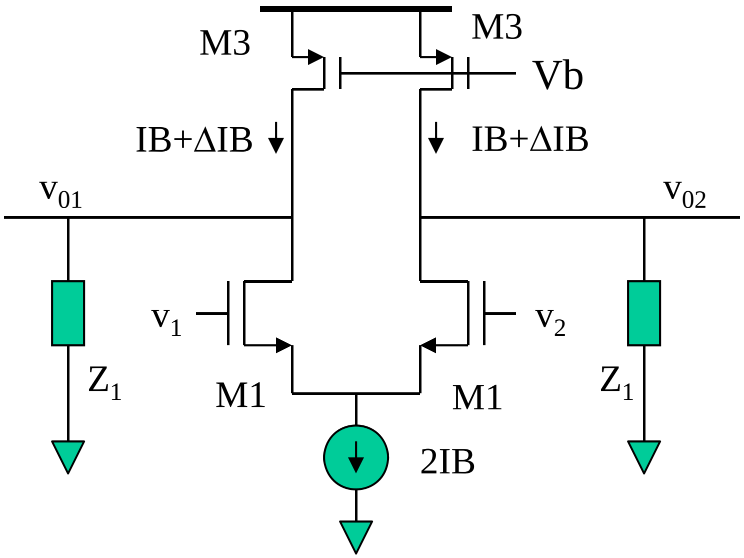
- ➢**Ideal voltage gain** $$A_{dd} = \frac{v_{01} - v_{02}}{v_{in2} - v_{in1}} = \frac{Z_f}{Z_1}$$
- ➢**Ideally even-order distortions are cancelled**
- ➢**Ideally common-mode signals are rejected**
- ➢**What sets the output common-mode of these circuits?**
  - ➢**Function of the amplifier output resistance**



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

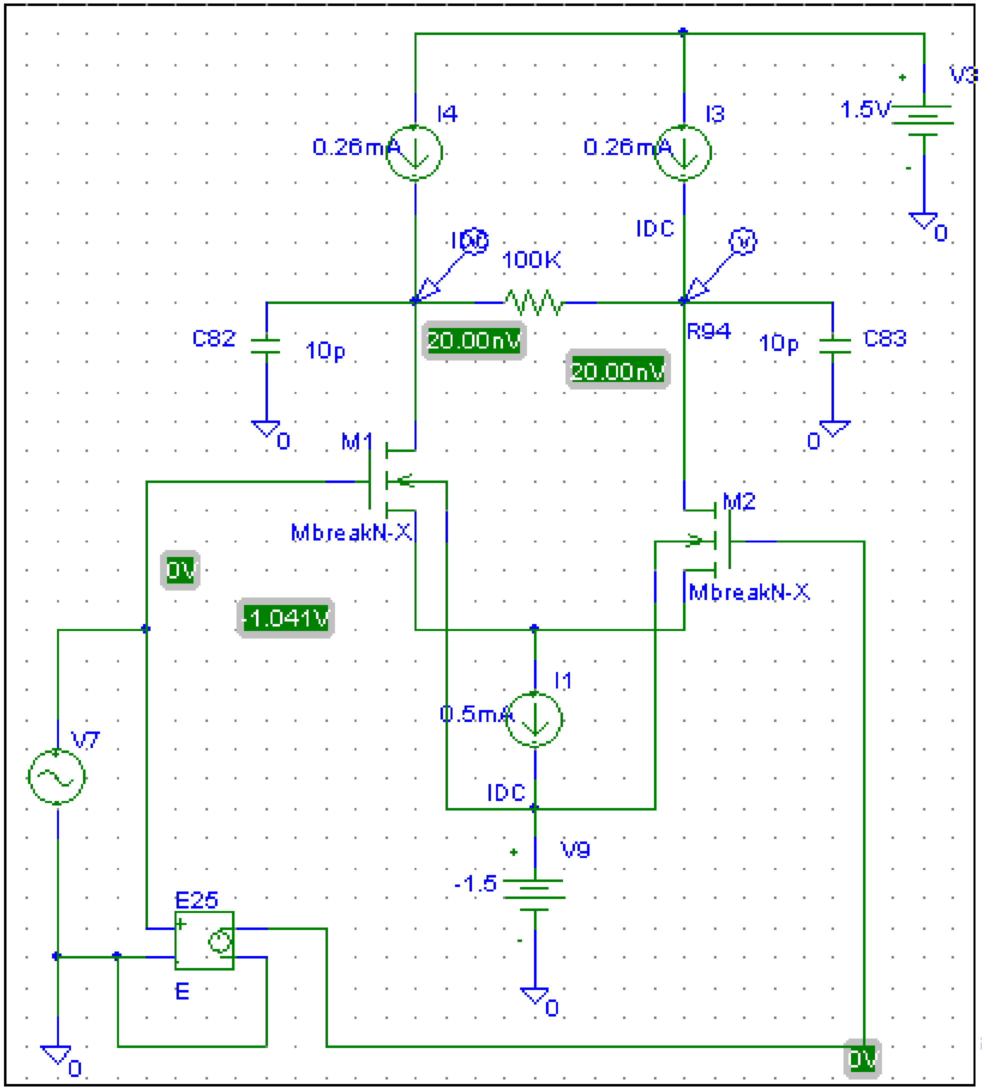
✓THD increases

✓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 this issue can be fixed?

Fully-Differential Amplifiers: Characterization

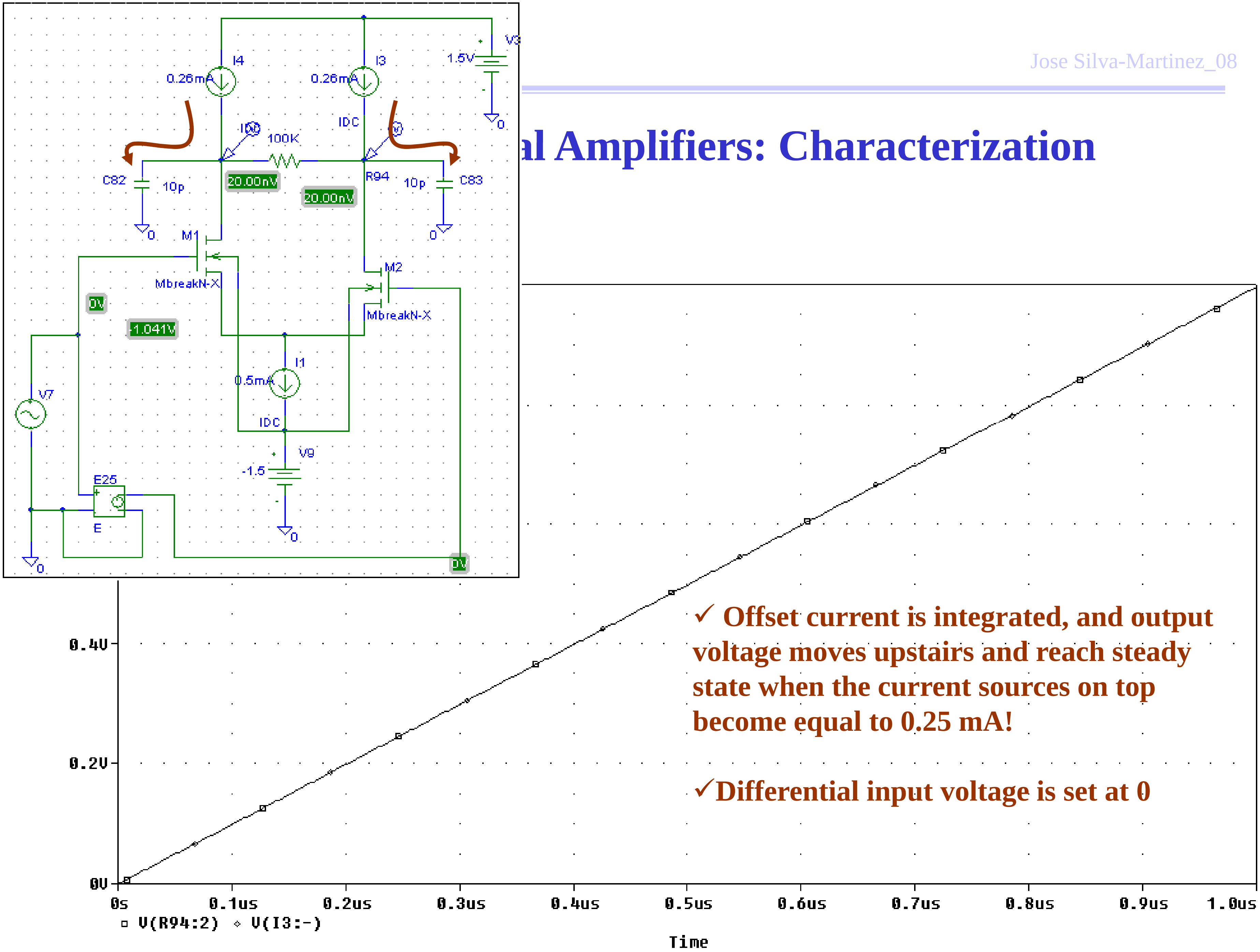


✓**Common-mode current offset of 0.01 mA per side is added on purpose**

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

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

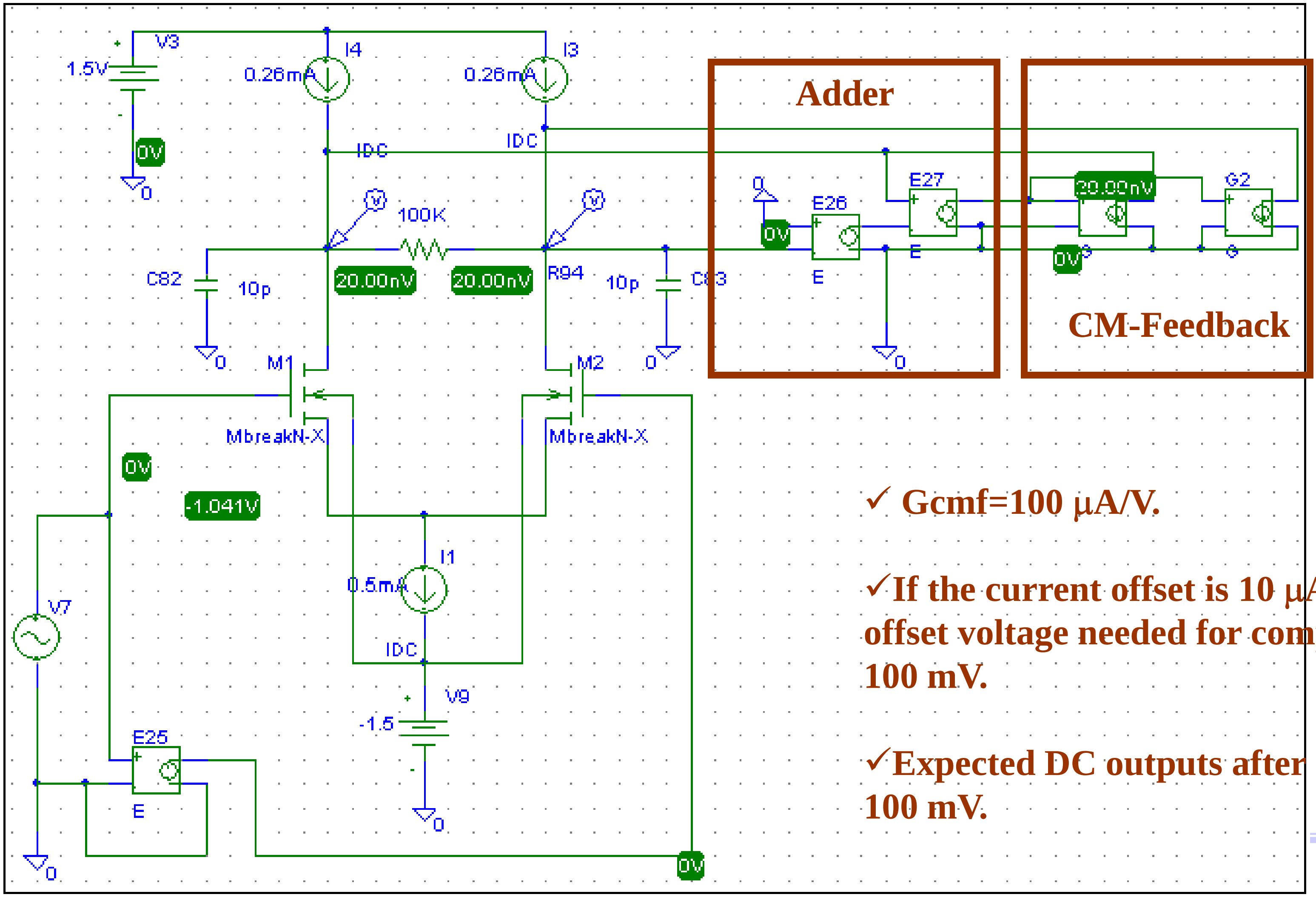
al Amplifiers: Characterization



✓ 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!

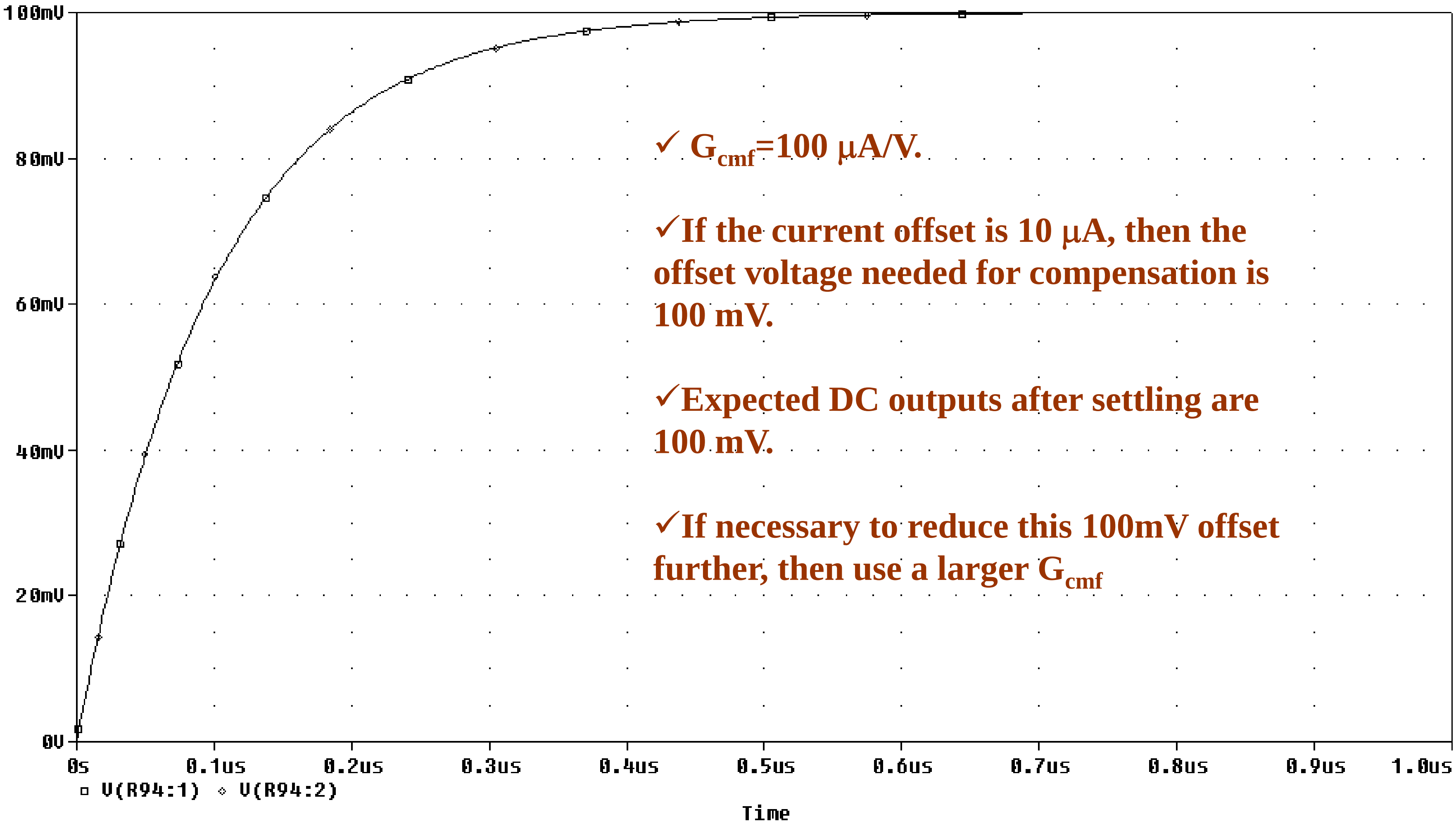
✓Differential input voltage is set at 0

Fully-Differential Amplifiers: Common-mode Feedback

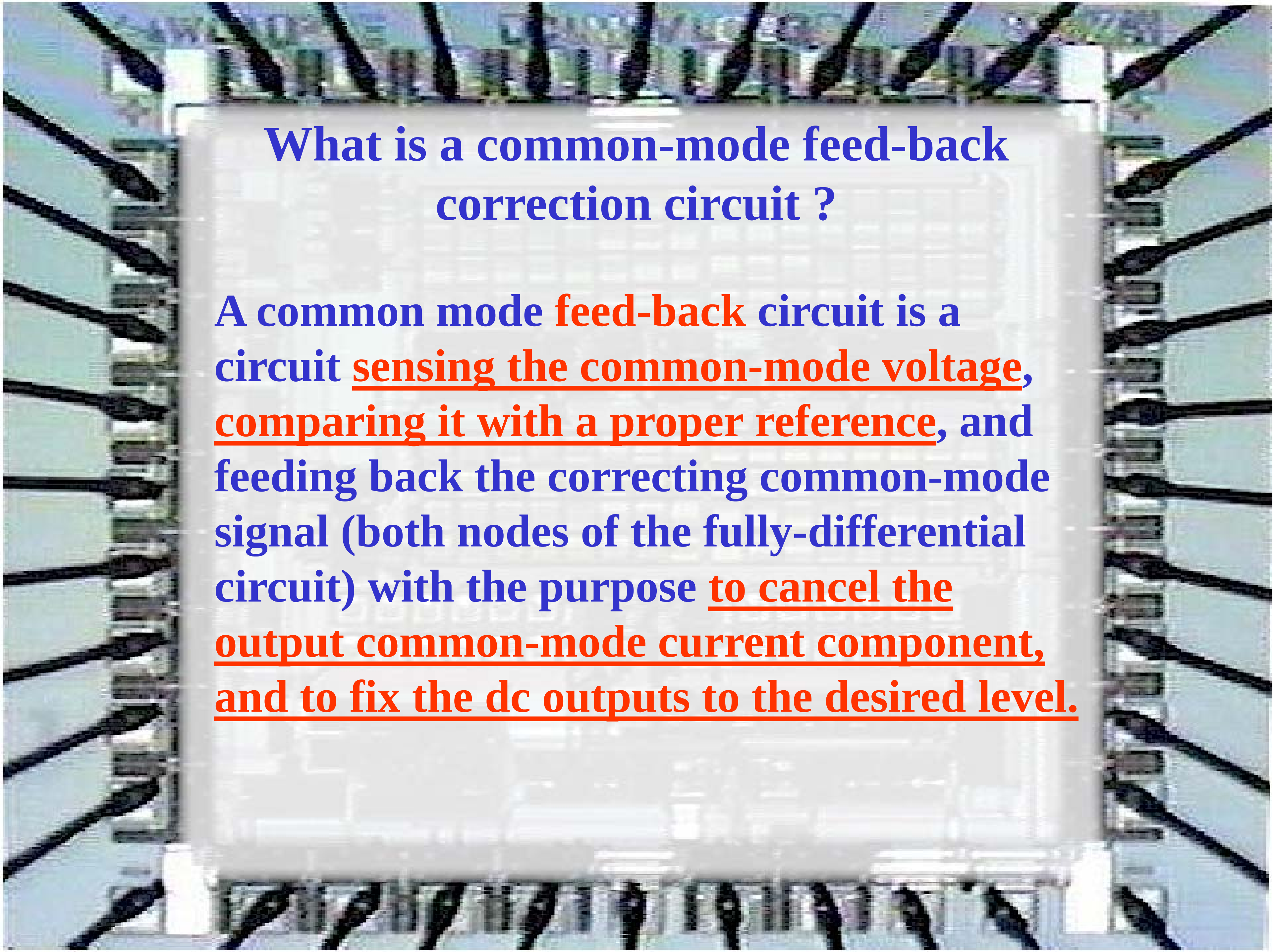


- ✓ Gcmf=100 µA/V.
- ✓If the current offset is 10 µA, then the offset voltage needed for compensation is 100 mV.
- ✓Expected DC outputs after settling are 100 mV.

Fully-Differential Amplifiers: Common-mode Feedback



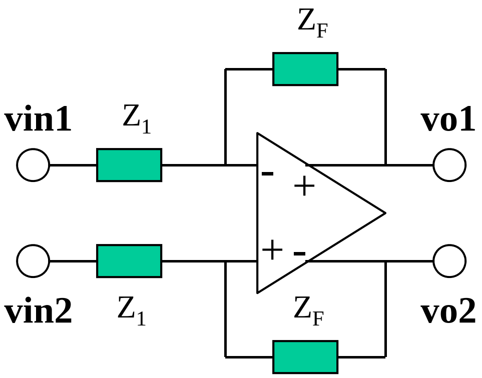
- ✓ G_{cmf}=100 μA/V.
- ✓If the current offset is 10 μA, then the offset voltage needed for compensation is 100 mV.
- ✓Expected DC outputs after settling are 100 mV.
- ✓If necessary to reduce this 100mV offset further, then use a larger G_{cmf}



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

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

Fully-Differential Filters: CMFB Principle



- A common-mode feedback loop must be used: Circuit must operate on the common-mode signals only!

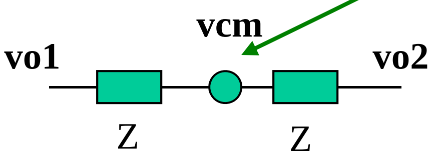
- BASIC IDEA: CMFB is a circuit with very small impedance for the common-mode signals but transparent for the differential signals.

- Use a common-mode detector (eliminates the effect of differential signals and detect common-mode signals)

- Analyze the common-mode feedback loop: Large transconductance gain and enough phase margin

- Minimum power consumption

Simplest common-mode detector



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

Next Time

- Common-Mode Feedback Techniques