ECEN 607 (ESS)

Additional notes on the Flipped Voltage Follower

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Local Feedback Loops

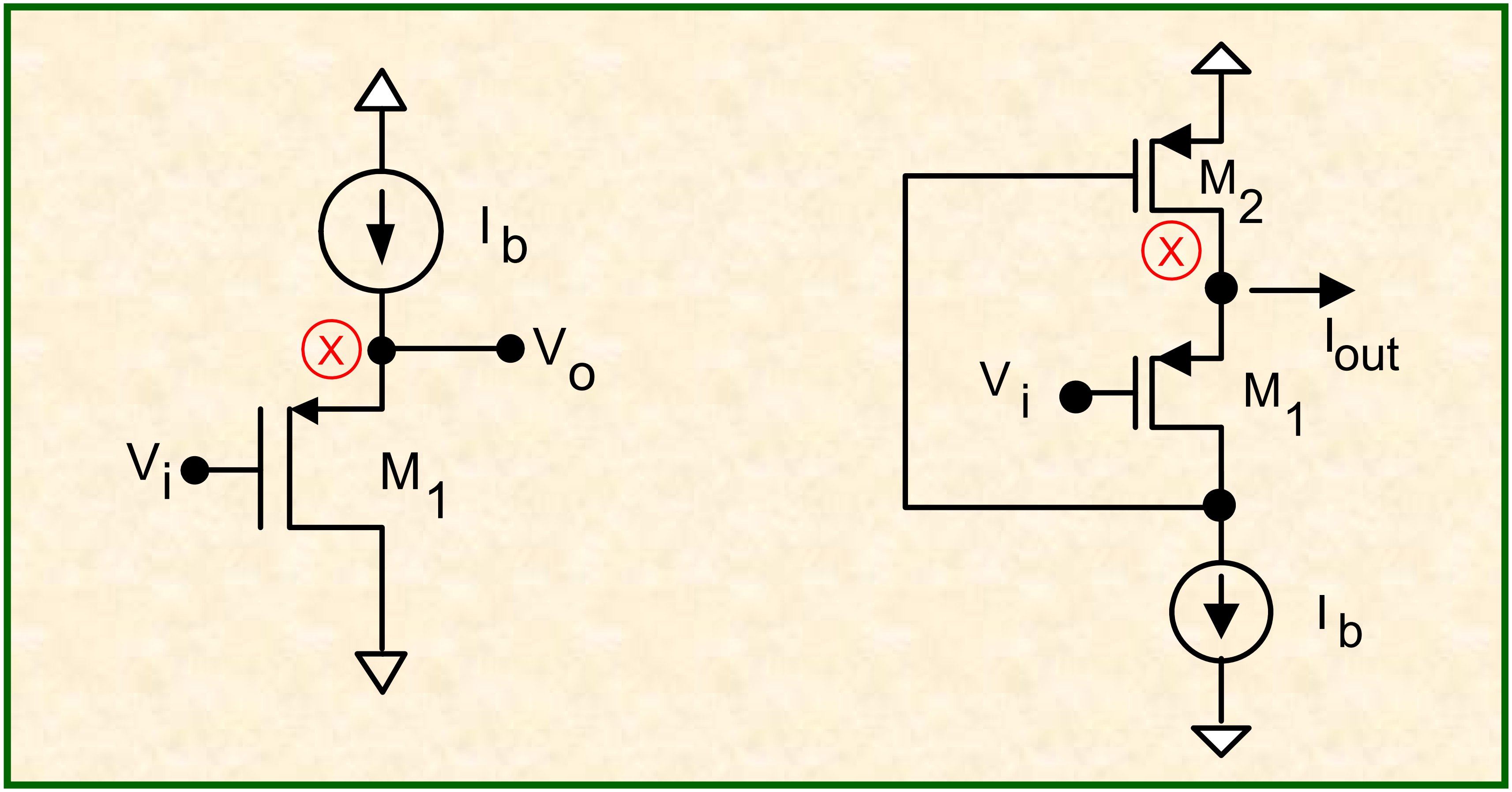
Basic Idea

V. Ivanov, J. Zhou and I.M. Filanovsky, "A 100-dB CMRR CMOS Operational Amplifier With Single-Supply Capability," IEEE Transactions on Circuits and Systems II: Express Briefs, vol. 54, no. 5, May 2007, pp.397-401

- To improve performance of simple transistors:
  - » By adding local feedback loops to:
    - » Decrease/increase impedance levels at certain nodes.
    - » Decrease/increase signal swing at certain nodes.
- Drawbacks:
  - » Feedback always implies stability problems
- Advantages:
  - » Local Feedback is faster and does not require compensation if properly designed.
  - » It allows easy Class AB implementation

Local Feedback Loops

A possible Implementation



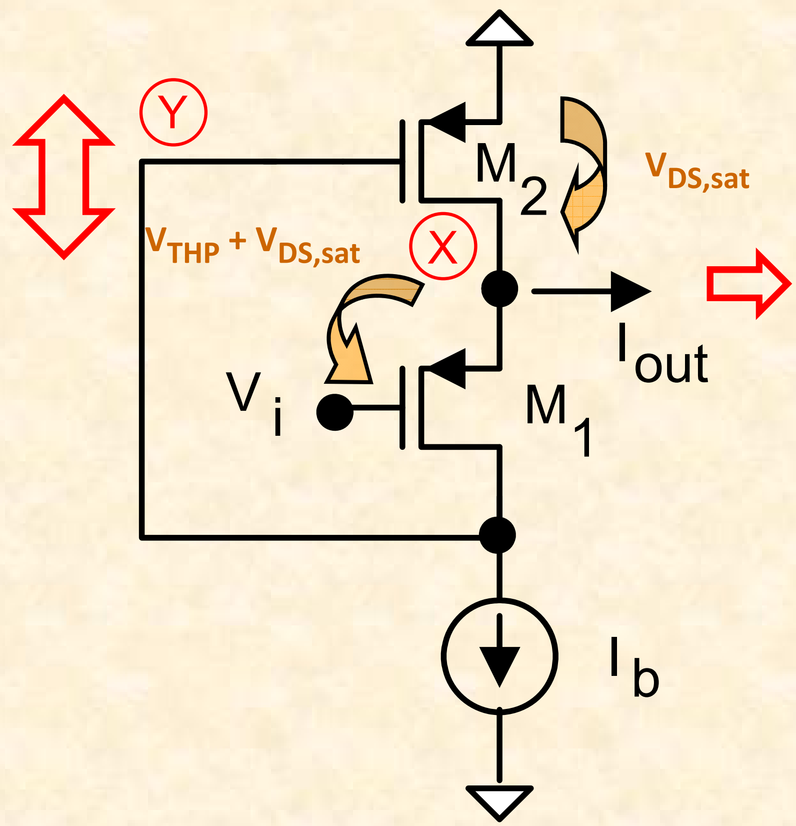
Voltage Follower

Flipped Voltage Follower(FVF)

Local Feedback Loops

Flipped Voltage Follower (FVF)

- V_X is defined by the value of V_i and I_b and follows the variations of V_i
- The circuit is able to source (I_{out}) currents much larger than I_b
- Low impedance at node X
  $R_X=1/(g_{m2}\, g_{m1}\, r_{o1})$



$$V_{DD,min} = |V_{THP}| + 2V_{DS,sat}$$

Local Feedback Loops

Flipped Voltage Follower (FVF)

- It is able to operate with Low-Voltage supply

$$V_{DD}^{MIN}=|V_{TP}|+2V_{DS,sat}$$

- It features a low impedance node:

$$R_X \approx 1/(g_{m2}\, g_{m1}\, r_{o1})$$

- And a high impedance node

$$R_i \approx \infty$$

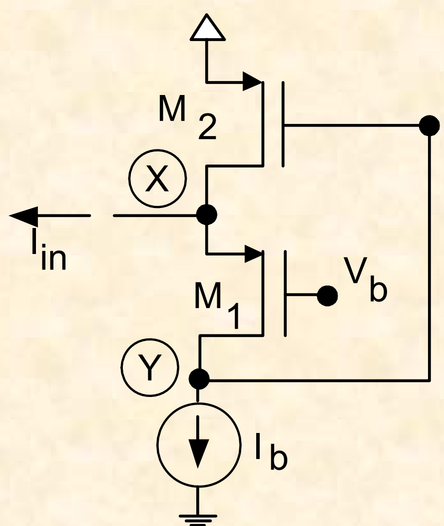
- There are no stability problems [*]
- It is able to provide a load with currents much larger than the bias current → **Class-AB**

[*] R.G. Carvajal, J. Ramírez-Angulo, A. López-Martin, A. Torralba, J. Galán, A. Carlosena and F. Muñoz, "The Flipped Voltage Follower: A useful cell for low-voltage low-power circuit design," **IEEE Trans. on Circuits and Systems-I**, vol 52, no. 7, Julio 2005.

LFL: Basic Cells

Local Feedback Loops: Class-AB operation

➳ Objective: Design cells for $V_{DD}<V_{DDmin}$ featuring Class-AB behavior



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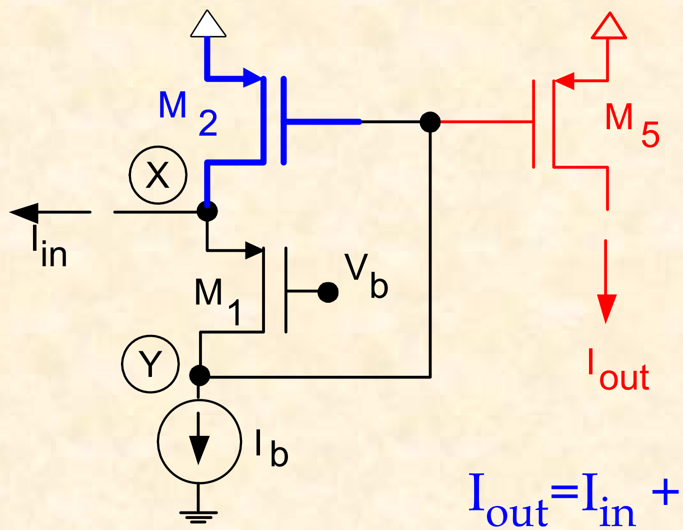
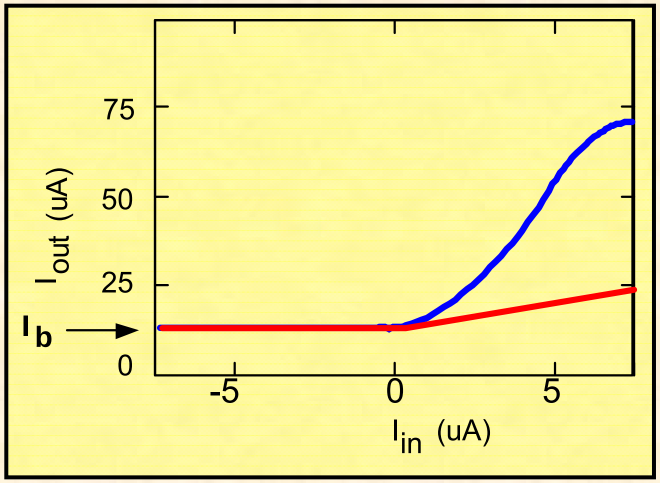


$I_{out}=I_{in} + I_b$

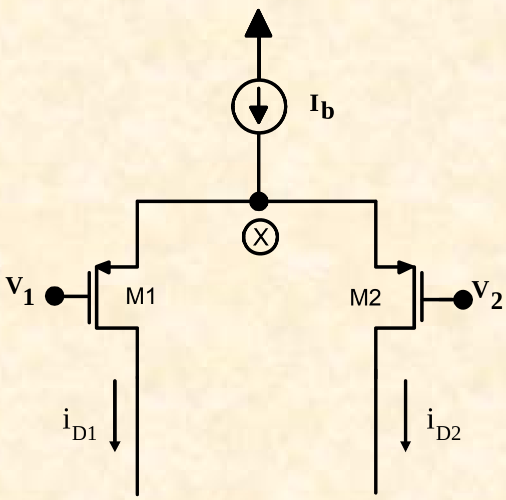


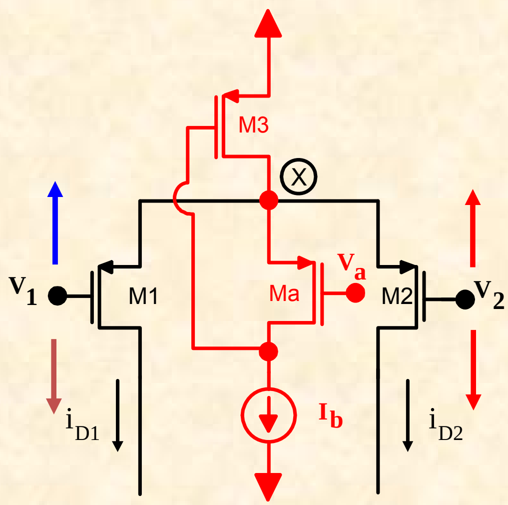
Current Sensing

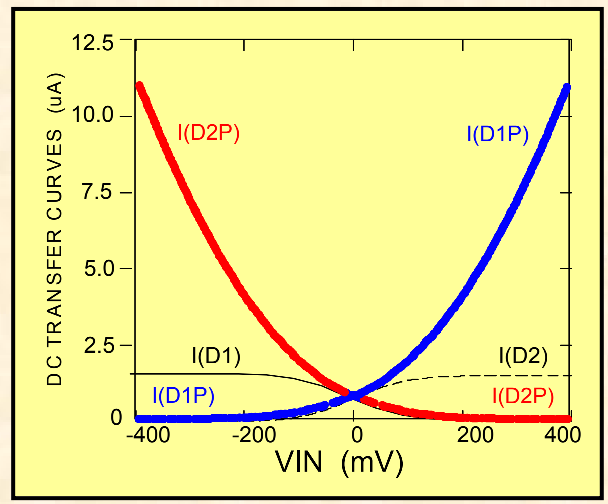
LFL: Basic Cells

Local Feedback Loops: Class-AB operation

➳ Objective: Design cells for $V_{DD}<V_{DDmin}$ featuring Class-AB behavior







Class-A differential pair

Class-AB pseudo differential pair

Comparison

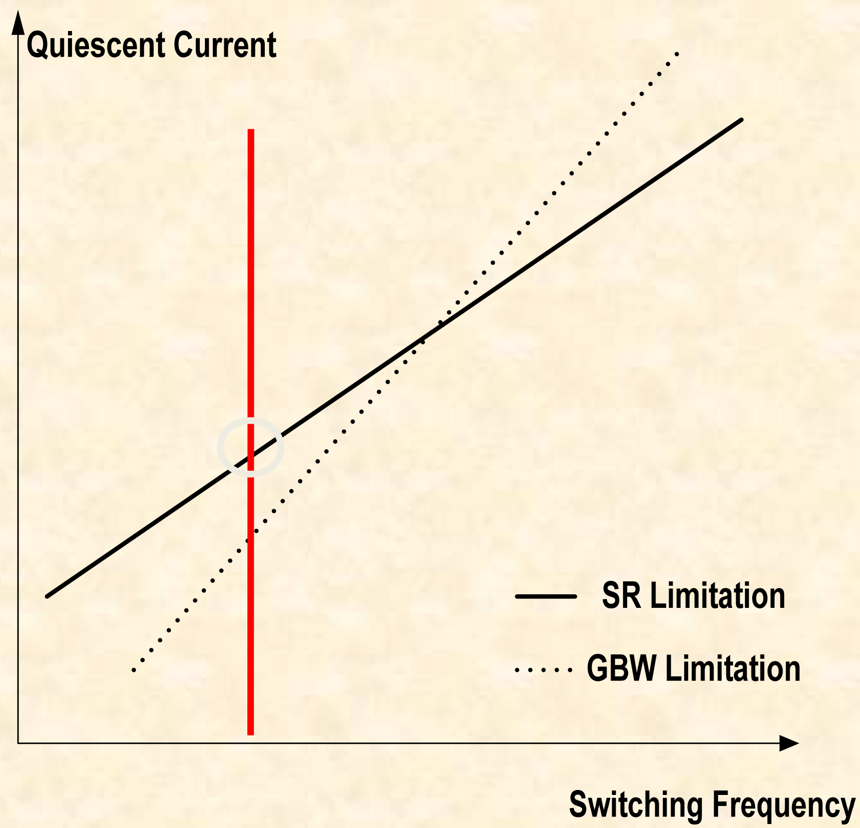
LFL: Basic Cells

Local Feedback Loops: Class-AB operation

- **Objective:** Design cells for $V_{DD}<V_{DDmin}$ featuring Class-AB behavior

- Quiescent Current in Class-A based SC circuits:
  - Limits Slew-Rate
  - Limits GBW
- Depending on clock freq.:
  - One of them sets I^Q
  - For low freq. SR limits.

G. Giustolisi and G. Palumbo, "A novel 1-V class-AB transconductor for improving speed performance in SC applications,". **ISCAS 2003**, vol. 1, 25-28 May 2003 pp. 153-156



LFL: Basic Cells

Local Feedback Loops: Class-AB operation

➸ Objective: Design cells for $V_{DD}<V_{DDmin}$ featuring Class-AB behavior

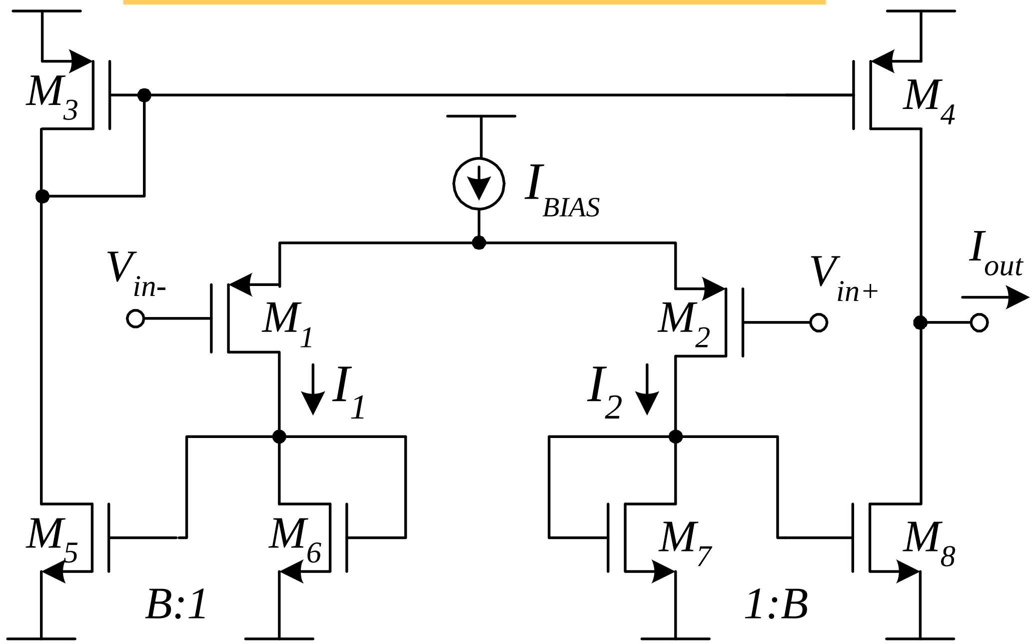
- Adaptive biasing+LCMFB = Super Class AB
- Improvements:
  - Slew rate
  - Gain-Bandwidth product
  - Current efficiency
- Applications
  - Low-voltage low-power SC circuits
  - Buffers for large load caps and testing

LFL: Basic Cells

Local Feedback Loops: Class-AB operation

➳ Objective: Design cells for $V_{DD}<V_{DDmin}$ featuring Class-AB behavior

Conventional Class A OTA



Slew Rate: BI_{BIAS}/C_L

GB: $Bg_{m1,2}/(2\pi C_L)$

Current Efficiency: $B/(B+1)$

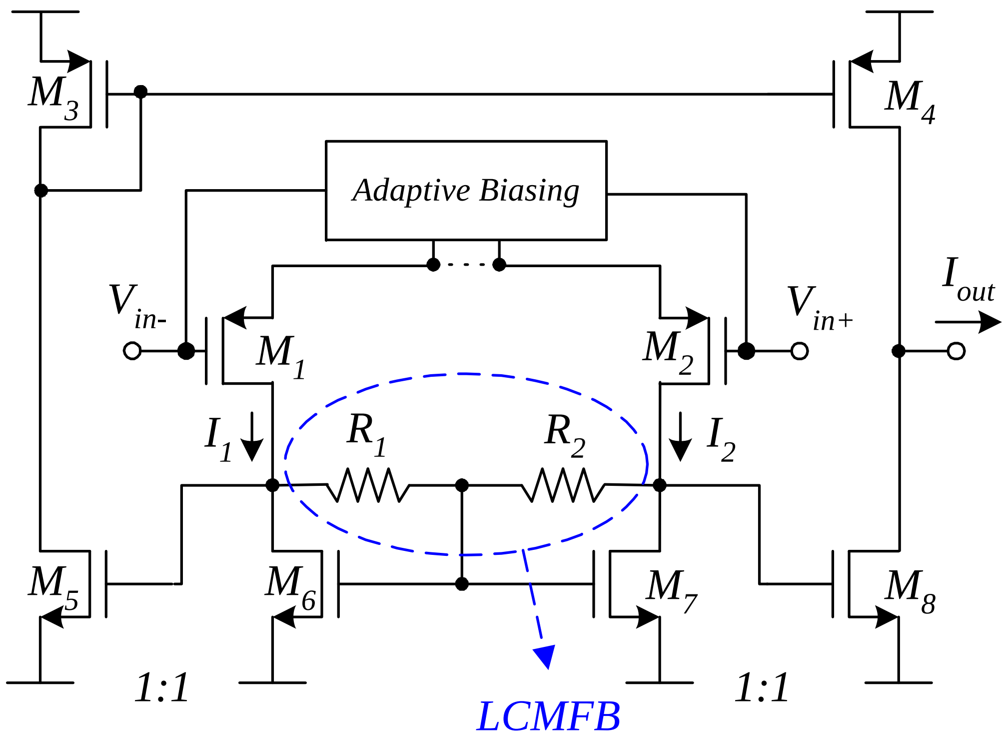
Larger B increases all this but also increases power consumption and decreases phase margin

LFL: Basic Cells

Local Feedback Loops: Class-AB operation

- **Objective:** Design cells for $V_{DD}<V_{DDmin}$ featuring Class-AB behavior

Super Class-AB OTA



- Adpatative biasing:
  - ↑ Slew rate
- LCMFB:
  - ↑↑ Slew rate
  - ↑ GBW
  - ↑ Current
  - Efficiency

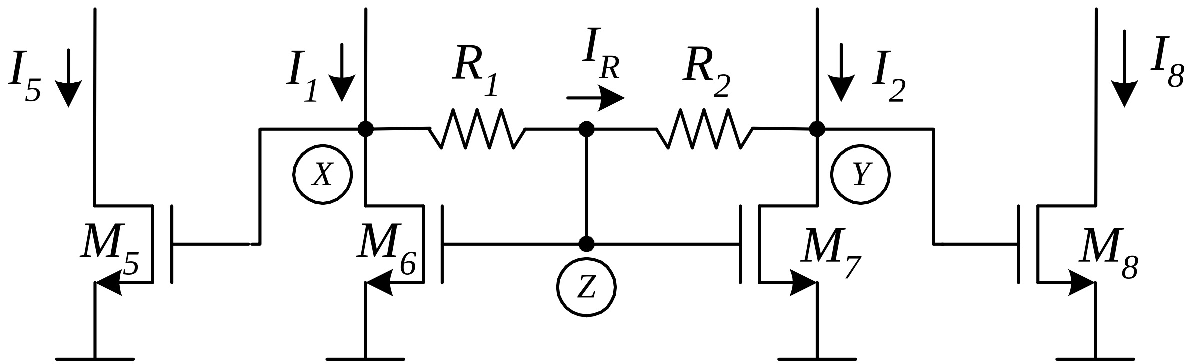
LFL: Basic Cells

Local Feedback Loops: Class-AB operation

➳ Objective: Design cells for $V_{DD}<V_{DDmin}$ featuring Class-AB behavior

Local Common-Mode Feedback (I)

Quiescent conditions



$$V_X = V_Y = V_Z = V_{TH} + \sqrt{\frac{2I_B}{\beta_{6,7}}}$$

I_B: Quiescent value of I_1 and I_2

Low quiescent power consumption

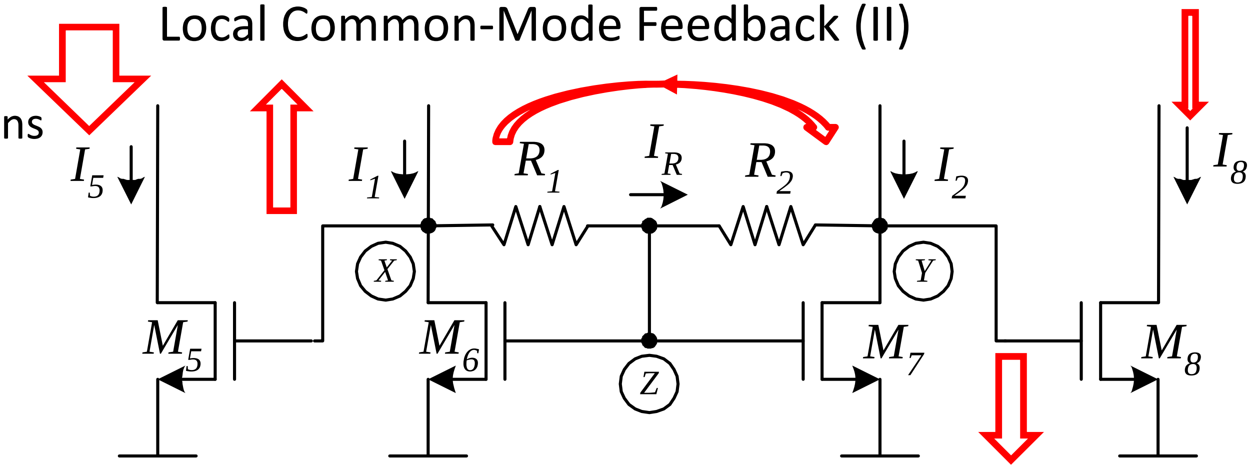
LFL: Basic Cells

Local Feedback Loops: Class-AB operation

➳ Objective: Design cells for $V_{DD}<V_{DDmin}$ featuring Class-AB behavior

Local Common-Mode Feedback (II)

Dynamic conditions



$$V_Z = V_{TH} + \sqrt{\frac{2I_{cm}}{\beta_{6,7}}}$$

$$V_X = V_Z + \frac{R_1 I_d}{2}$$

$$V_Y = V_Z - \frac{R_2 I_d}{2}$$

If $I_1>I_2$:

$$I_5 = \frac{\beta_5}{2}\left(\sqrt{\frac{2I_{cm}}{\beta_{6,7}}} + \frac{R_1 I_d}{2}\right)^2$$

$$I_{out}=I_5-I_8 \approx I_5$$

where $I_{cm} = (I_1 + I_2)/2$ *and* $I_d = I_1 - I_2$

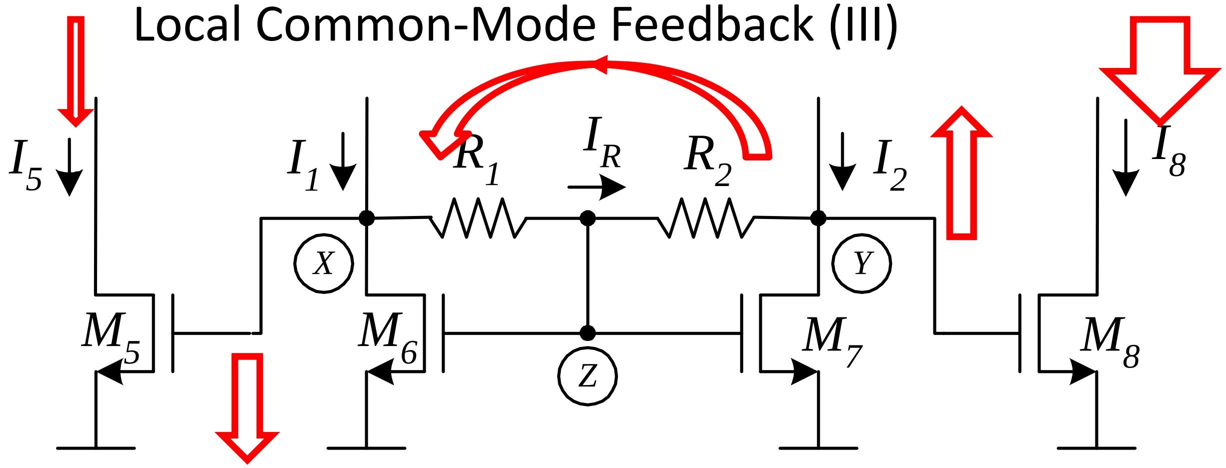
LFL: Basic Cells

Local Feedback Loops: Class-AB operation

➳ Objective: Design cells for $V_{DD}<V_{DDmin}$ featuring Class-AB behavior

Local Common-Mode Feedback (III)

Dynamic conditions



$$V_Z = V_{TH} + \sqrt{\frac{2I_{cm}}{\beta_{6,7}}}$$

$$V_X = V_Z + \frac{R_1 I_d}{2}$$

$$V_Y = V_Z - \frac{R_2 I_d}{2}$$

If $I_1<I_2$:

$$\begin{cases} I_8 = \frac{\beta_8}{2}\left(\sqrt{\frac{2I_{cm}}{\beta_{6,7}}} - \frac{R_2 I_d}{2}\right)^2 \\ I_{out}=I_5-I_8 \approx -I_8 \end{cases}$$

where $I_{cm} = (I_1 + I_2)/2$ *and* $I_d = I_1 - I_2$

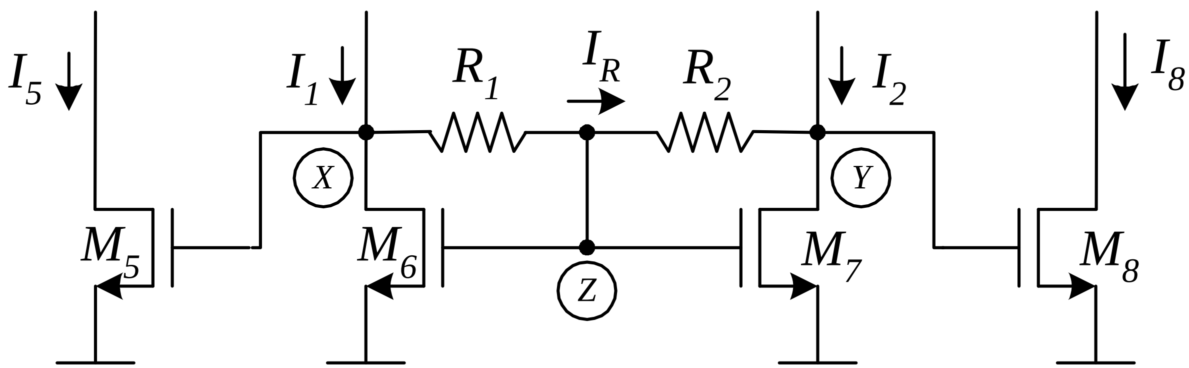
LFL: Basic Cells

Local Feedback Loops: Class-AB operation

➳ Objective: Design cells for $V_{DD}<V_{DDmin}$ featuring Class-AB behavior

Local Common-Mode Feedback (IV)

Dynamic conditions



General expression for $I_1 \neq I_2$:

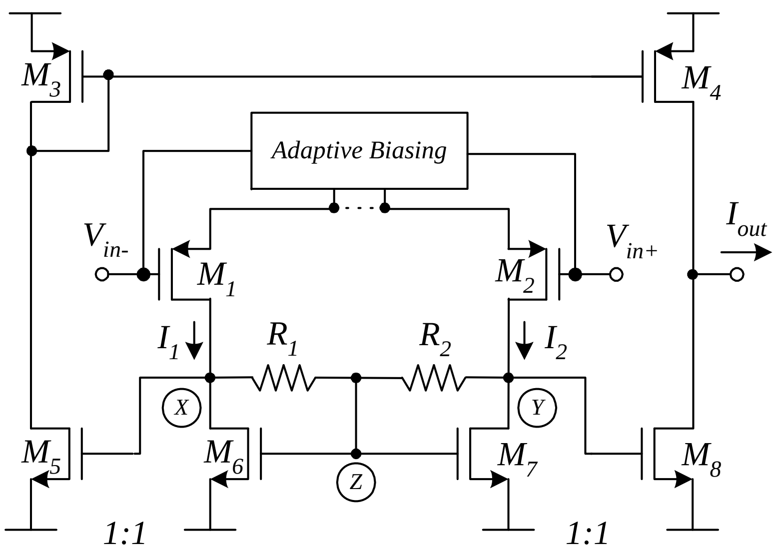
$$I_{out} = I_5 - I_8 \approx \pm \frac{\beta_{5,8}}{2}\left(\sqrt{\frac{2I_{cm}}{\beta_{6,7}}} + \frac{R_{1,2}\left|I_d\right|}{2}\right)^2$$

Quadratic boosting of differential current I_d

LFL: Basic Cells

Local Feedback Loops: Class-AB operation

➸ Objective: Design cells for $V_{DD}<V_{DDmin}$ featuring Class-AB behavior



Adaptive Biasing+LCMFB

GB product: $$GB = \frac{kg_{m1,2}g_{m5,8}R_{X,Y}}{2\pi C_L}$$

$\Rightarrow$ *Increase of* $kg_{m5,8}R_{X,Y}$

Large-signal output current:

$$I_{out} \approx \pm\frac{\beta_{5,8}}{2}\left(\sqrt{\frac{\beta_{1,2}}{\beta_{6,7}}}\left|V_{id}\right| + \frac{R_{1,2}\beta_{1,2}}{4}V_{id}^2\right)^2$$

Phase margin:

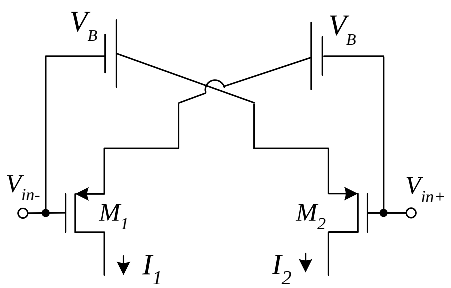
$$PM \approx 90^{\circ} - arctg\left(\frac{GBW}{f_{X,Y}}\right) \approx 90^{\circ} - arctg\left[kg_{m1,2}g_{m5,8}\left(R_{1,2} \parallel r_{o6,7} \parallel r_{o1,2}\right)^2 \frac{C_{GS5,8}}{C_L}\right]$$

High SR with low $R_{1,2}$ $\Rightarrow$ stability

LFL: Basic Cells

Local Feedback Loops: Class-AB operation

Adaptive Biasing of Input Pair: SI



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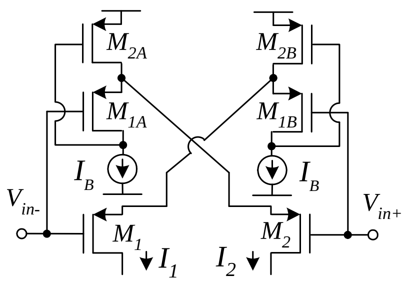
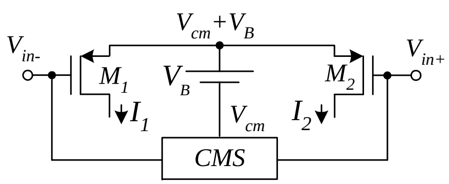


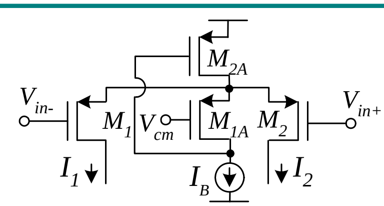
(b)

$$I_1 = \frac{\beta_{1,2}}{2}\left(\sqrt{\frac{2I_B}{\beta_{1,2}}}+V_{id}\right)^2 \quad I_2 < I_B \quad V_{id} > 0$$

$$I_2 = \frac{\beta_{1,2}}{2}\left(\sqrt{\frac{2I_B}{\beta_{1,2}}}-V_{id}\right)^2 \quad I_1 < I_B \quad V_{id} < 0$$



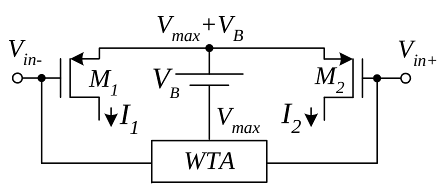
(c)



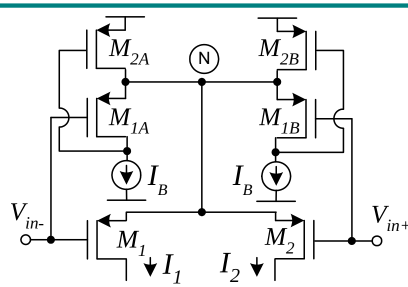
(d)

$$I_1 = \frac{\beta_{1,2}}{2}\left(\sqrt{\frac{2I_B}{\beta_{1,2}}}+\frac{V_{id}}{2}\right)^2 \quad I_2 < I_B \quad V_{id} > 0$$

$$I_2 = \frac{\beta_{1,2}}{2}\left(\sqrt{\frac{2I_B}{\beta_{1,2}}}-\frac{V_{id}}{2}\right)^2 \quad I_1 < I_B \quad V_{id} < 0$$



(e)



(f)

$$I_1 = \frac{\beta_{1,2}}{2}\left(\sqrt{\frac{2I_B}{\beta_{1,2}}}+V_{id}\right)^2 \quad I_2 = I_B \quad V_{id} > 0$$

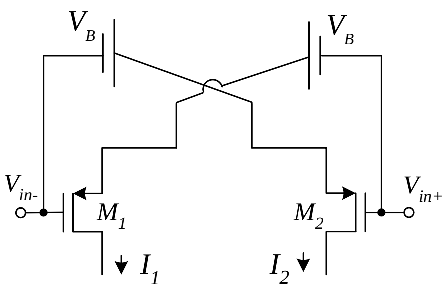
$$I_2 = \frac{\beta_{1,2}}{2}\left(\sqrt{\frac{2I_B}{\beta_{1,2}}}-V_{id}\right)^2 \quad I_1 = I_B \quad V_{id} < 0$$

Strong inversion: Quadratic boosting of V_{id} not limited by I_B

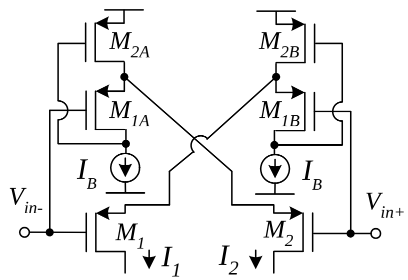
LFL: Basic Cells

Local Feedback Loops: Class-AB operation

Adaptive Biasing of Input Pair: WI

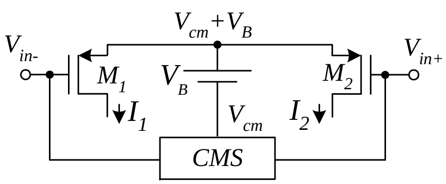


(a)



(b)

$$I_1 = I_B e^{\frac{V_{id}}{nU_T}} \qquad I_2 = I_B e^{-\frac{V_{id}}{nU_T}}$$



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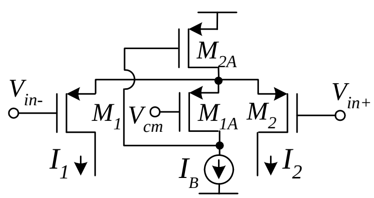
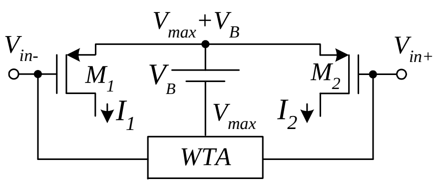


(d)

$$I_1 = I_B e^{\frac{V_{id}}{2nU_T}} \qquad I_2 = I_B e^{-\frac{V_{id}}{2nU_T}}$$



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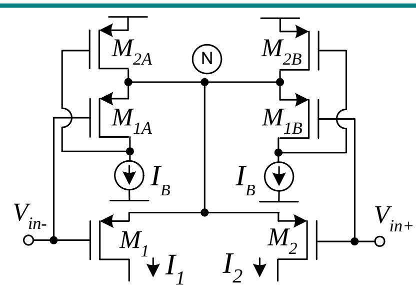


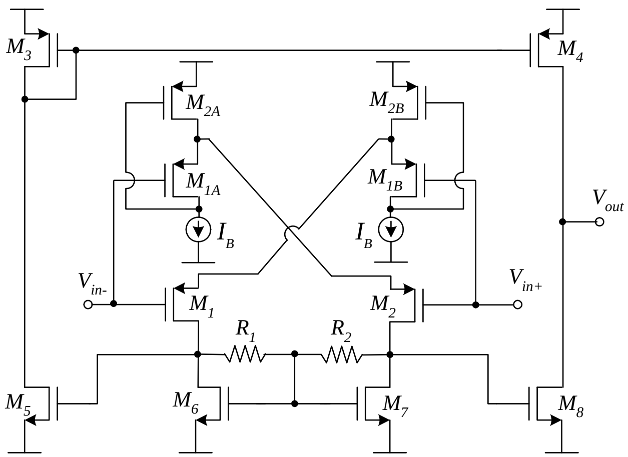
(f)

$$I_1 = \max\left(I_B e^{\frac{V_{id}}{nU_T}}, I_B \right) \qquad I_2 = \max\left(I_B e^{-\frac{V_{id}}{nU_T}}, I_B \right)$$

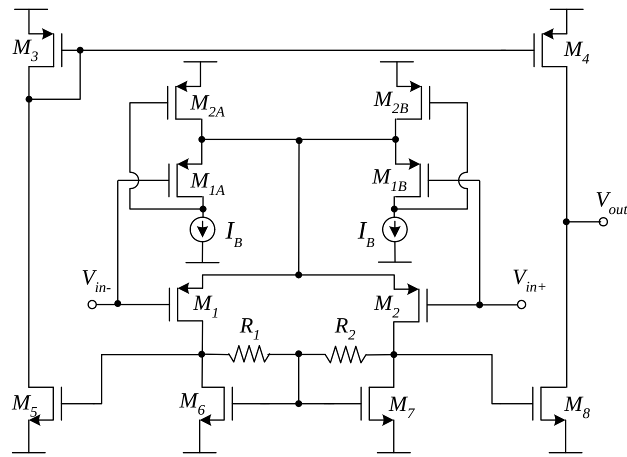
Weak inversion: Exponential boosting of V_{id} not limited by I_B

LFL: Basic Cells

Local Feedback Loops: Class-AB operation

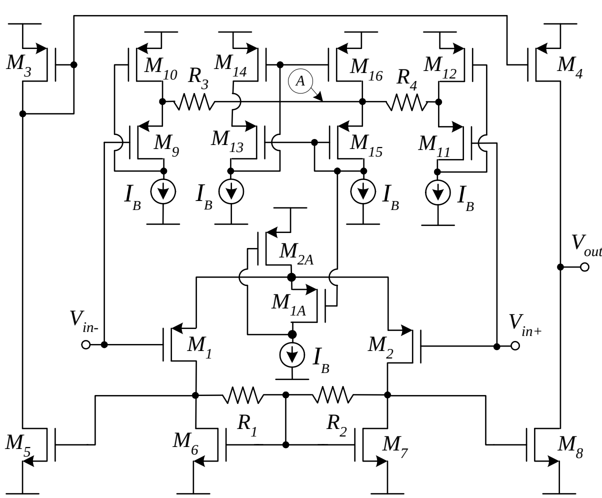


(a)



(b)

Super Class AB OTA Topologies



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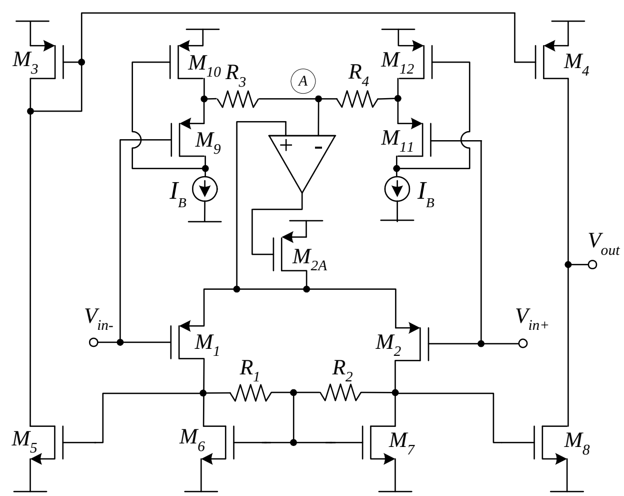
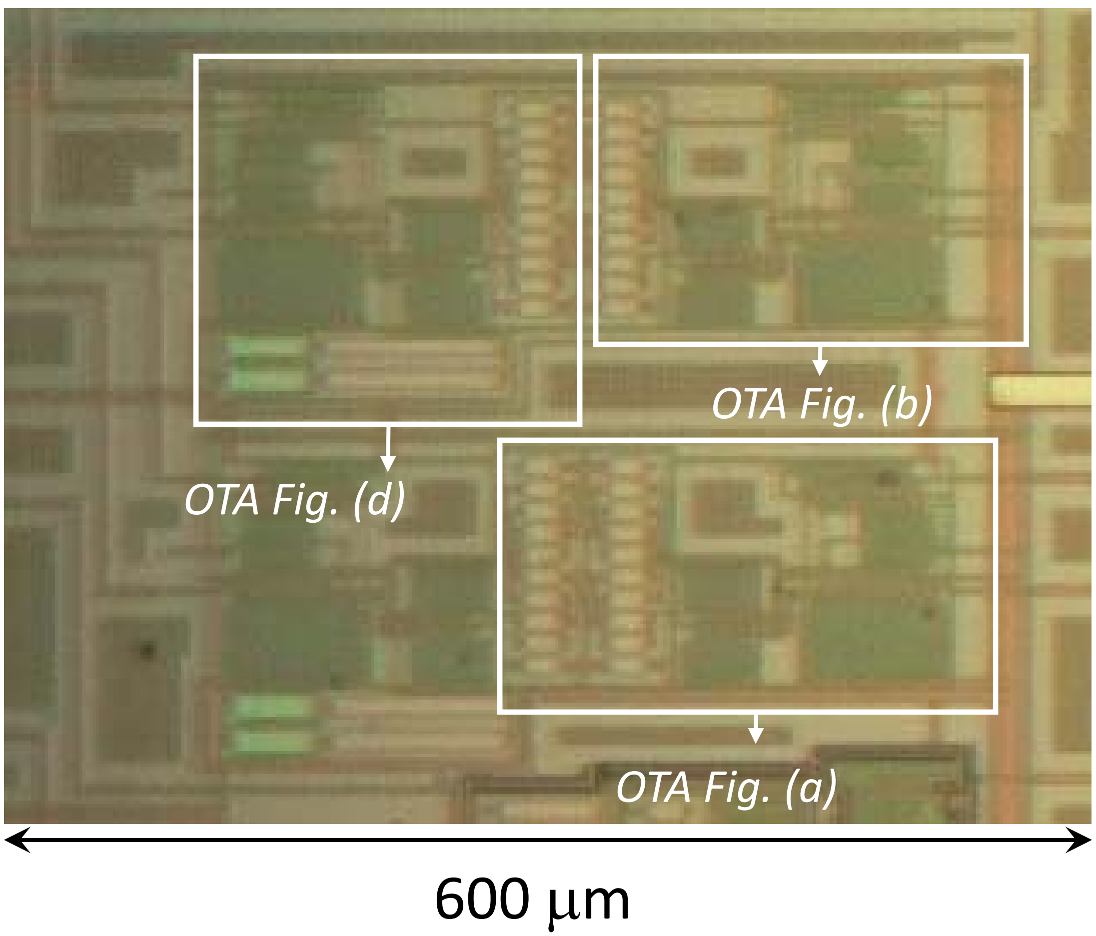


(d)

LFL: Basic Cells

Local Feedback Loops: Class-AB operation

Measurement Results (I)



Technology:

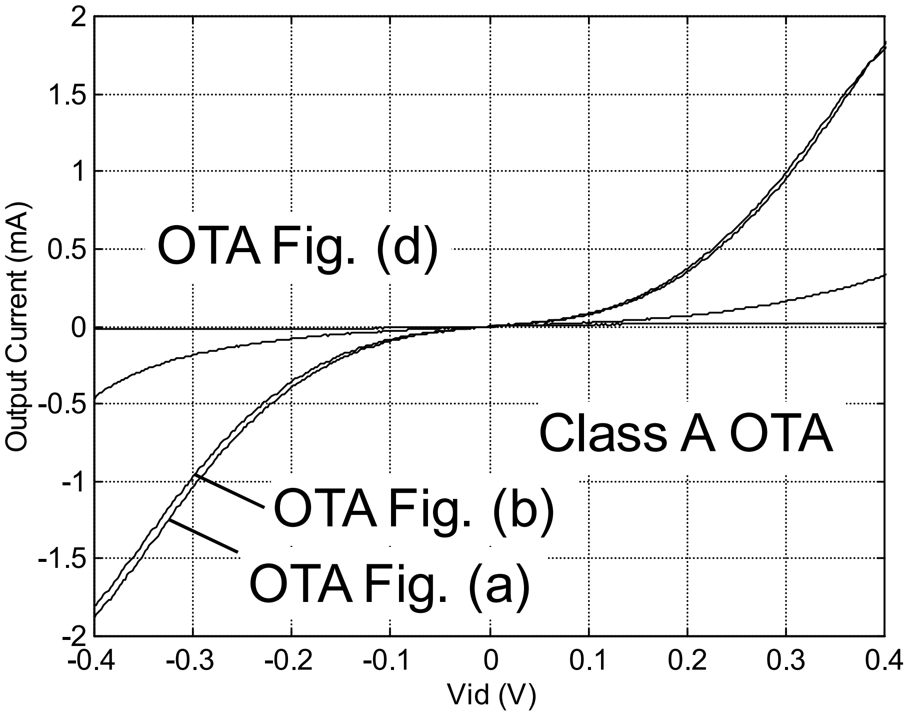
- ✓ 0.5 μm CMOS
- ✓ Double Poly
- ✓ $V_{THP} \approx -0.96V$
- ✓ $V_{THN} \approx 0.67V$

Meas. conditions:

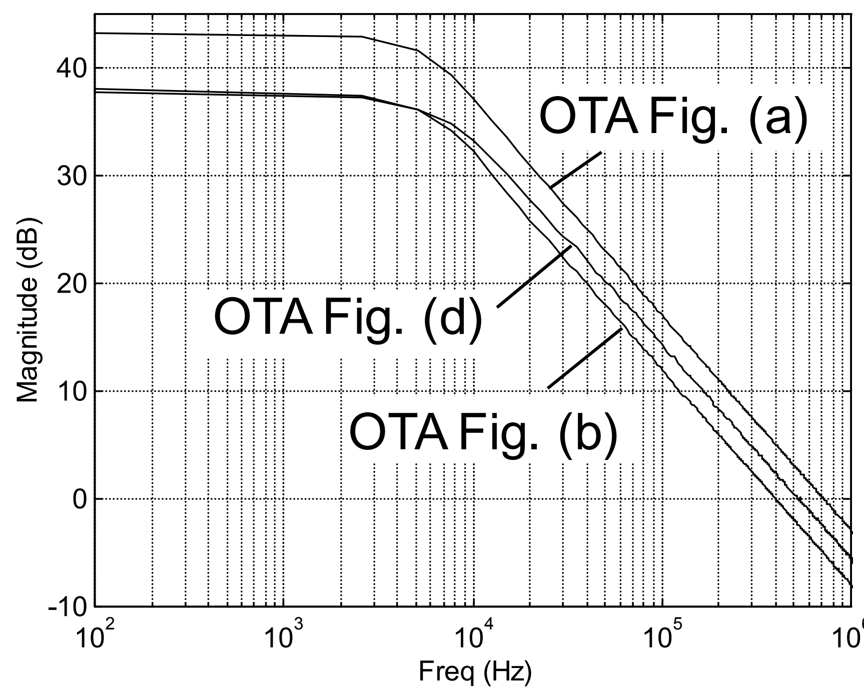
- ✓ $V_{DD} = -V_{SS} = 1$ V
- ✓ $I_B = 10$ μA
- ✓ $C_L = 80$pF

LFL: Basic Cells

Local Feedback Loops: Class-AB operation



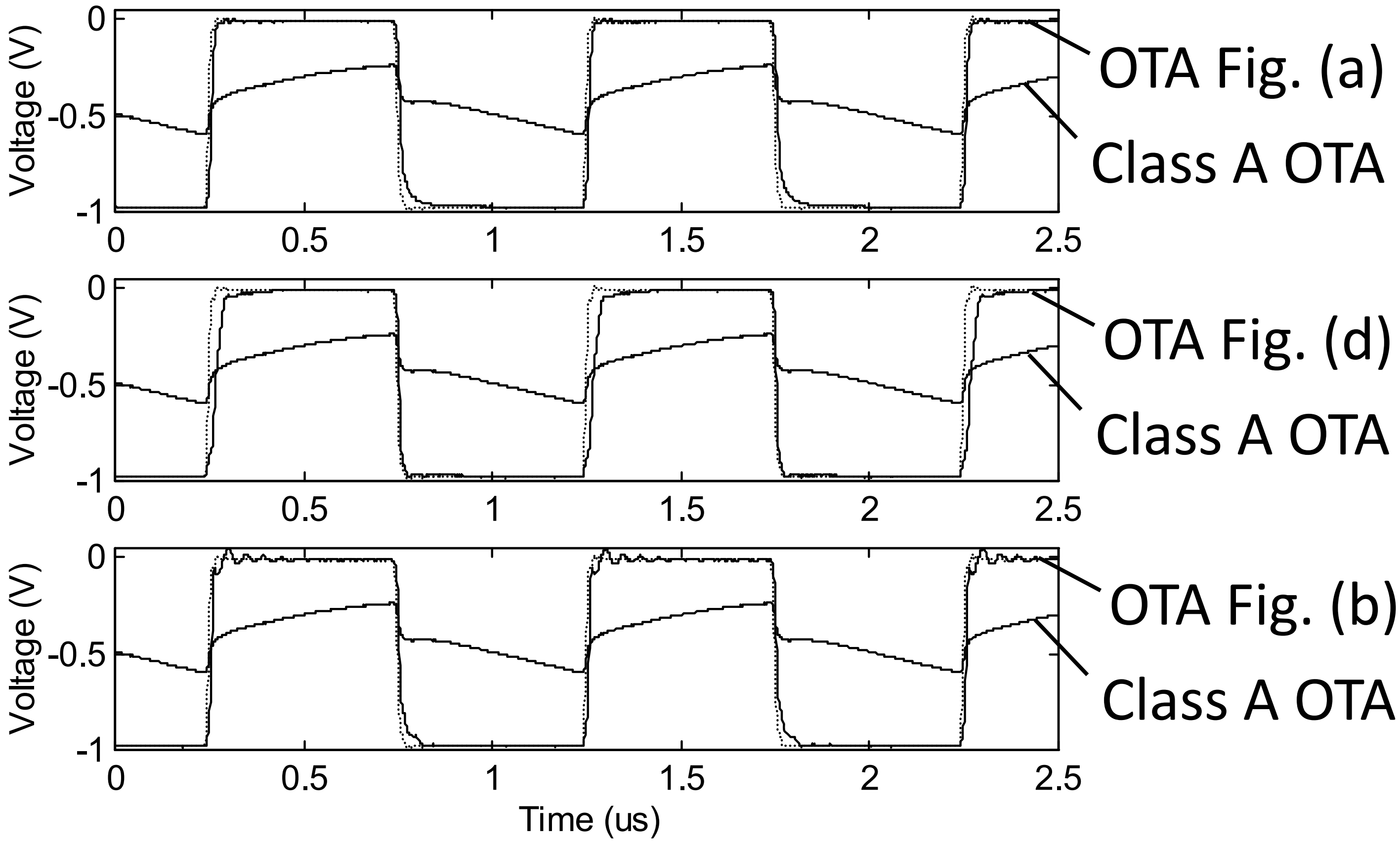
Measured dc output characteristics of the OTAs



Measured open-loop frequency response of the OTAs

LFL: Basic Cells

Local Feedback Loops: Class-AB operation



Transient response of the OTAs in unity-gain configuration

LFL: Basic Cells

Local Feedback Loops: Super Class-AB operation

PARAMETER	Class A OTA	OTA Fig. 3(a)	OTA Fig. 3(b)	OTA Fig. 3(d)
Slew Rate (positive)	0.35 V/μs	100 V/μs	92 V/μs	42 V/μs
Slew Rate (negative)	-0.4 V/μs	-78 V/μs	-76 V/μs	-80 V/μs
Pos. settling (1%)	3.1 μs	29 ns	66 ns	100 ns
Neg. settling (1%)	3.6 μs	57 ns	62 ns	33 ns
GBW	200 kHz	725 kHz	410 kHz	470 kHz
Equ. Input Noise (1 MHz)	223 μV_{rms}	230 μV_{rms}	230 μV_{rms}	252 μV_{rms}
THD @ 100 kHz, 0.9V_{pp}	-40 dB	-56 dB	-43 dB	-41 dB
Dynamic range	63 dB	66 dB	63.7 dB	62.5 dB
DC gain	30 dB	43 dB	37.5 dB	37.5 dB
CMRR	54 dB	68 dB	70 dB	69 dB
PSRR+ (dc)	48 dB	55 dB	50 dB	57 dB
PSRR- (dc)	44 dB	58 dB	53 dB	46 dB
Static power consumption	80 μW	120 μW	120 μW	140 μW
Die area	0.011 mm^2	0.024 mm^2	0.024 mm^2	0.042 mm^2

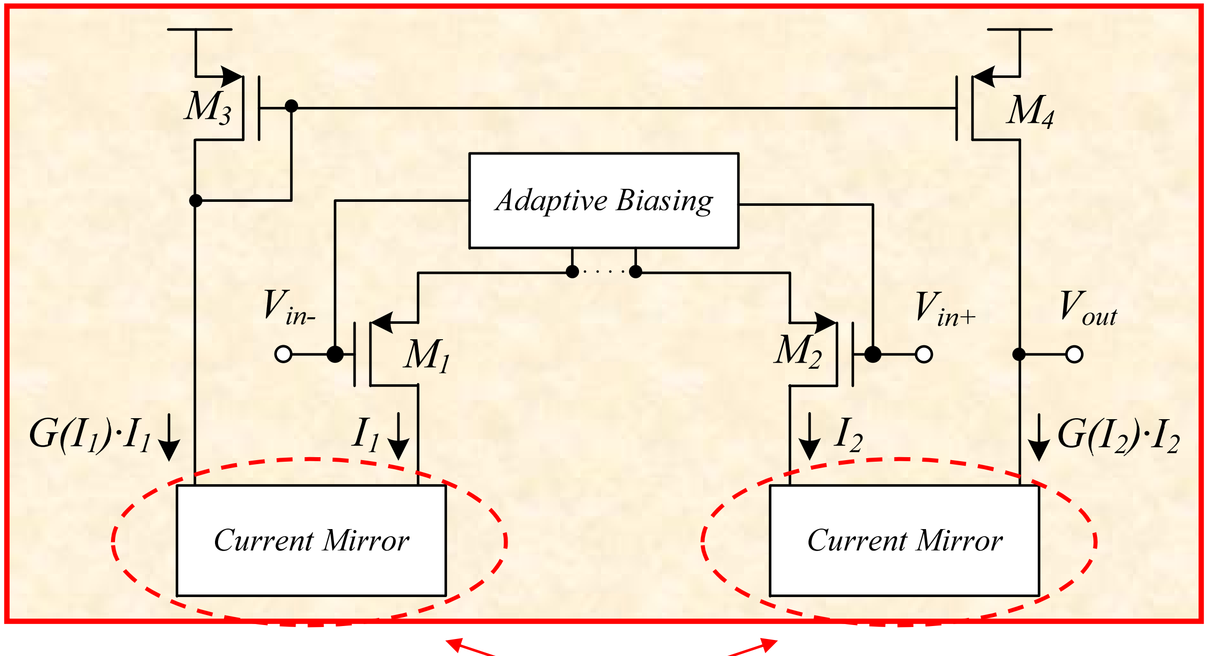
Performance parameters of the OTAs

Antonio J. López Martín, Sushmita Baswa, Jaime Ramírez Angulo, R.G. Carvajal, "Low-Voltage Power-Efficient Super Class AB CMOS OTA Cells with Very High Slew Rate and Power Efficiency," **IEEE Journal of Solid-State Circuits**, vol. 40, no. 5, pp. 1068-1077, Mayo de 2005

LFL: Basic Cells

Local Feedback Loops: Super Class-AB operation

Proposed Circuit Topology

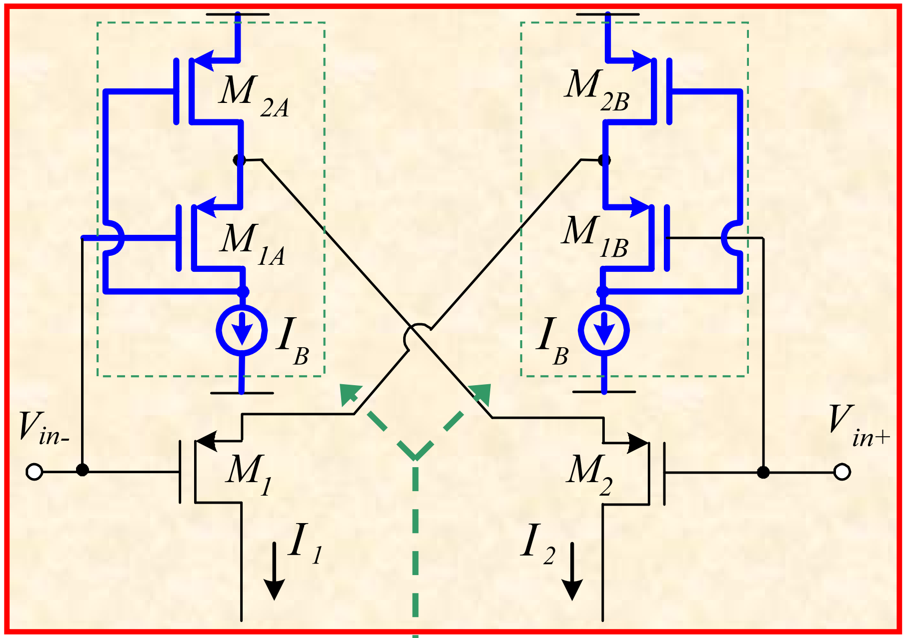


NonLinear Active Load

LFL: Basic Cells

Local Feedback Loops: Super Class-AB operation

Class-AB Input Stage



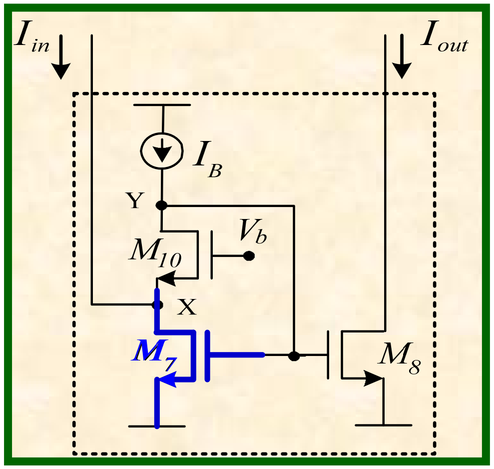
Local Feedback

$$I_1 = \frac{\beta_{1,2}}{2}\left(\sqrt{\frac{2I_B}{\beta_{1,2}}} + V_{id}\right)^2 \qquad I_2 < I_B \qquad V_{id} > 0$$

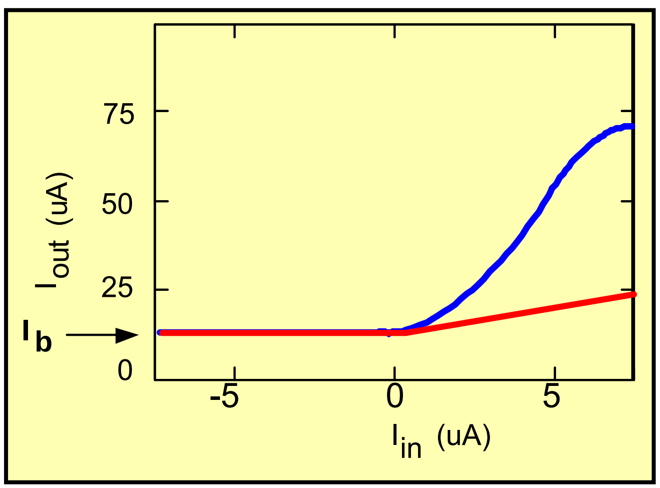
$$I_2 = \frac{\beta_{1,2}}{2}\left(\sqrt{\frac{2I_B}{\beta_{1,2}}} - V_{id}\right)^2 \qquad I_1 < I_B \qquad V_{id} < 0$$

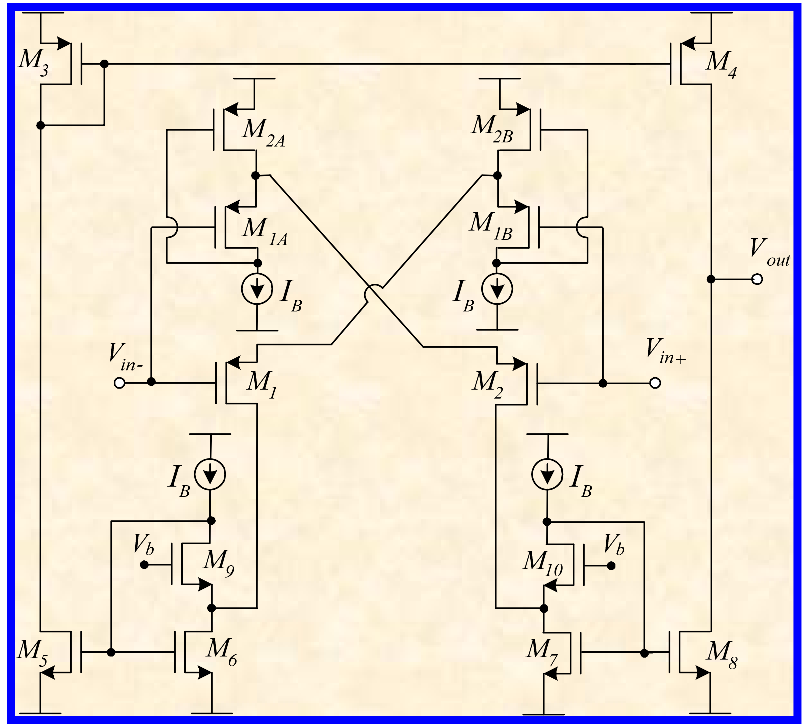
LFL: Basic Cells

Local Feedback Loops: Super Class-AB operation



Class AB current mirror



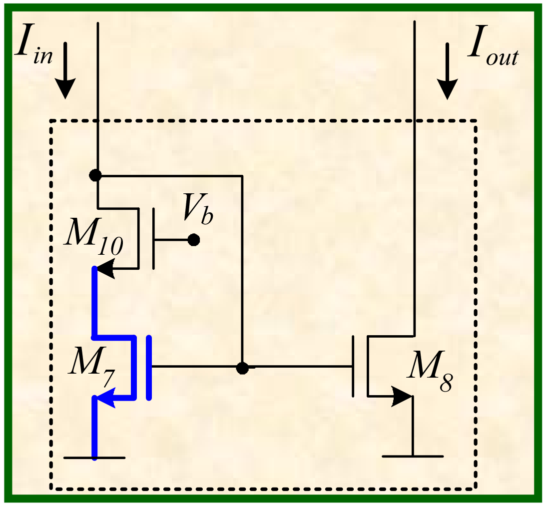


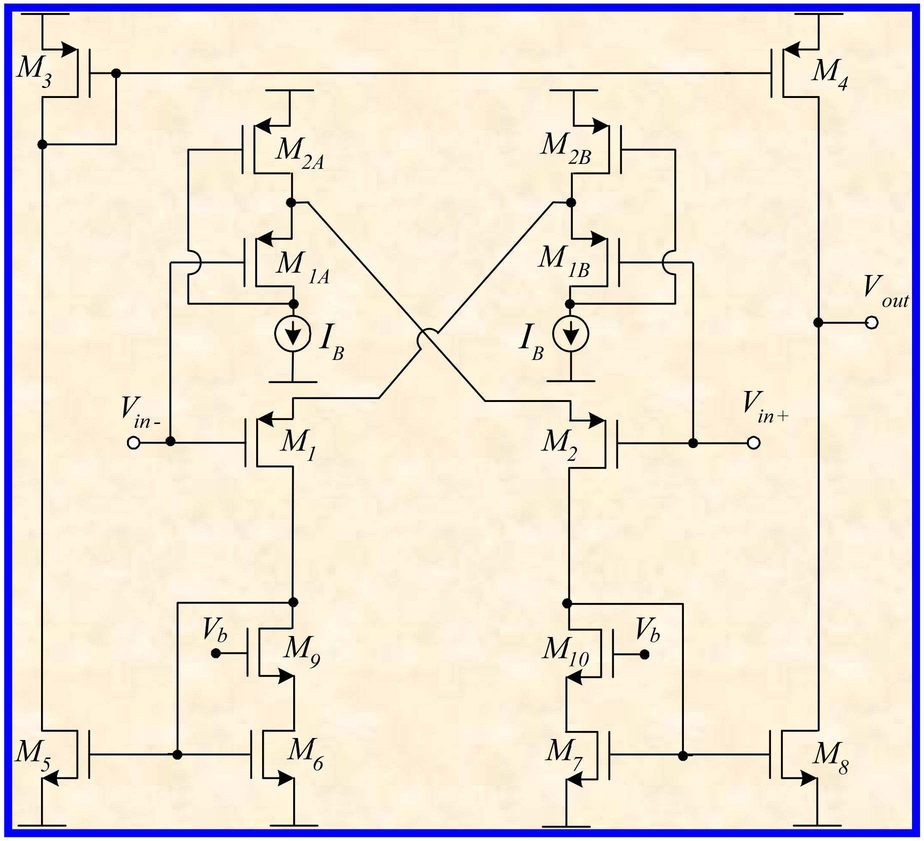
1st proposed OTA

LFL: Basic Cells

Local Feedback Loops: Super Class-AB operation

Non-linear current mirror



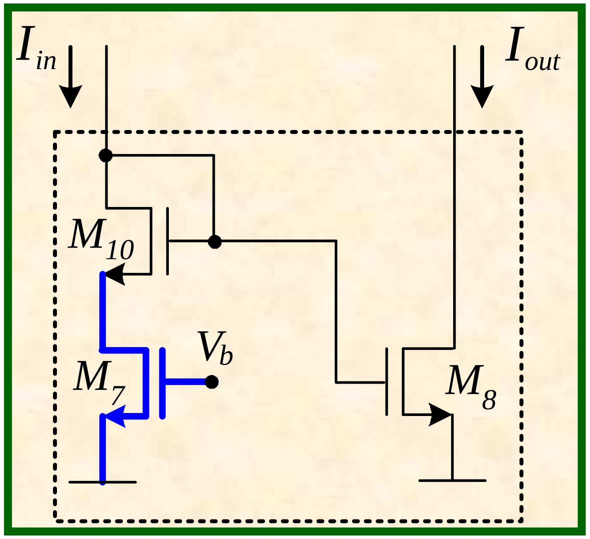


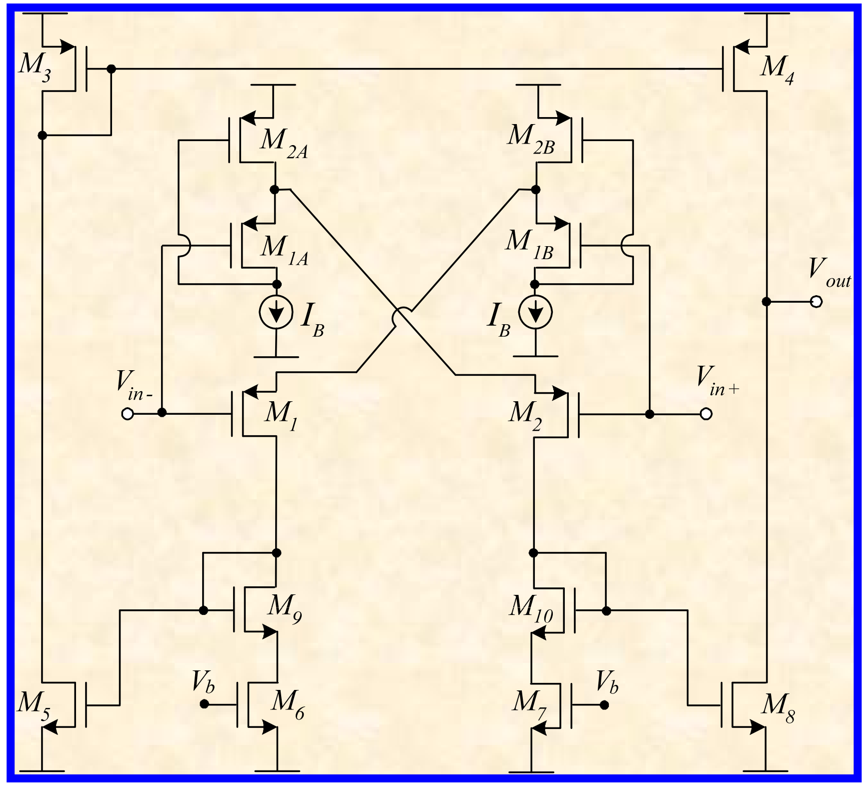
2nd proposed OTA

LFL: Basic Cells

Local Feedback Loops: Super Class-AB operation

Non-linear source degenerated current mirror

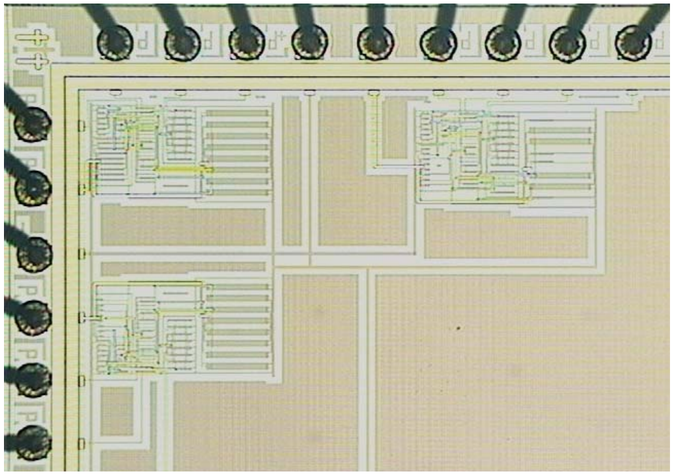




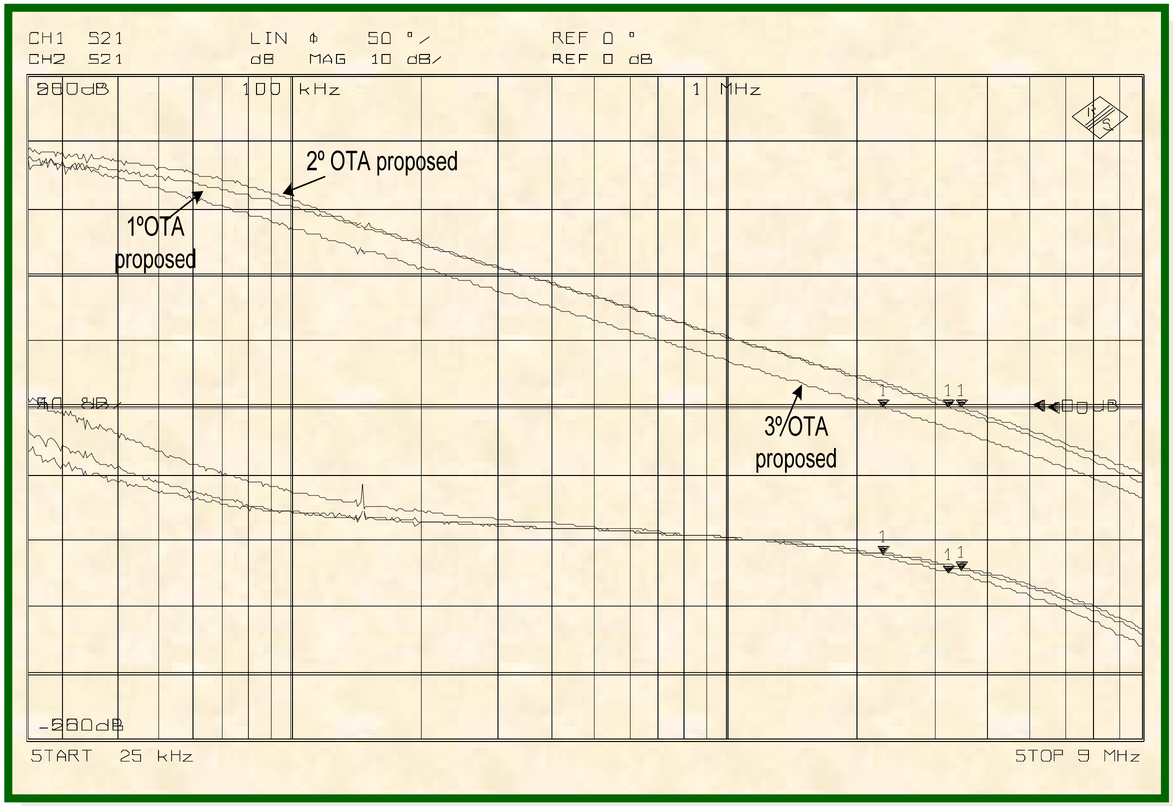
3rd proposed OTA

LFL: Basic Cells

Local Feedback Loops: Super Class-AB operation



V_{DD}=±1V
I_B=10µA
C_L=80pF

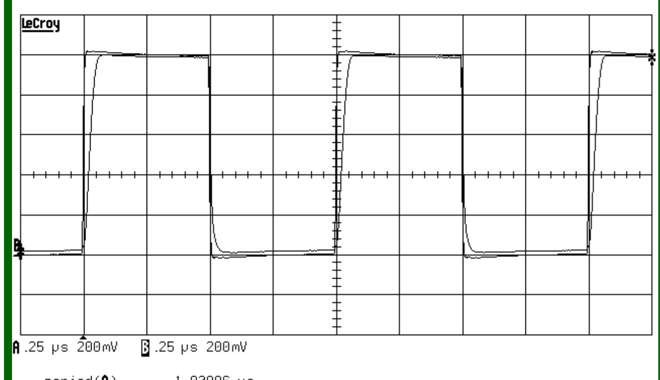


AMI 0.5 µm CMOS Technology

Frequency Response

LFL: Basic Cells

Local Feedback Loops: Super Class-AB operation



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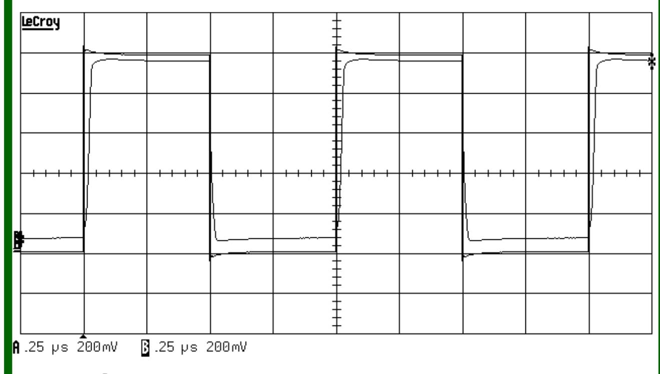

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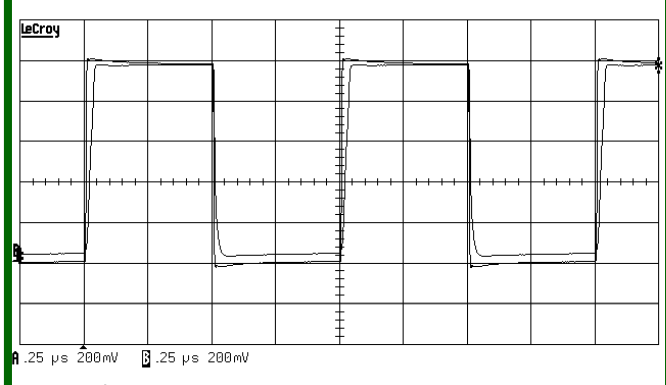

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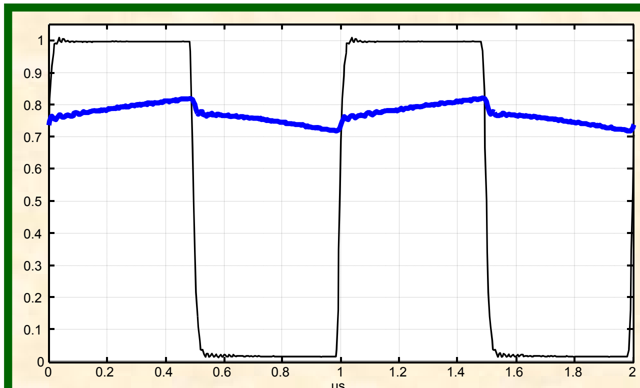

[redacted]

LFL: Basic Cells

Local Feedback Loops: Super Class-AB operation

Measured performance of the fabricated OTAs

Slew Rate (positive)	0.35 V/μs	10 V/μs	20 V/μs	14 V/μs
Slew Rate (negative)	-0.4 V/μs	-15 V/μs	-54 V/μs	-28 V/μs
GBW	200 kHz	3.27 MHz	3.46 MHz	2.3 MHz
Static power consumption	80 μW	220 μW	140 μW	140 μW