Continuous-time filters

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Applications and problems

- Applications
  - Anti-aliasing filters
  - Video and HF filters : hard-disk drives
  - Channel select filters
  - Low-power filters
- Problems:
  - Tuning for high precision: mismatch < 5 %
  - Distortion : THD < -60 dB
  - Low power supply voltages
  - High quality factors : Q > 50 ?

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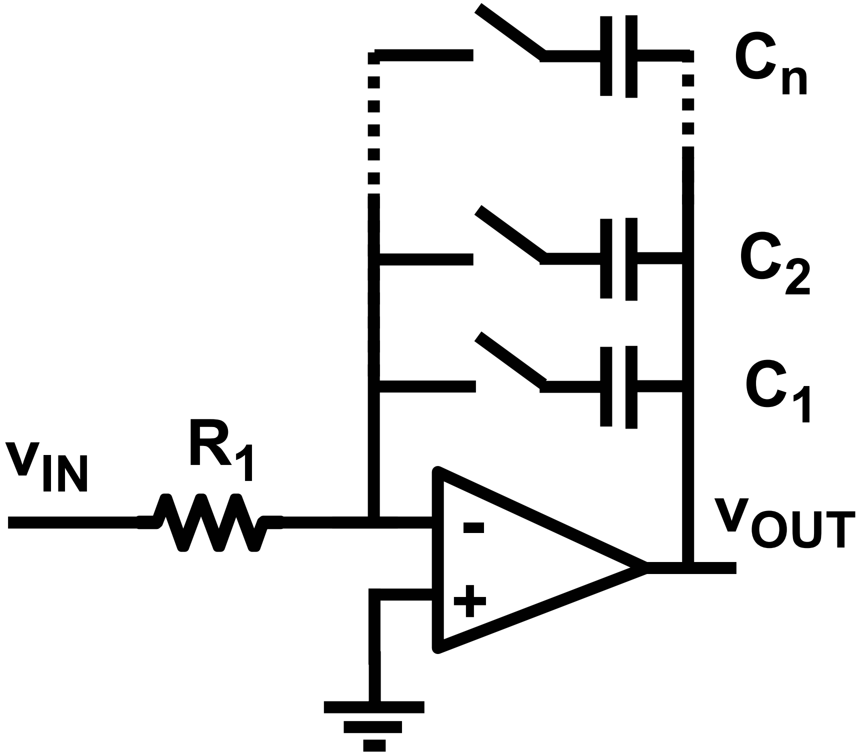
- ◆ **Active RC filters**
- ◆ **MOSFET-C filters**
- ◆ **GmC filters**
- ◆ **Comparison**

Ref.: Tsividis, Voorman, Integrated Cont.-time filters, IEEE Press 1993
J. Silva-Martinez, Kluwer 1993,
W. Dehaene, JSSC, July 1997, 977-988

Active RC filters

Opamps and passive components (R, C)



Advantages :
S/N up to 100 dB
THD very low < - 90 dB

Disadvantages :
Opamps :
only for low frequencies
Errors on R, C ≈ 20 %
>> tune C's

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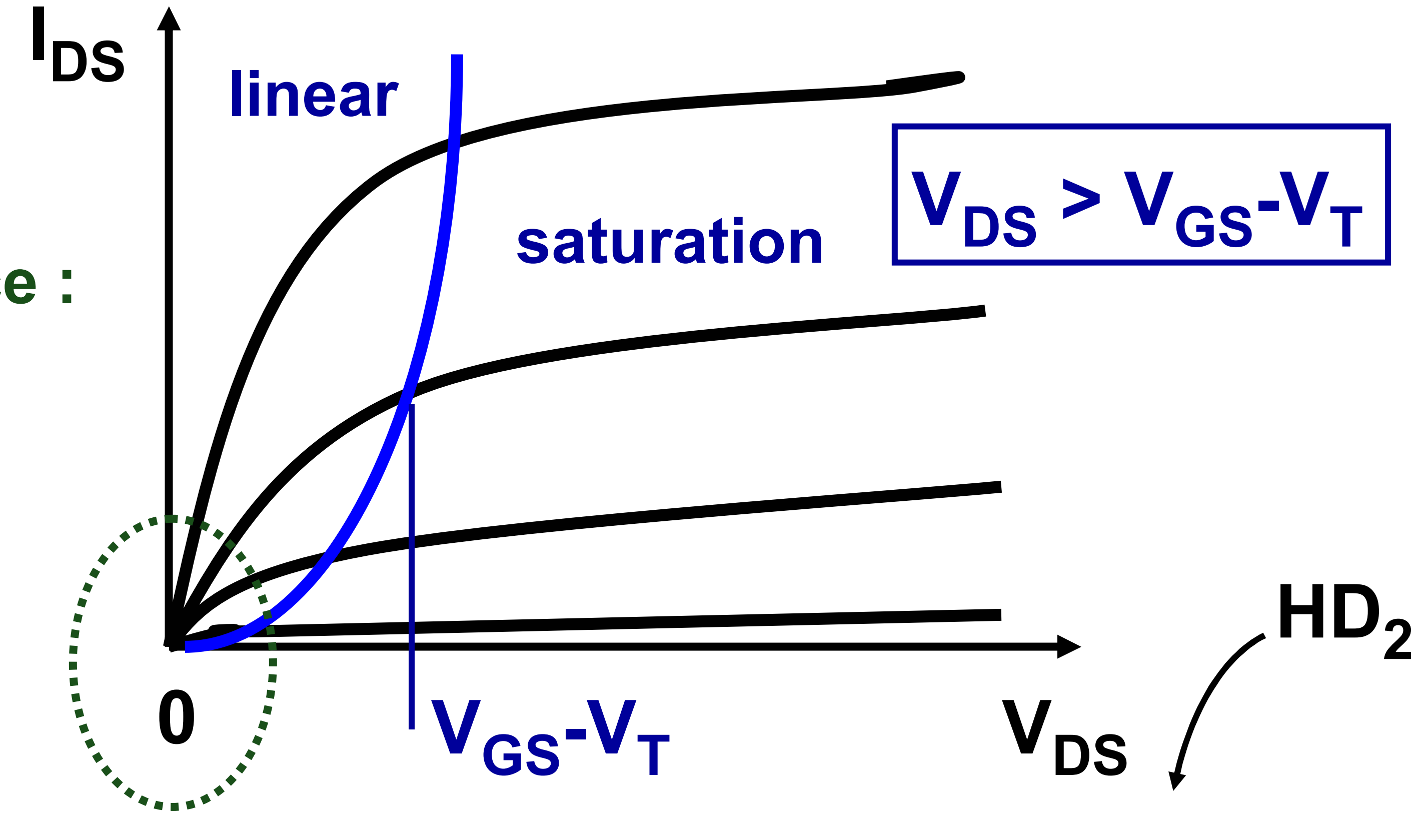
Ref.: Silva-Martinez, Dehaene, ..

MOST resistors

On-resistance :

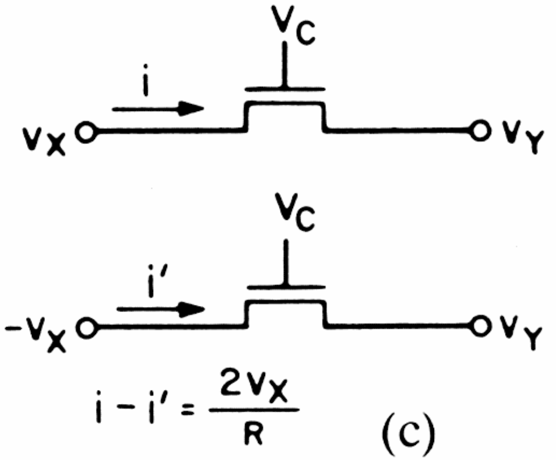
$$R_{on} = \frac{1}{\beta\,(V_{GS}-V_T)}$$

$$\beta = KP\,\frac{W}{L}$$

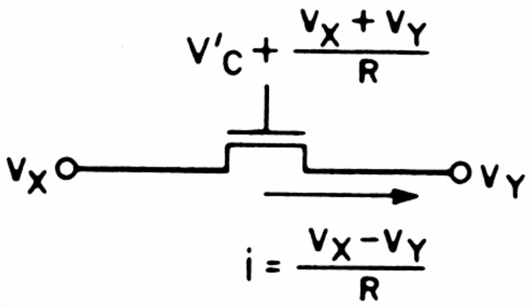


$$i_{DS} = KP\,\frac{W}{L}\left[(v_{GS}-v_T)v_{DS} - \frac{v_{DS}^{\,2}}{2}\right]$$

Examples of differential MOST-R's

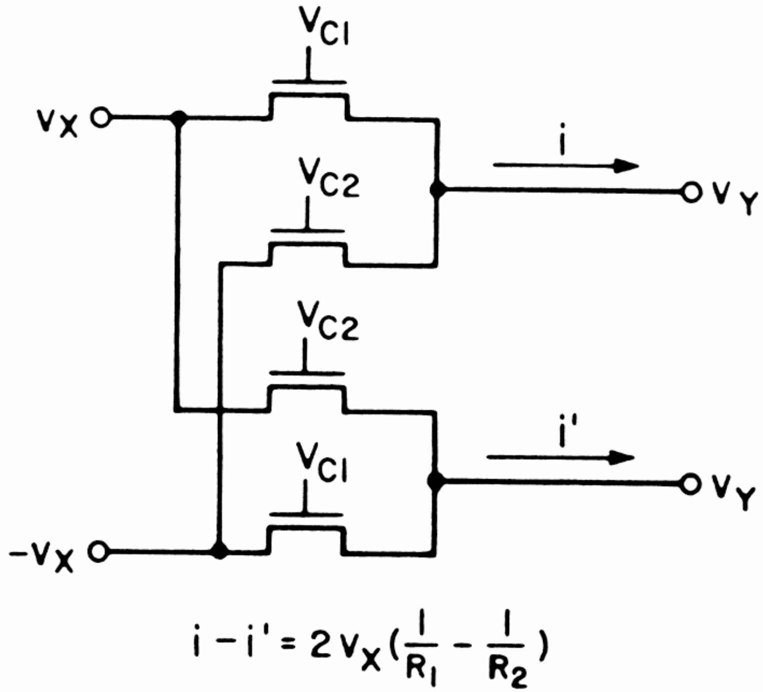


(c)



(d)

partial cancellation of even nonlin

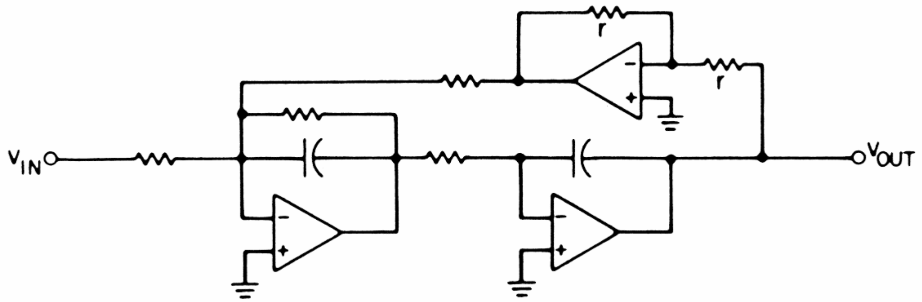


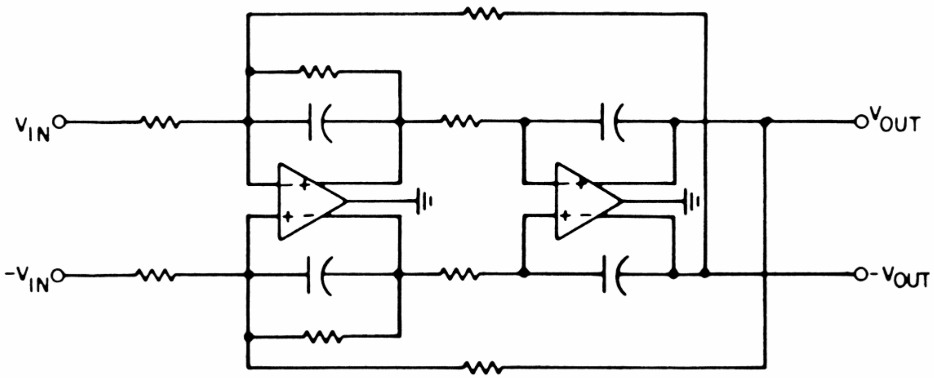
(h)

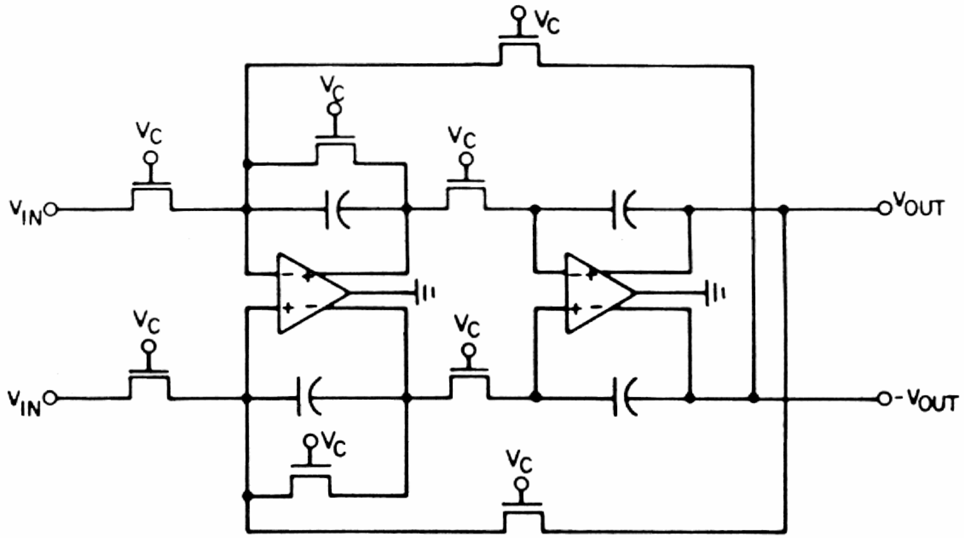
cancellation of even
and odd nonlinearities

Ref. Tsividis JSSC Feb.86, 15-30; Ma.94, 166-176

From active RC to MOSFET-C filter







Ref. Tsividis JSSC Feb.86, 15-30

Large R_{ON} values at high frequencies

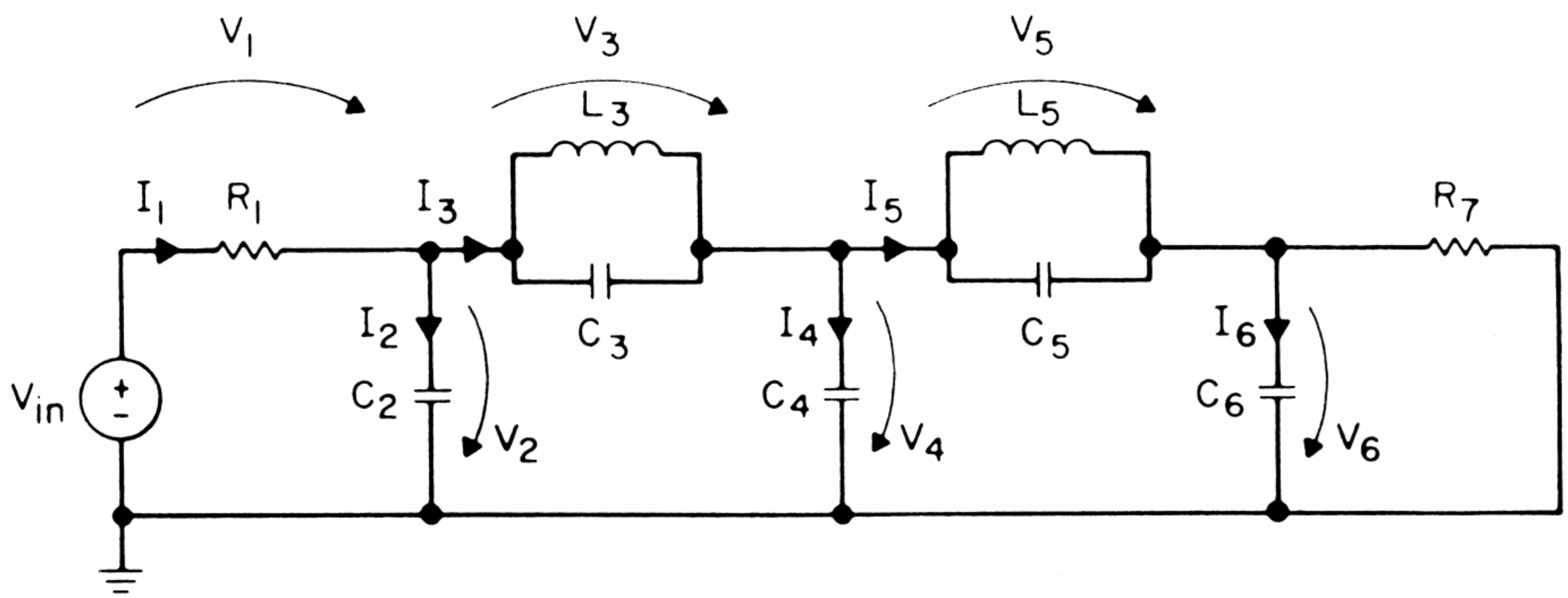
For low-frequency low-pass filter with f-3dB

$$f_{-3dB} = \frac{1}{2\pi R_{on} C} \approx \frac{KP\ W/L\ (V_{GS}-V_T)}{2\pi\ C}$$

For f_{-3dB} = 4 kHz; KP= 60 $\mu A/V^2$; $V_{GS}-V_T$ = 1 V; W = 2 μm; C = 10 pF
R_{on}= 4 MΩ. For matching W = 2 μm: L ≈ 500 μm ! The area is 10^{-5} cm^2

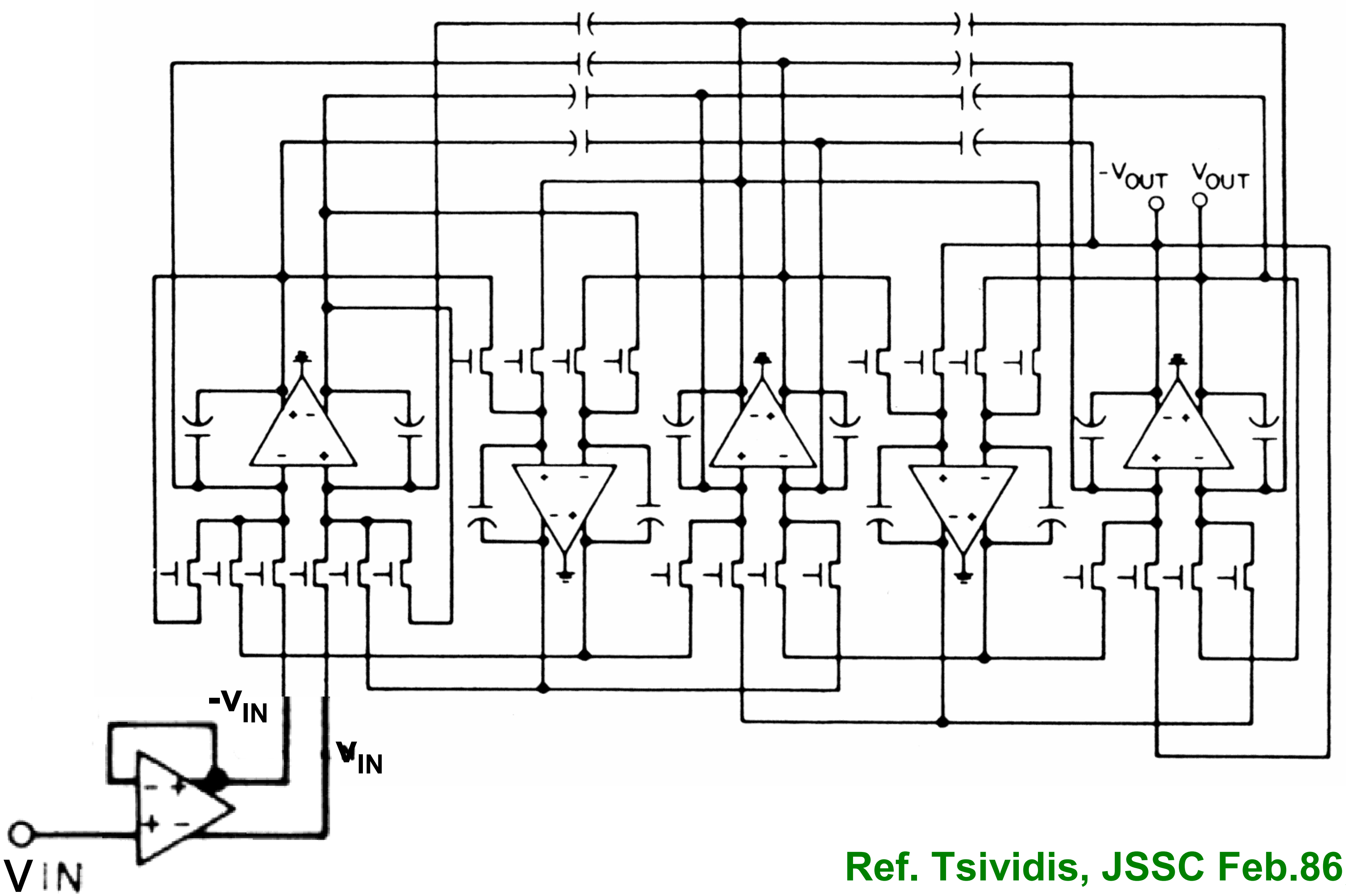
For $C_{ox} = 5.10^{-7}$ F/cm^2 (0.35 μm); C_{GS} = 5 pF;
High-frequency limit at ≈ 8 kHz or f_T ≈ 8 kHz !!!!!!

LC ladder filter



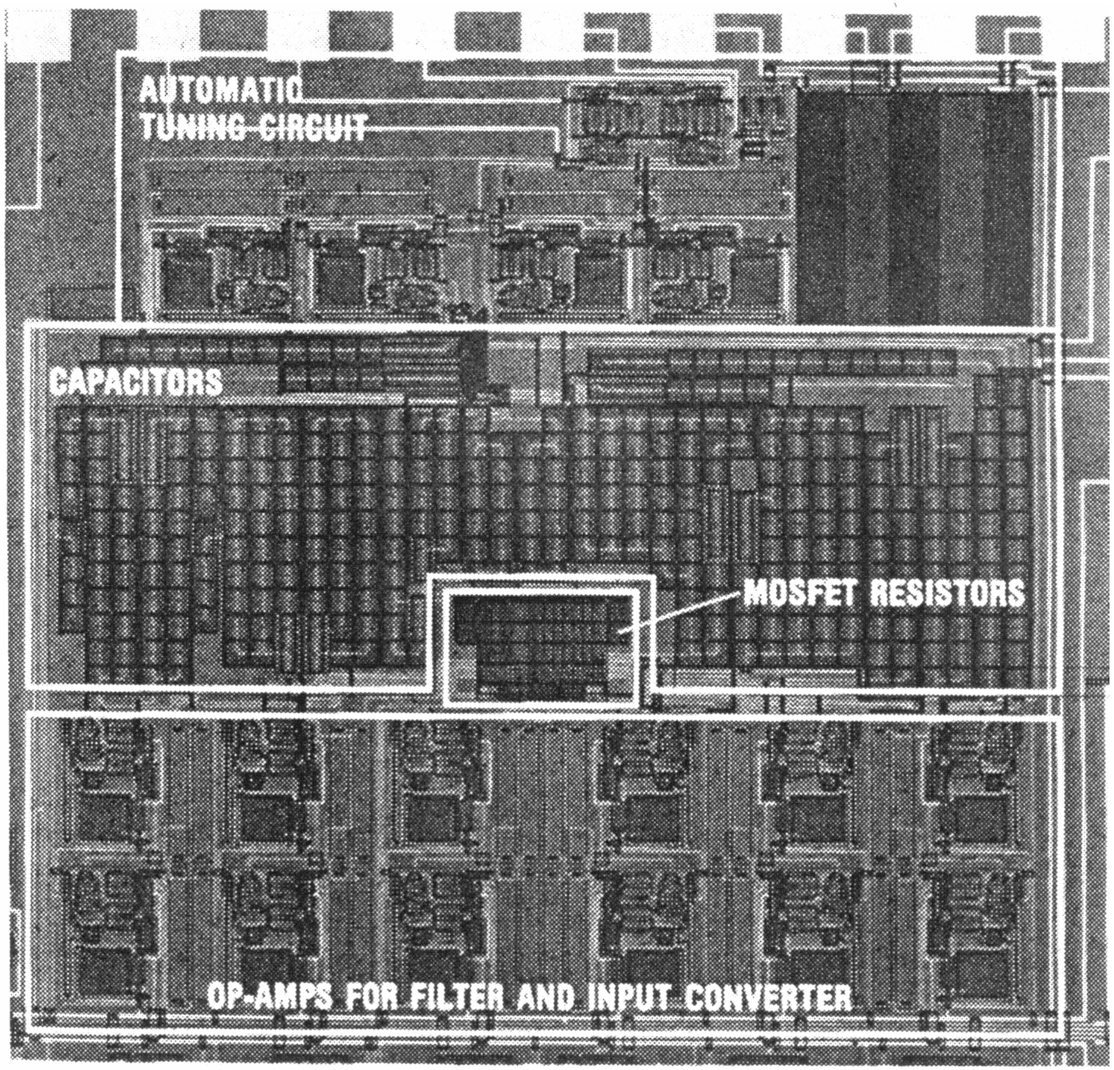
Ref. Banu
JSSC Dec.85,
1114-1121

Fifth-order low-pass filter



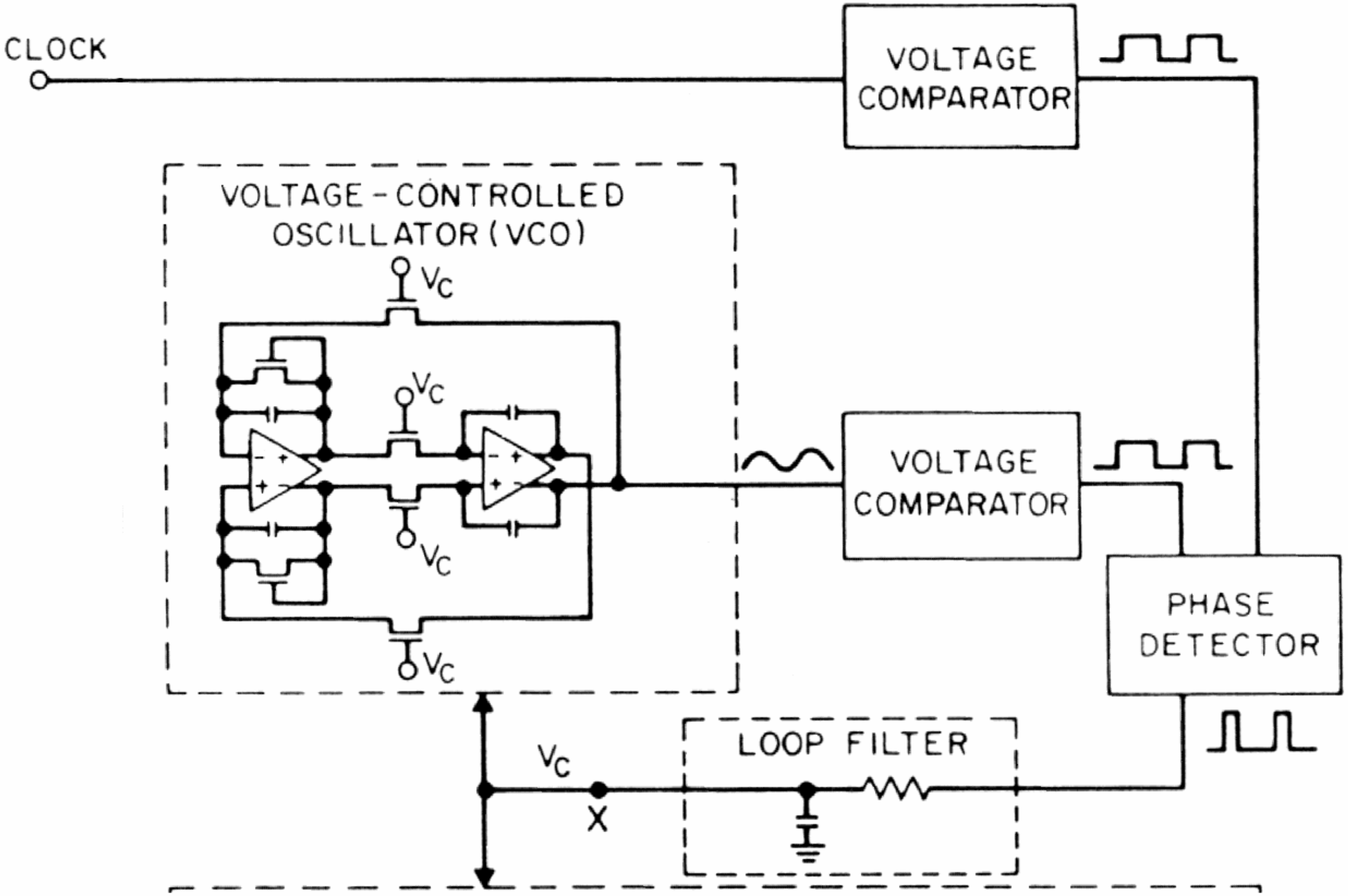
Ref. Tsividis, JSSC Feb.86, 15-30

Fifth-order elliptic low-pass filter



Ref. Tsividis
JSSC Feb.86,
15-30

PLL tuning



Filter

Problems:

Master/slave for each pole/zero

VCO + PLL at f_c

Signal feedthrough at f_c

Ref.
Banu JSSC Dec.85, 1114-1121
Krummenacher, JSSC June 88, 750-758
Khoury, JSSC Dec.91, 1988-1997

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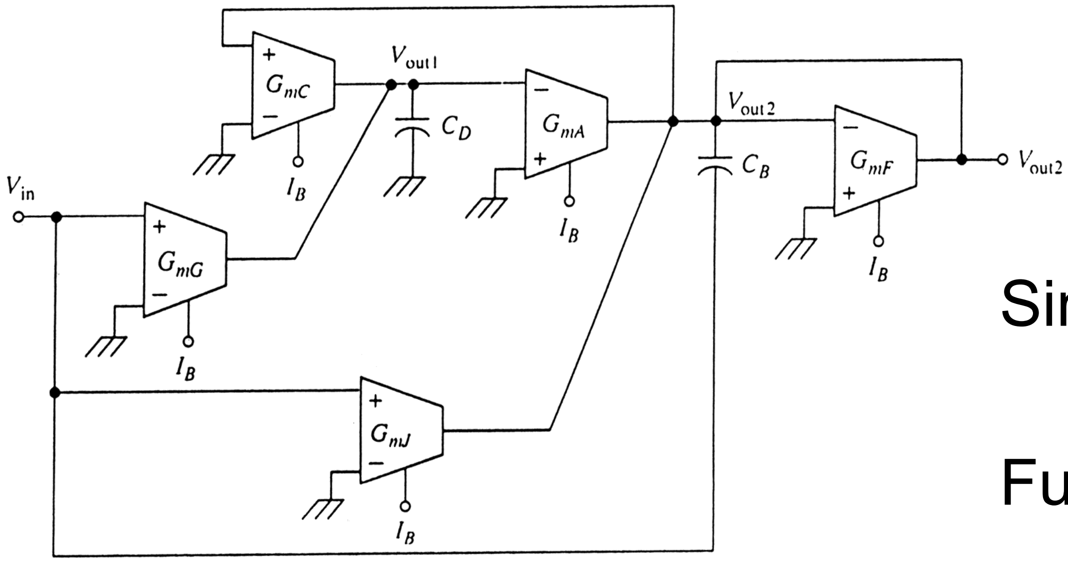
- MOSFET-C filters
- GmC filters
  - Transconductors
  - Tuning
- Comparison

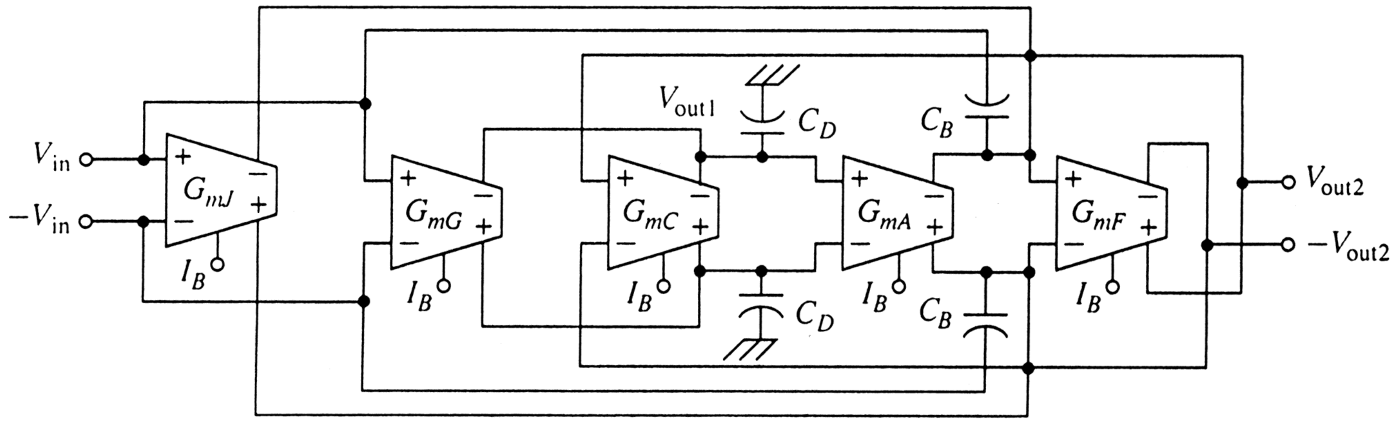
Ref.: Silva-Martinez, Dehaene, ..

Some GmC filters



Single-ended GmC filters

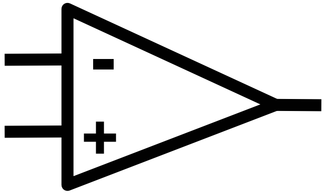
Fully-differential ...



GmC filter definition

Opamp

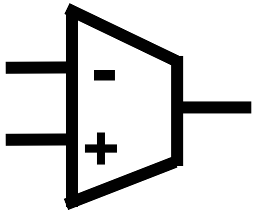
Operational
amplifier



$$A_v = \frac{v_{OUT}}{v_{IN}}$$

OTA

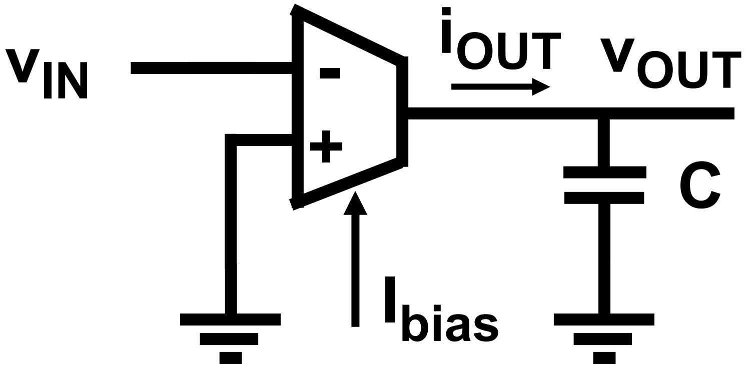
Operational
Transconduct.
amplifier



$$A_g = \frac{i_{OUT}}{v_{IN}}$$

$A_v =$ $= A_g R_L$

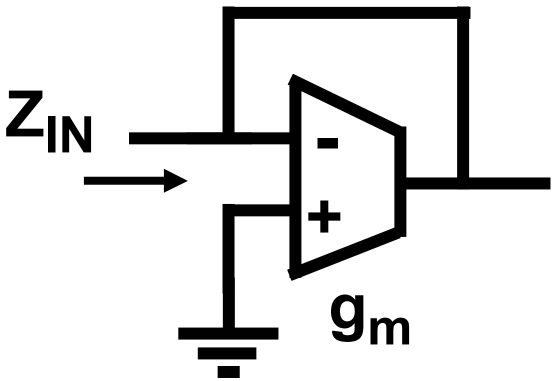
A_g or G_m (I_{bias})

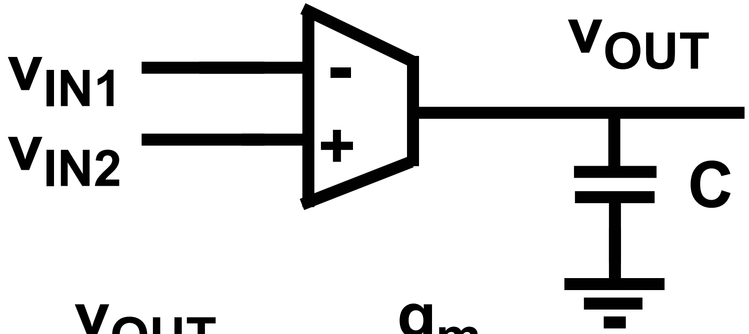


Adv.: High freq. operation
Easy tuning

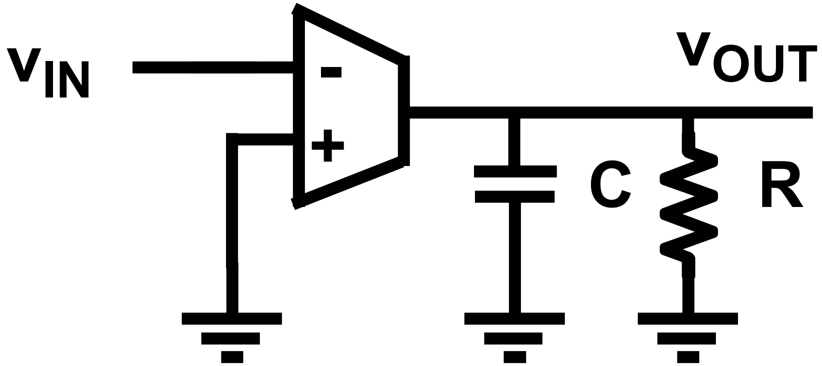
Disadv.: Distortion
Mismatch errors
Parasitic C's (low Q)

Simple GmC filters



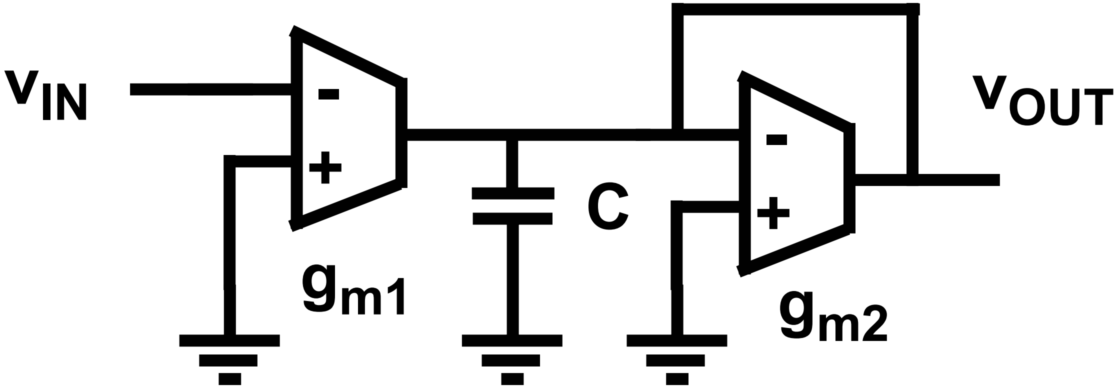


$$\frac{v_{OUT}}{v_{IN1} - v_{IN2}} = \frac{g_m}{sC}$$

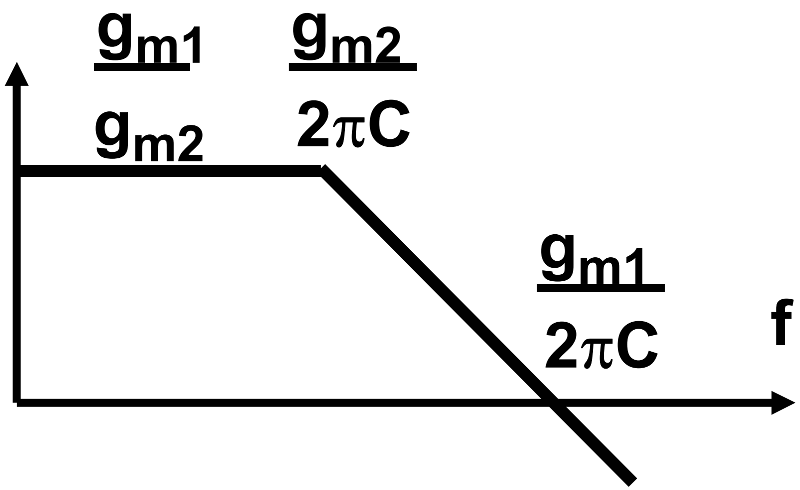


$$\frac{v_{OUT}}{v_{IN}} = \frac{g_m R}{1 + sRC}$$

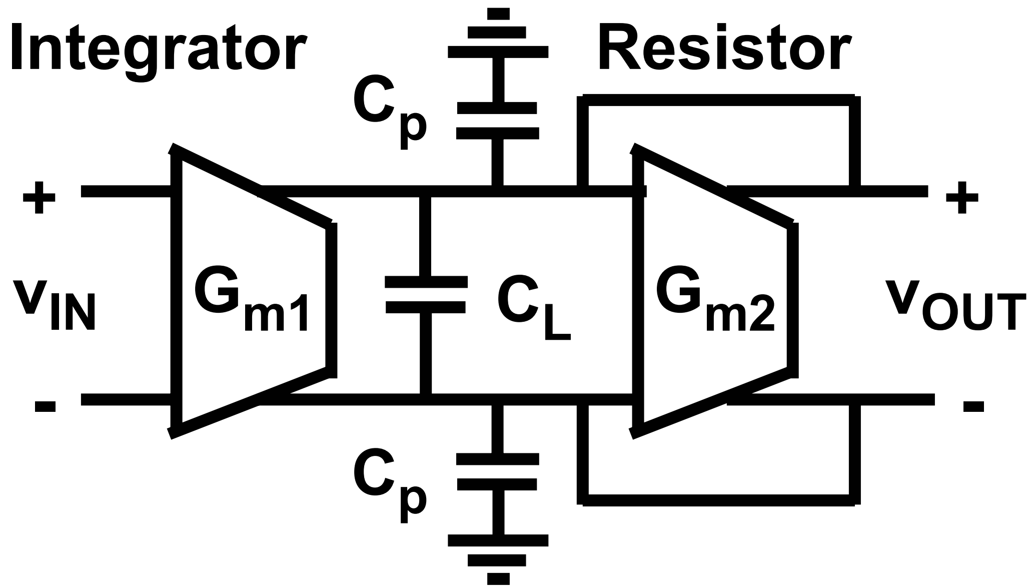
Simple GmC filters



$$\frac{v_{OUT}}{v_{IN}} = \frac{g_{m1}}{g_{m2} + sC}$$



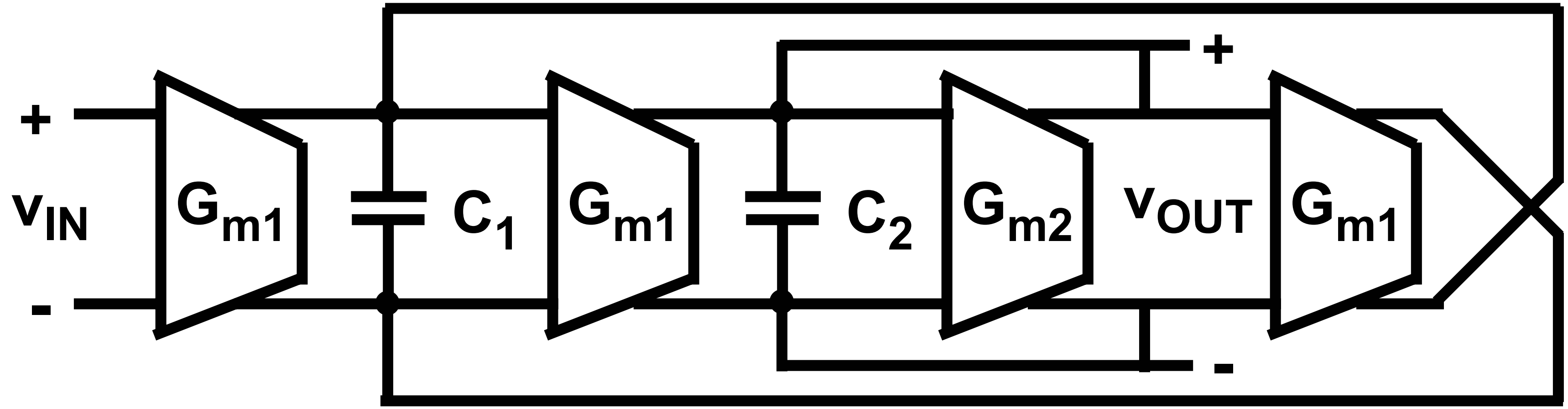
Simple fully-differential GmC filters



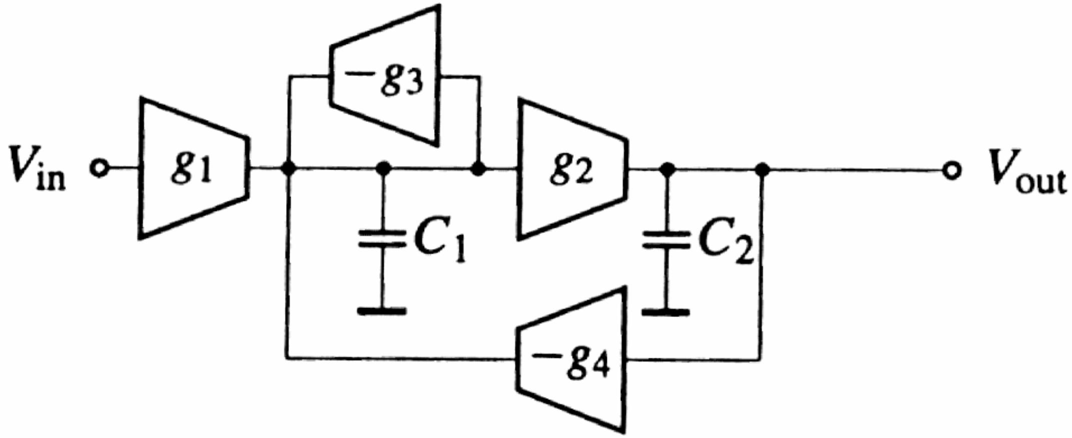
Lossy integrator

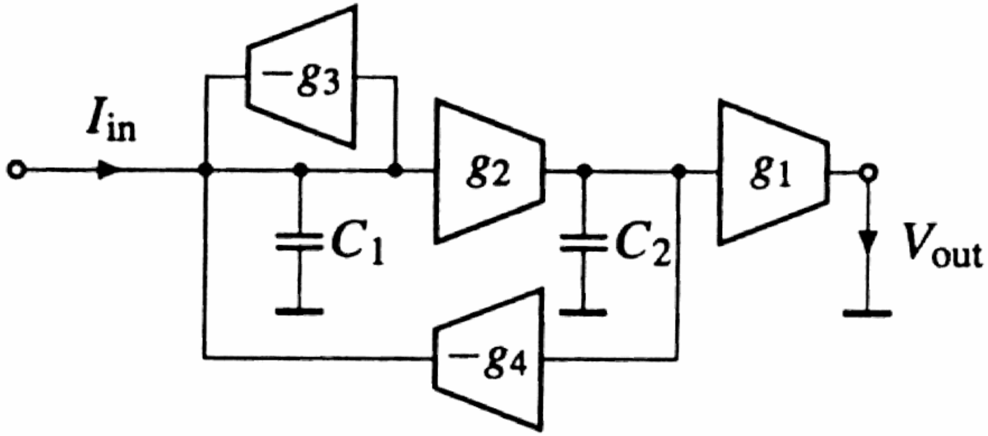
Sensitive to parasitic capacitances

Biquadratic cell

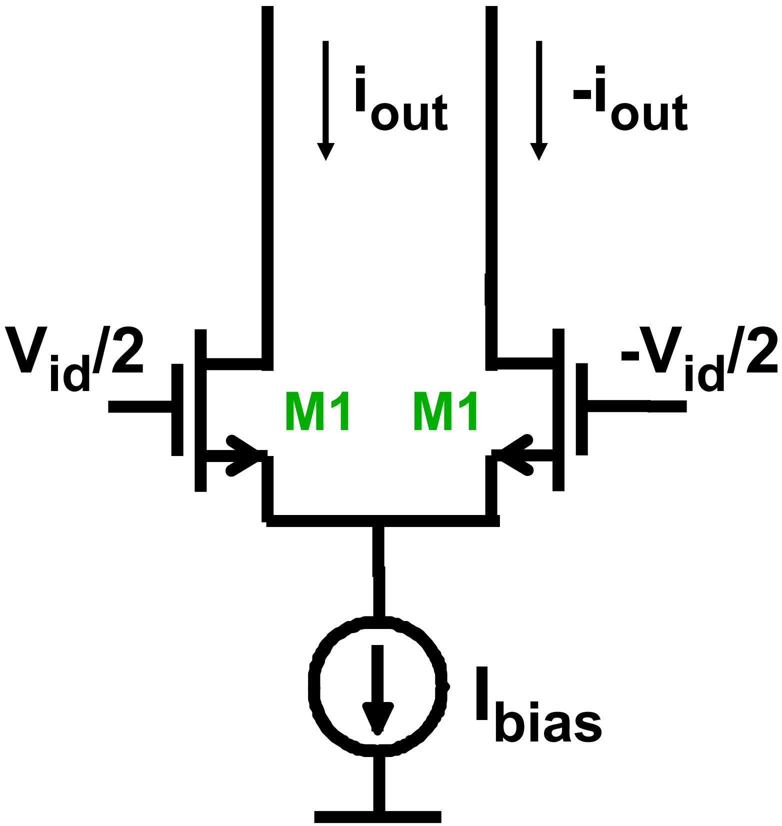


Voltage-mode & current-mode filters





A differential pair as a transconductor



$$IM_3 = 3HD_3 = \frac{3}{32}\,U^2$$

$$U = \frac{V_{Id}}{V_{GS} - V_T}$$

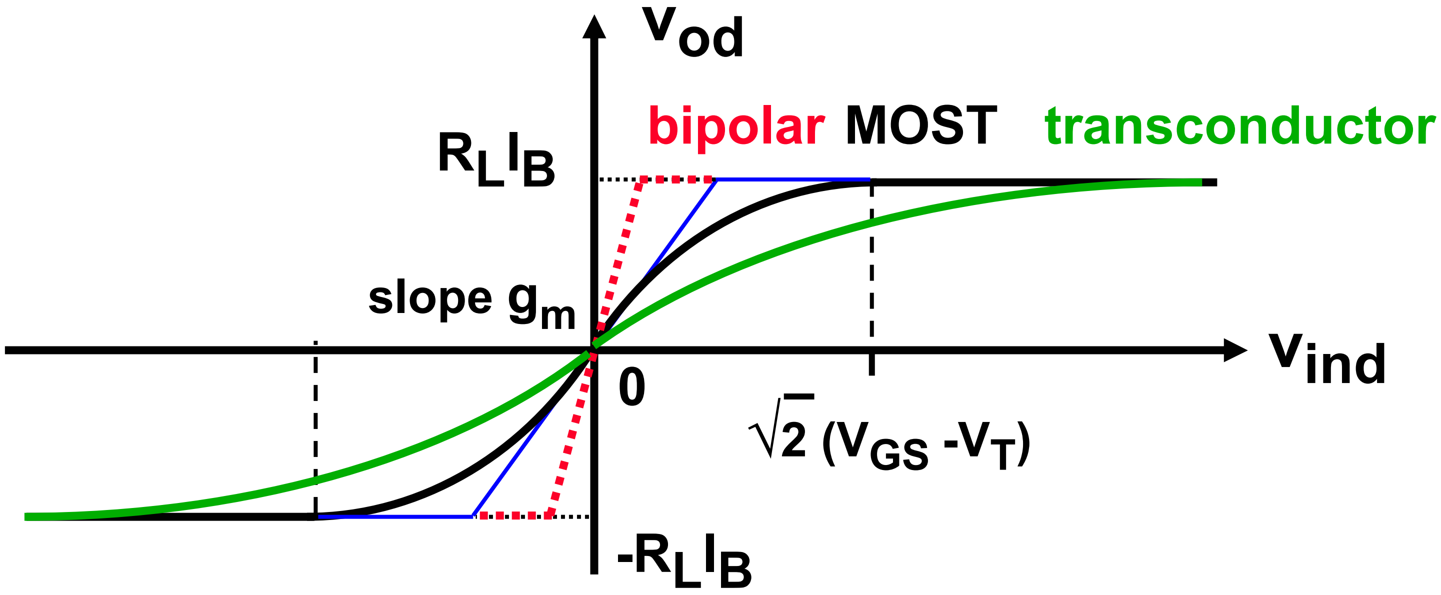
U is the relative current swing

$$\text{Max. } V_{idptp} \approx 2\sqrt{2}\,(V_{GS} - V_T)$$

$$IP_3 \approx 3.3\,(V_{GS} - V_T)$$

HD_3 = - 60 dB for V_{id} = 1 V requires V_{GS}-V_T = 6 V !!!

Amplifier or transconductor ?



Transconductor :

Wide input range : low distortion

Small gain g_m

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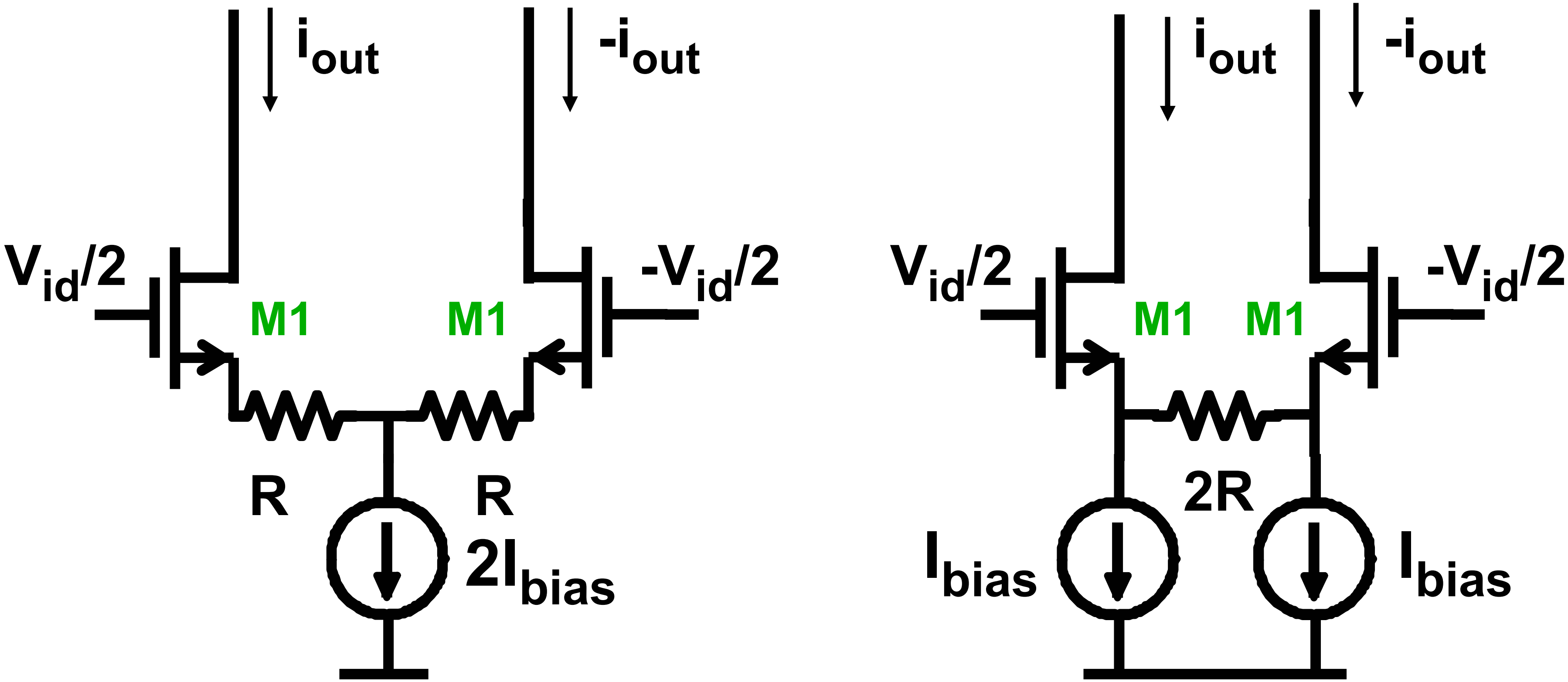
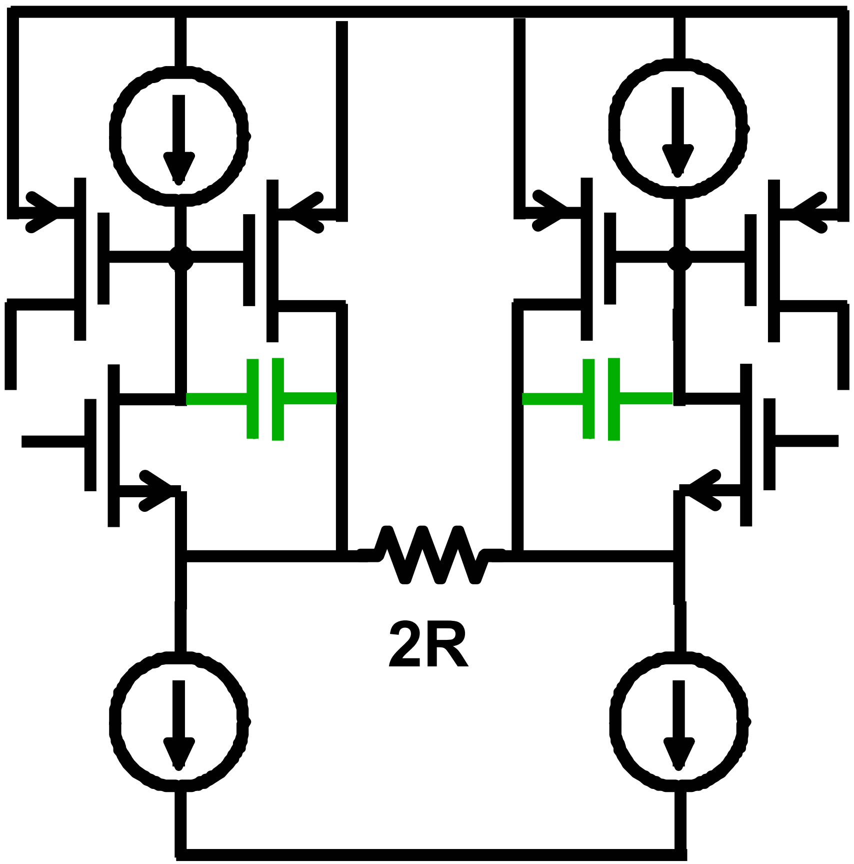
Increasing the IP_3 by feedback



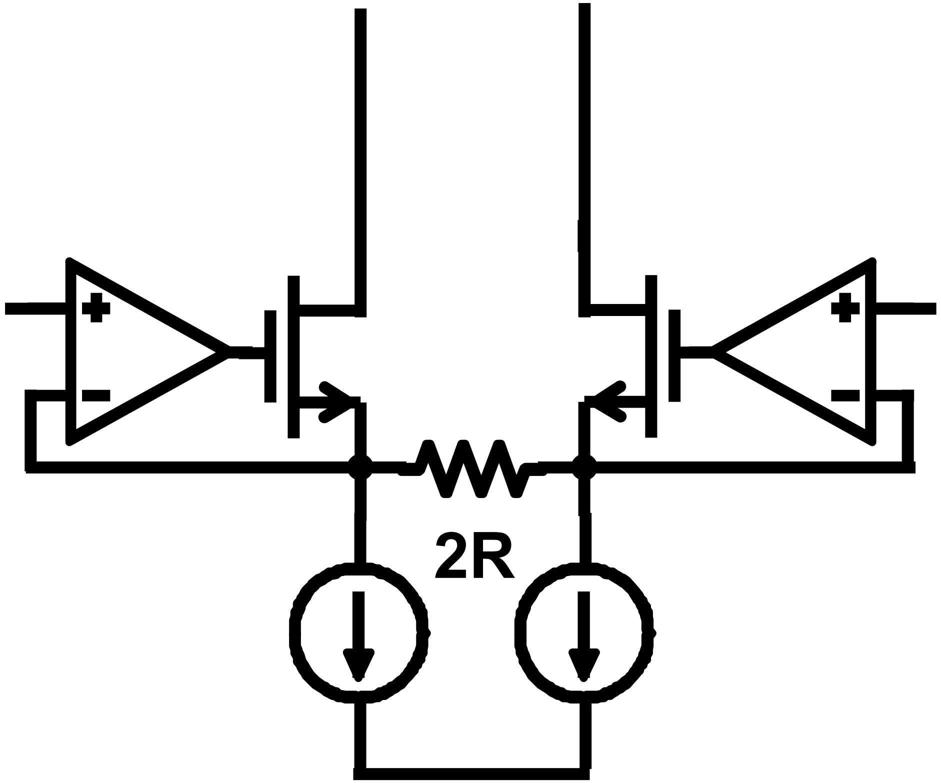
$IP_3 \approx 3.3\,(V_{GS}-V_T)(1+g_{m1}R)^2$ $\quad HD_3/n^2 \quad$ $n = 1+g_{m1}R$

HD_3 = - 60 dB for V_{id} = 1 V requires V_{GS}-V_T = 0.38 V and $g_{m1}R$ = 3 !!!

Increasing the IP_3 by FB and high loop gain

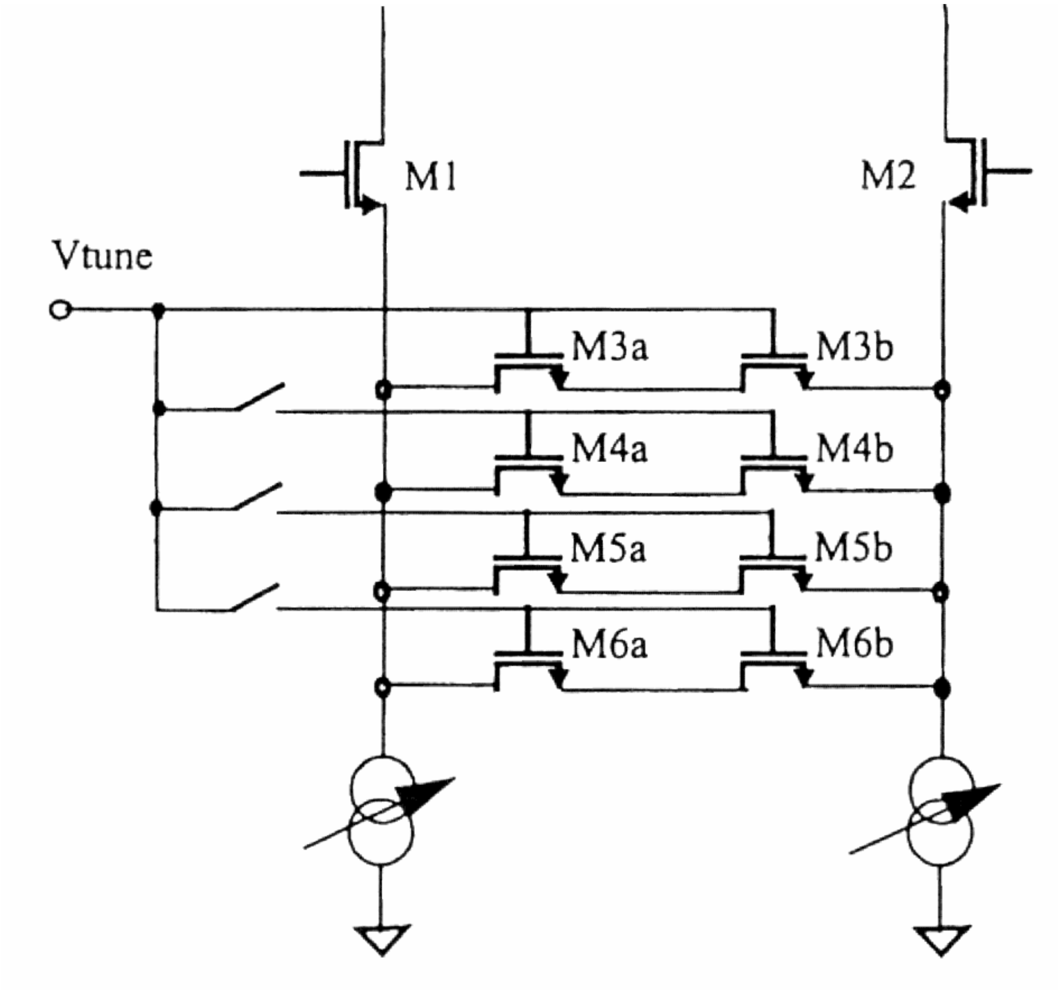


Additional local FB

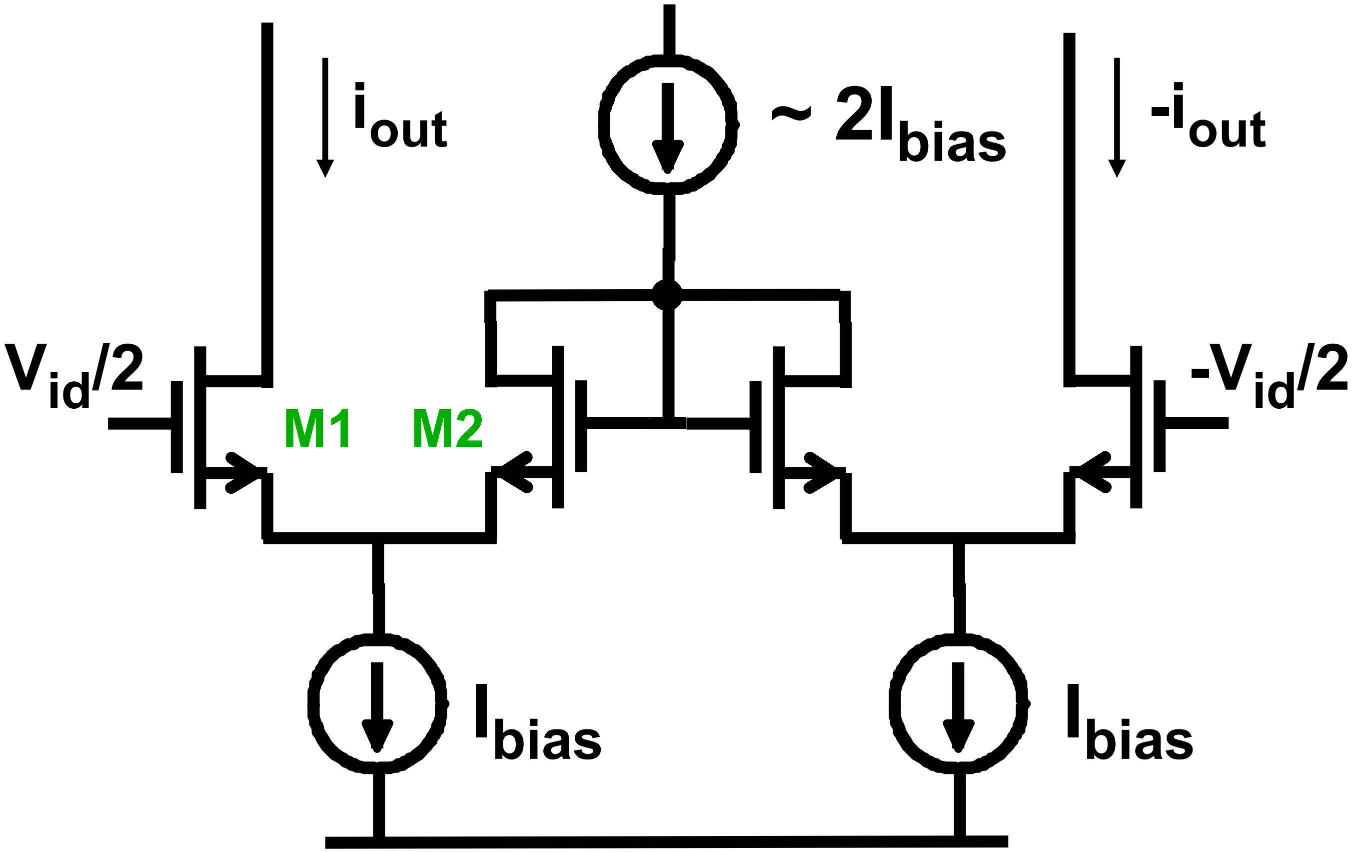


More FB with opamps

Tuneable resistances



By tuneable feedback



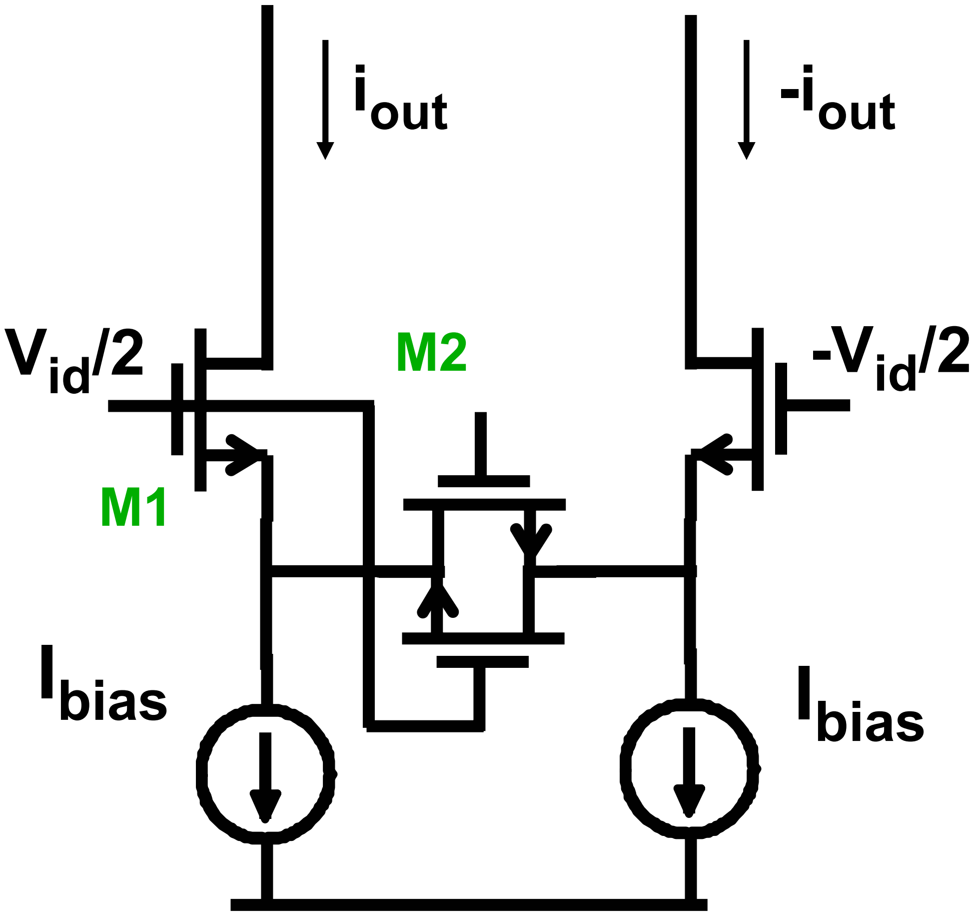
$$\frac{HD_3}{n^2}$$

$$n = 1 + \frac{g_{m1}}{g_{m2}}$$

$$IP_3 \approx 3.3\,(V_{GS} - V_T)n^2$$

Ref.Torrance etal CAS Nov.85, 1097-1104

By nonlinear feedback (input)



$$g_{mtot} = \frac{I_{bias}}{n\,(V_{GS1} - V_T)}$$

$$n = 1 + \frac{\beta_1}{4\beta_2} \qquad \frac{HD_3}{n^2}$$

$$IP_3 \approx 3.3\,(V_{GS1} - V_T)\,n^2$$

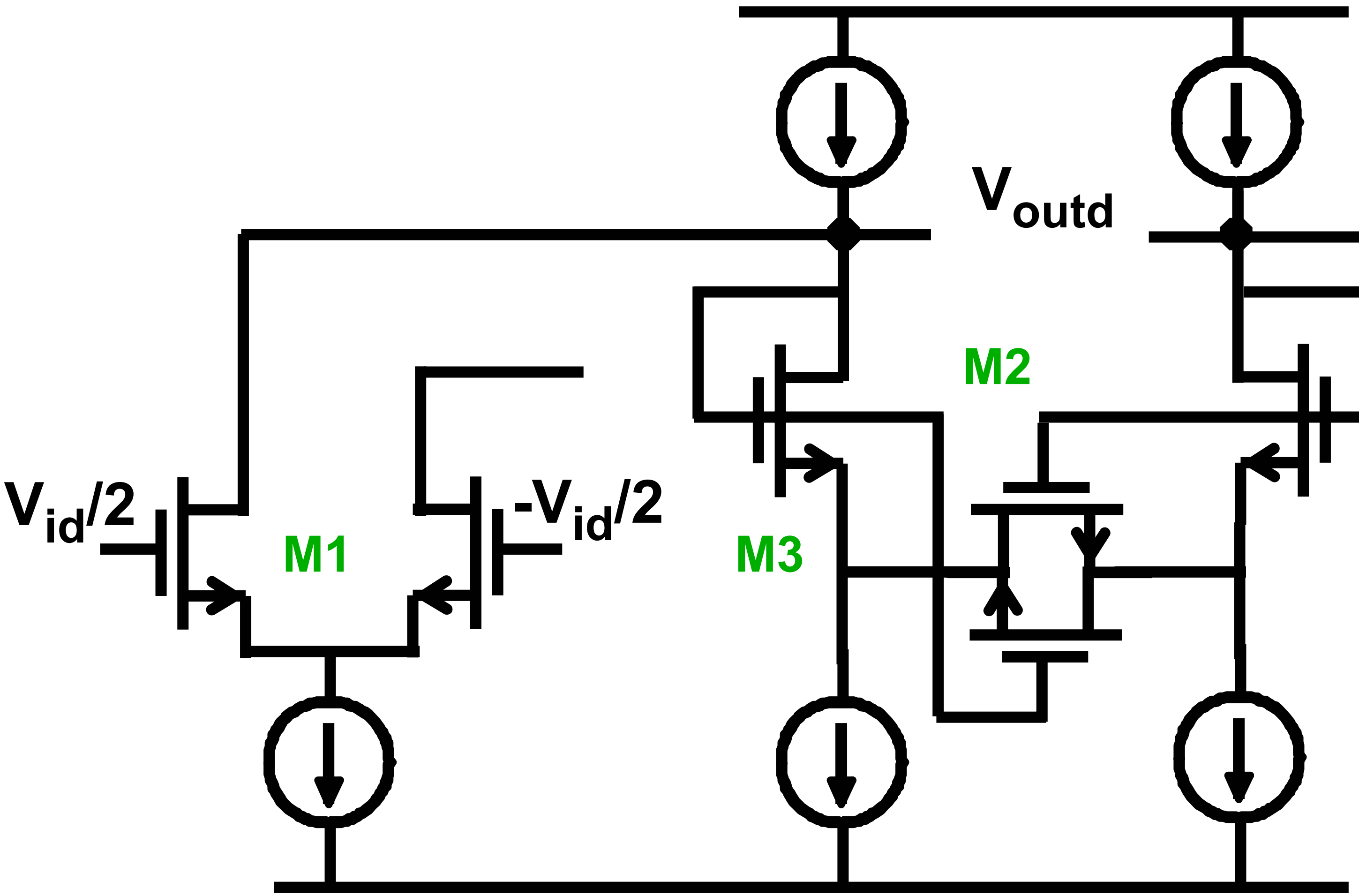
No extra current

No extra CM node !

But limited V_{GS}-V_T !

Ref. Krummenacher JSSC June 88, 750-758

By nonlinear feedback (as load)



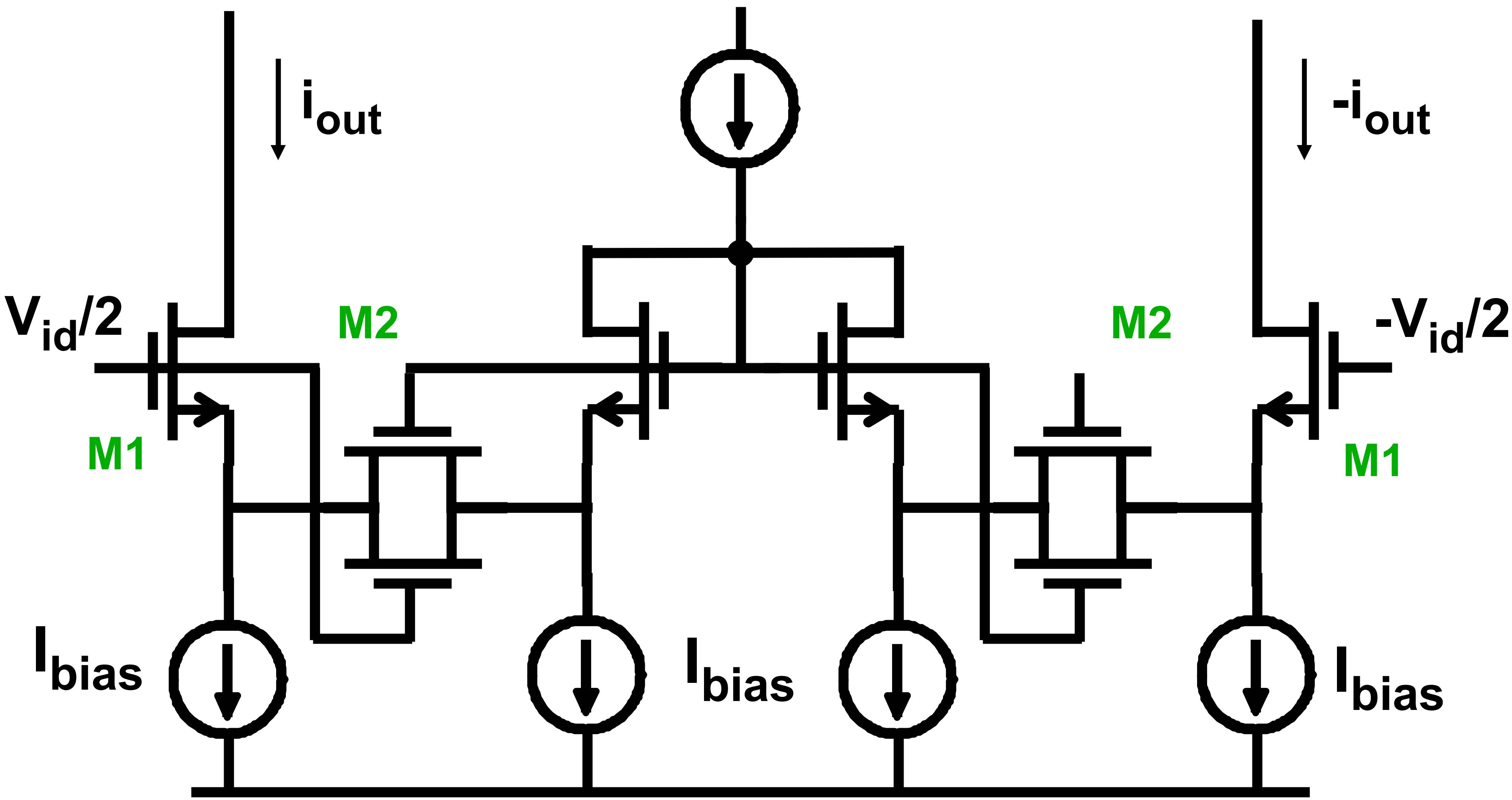
$$2R_{ind} \approx \frac{2\,n}{g_{m1}}$$

$$A_v = \frac{n\,g_{m3}}{g_{m1}}$$

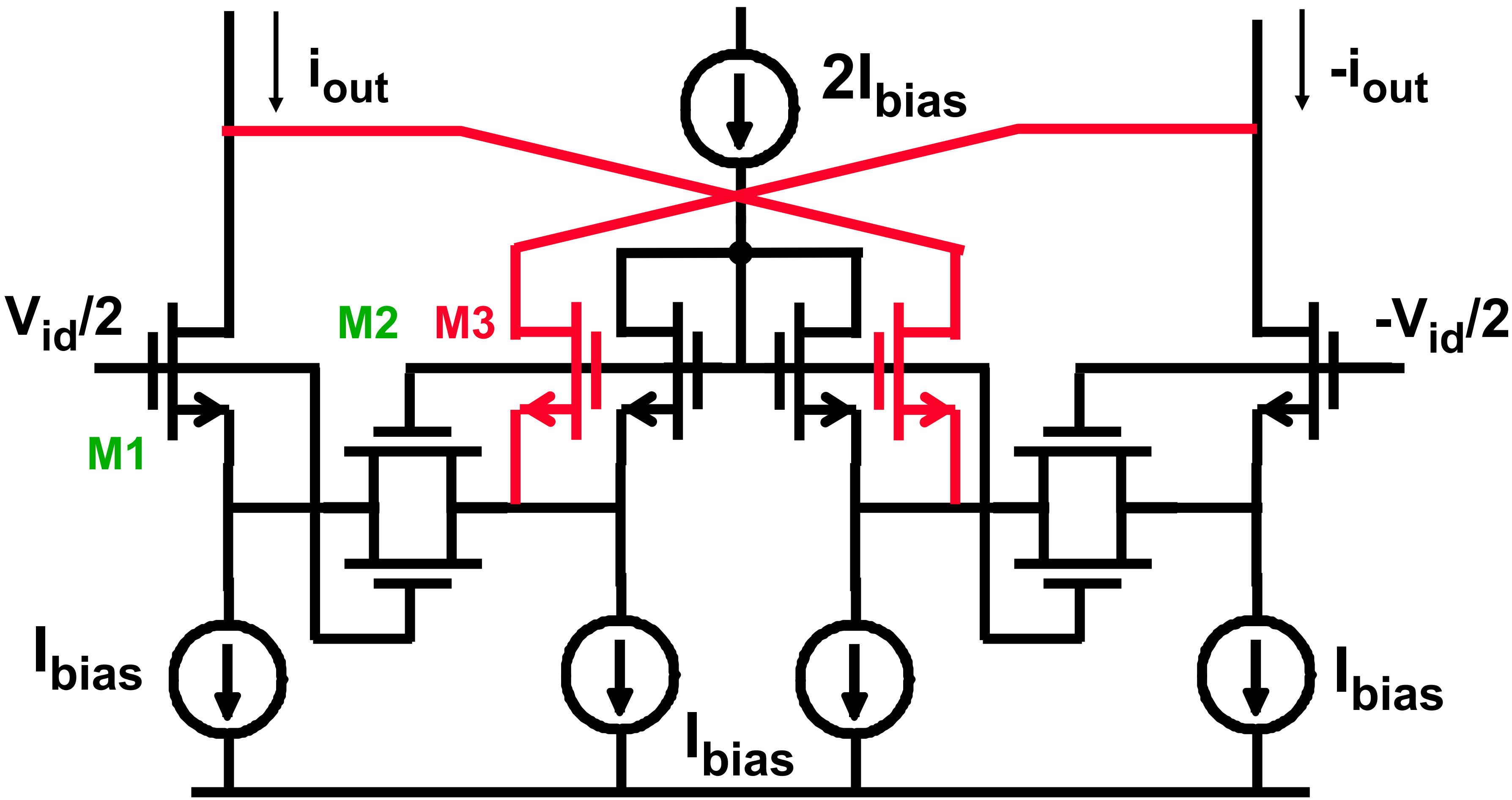
$$n = 1 + \frac{\beta_3}{4\beta_2}$$

Ref. Menolfi JSSC July 97, 968-976

Low-distortion combination : power !

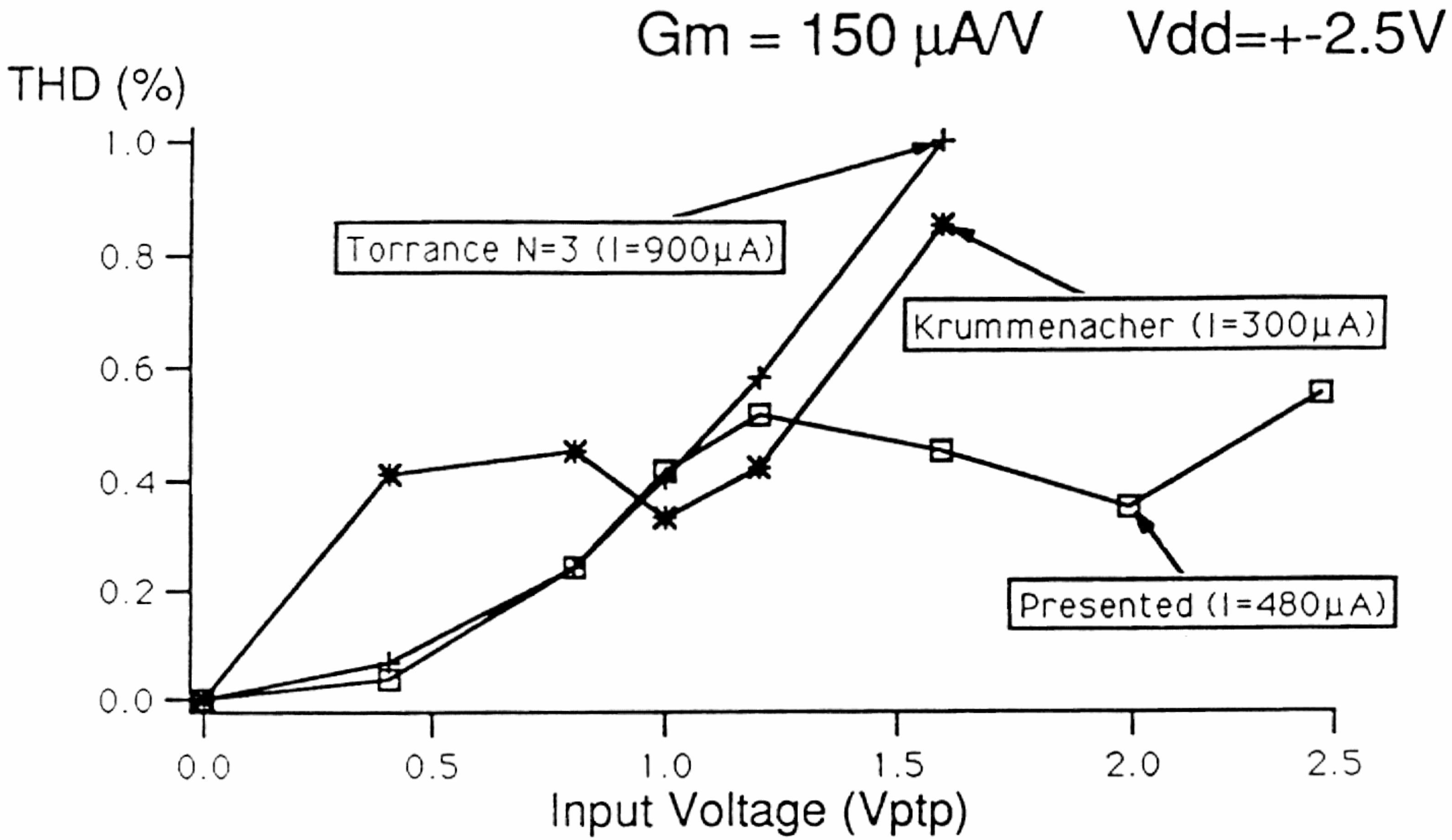


Reduced distortion by cross-coupling

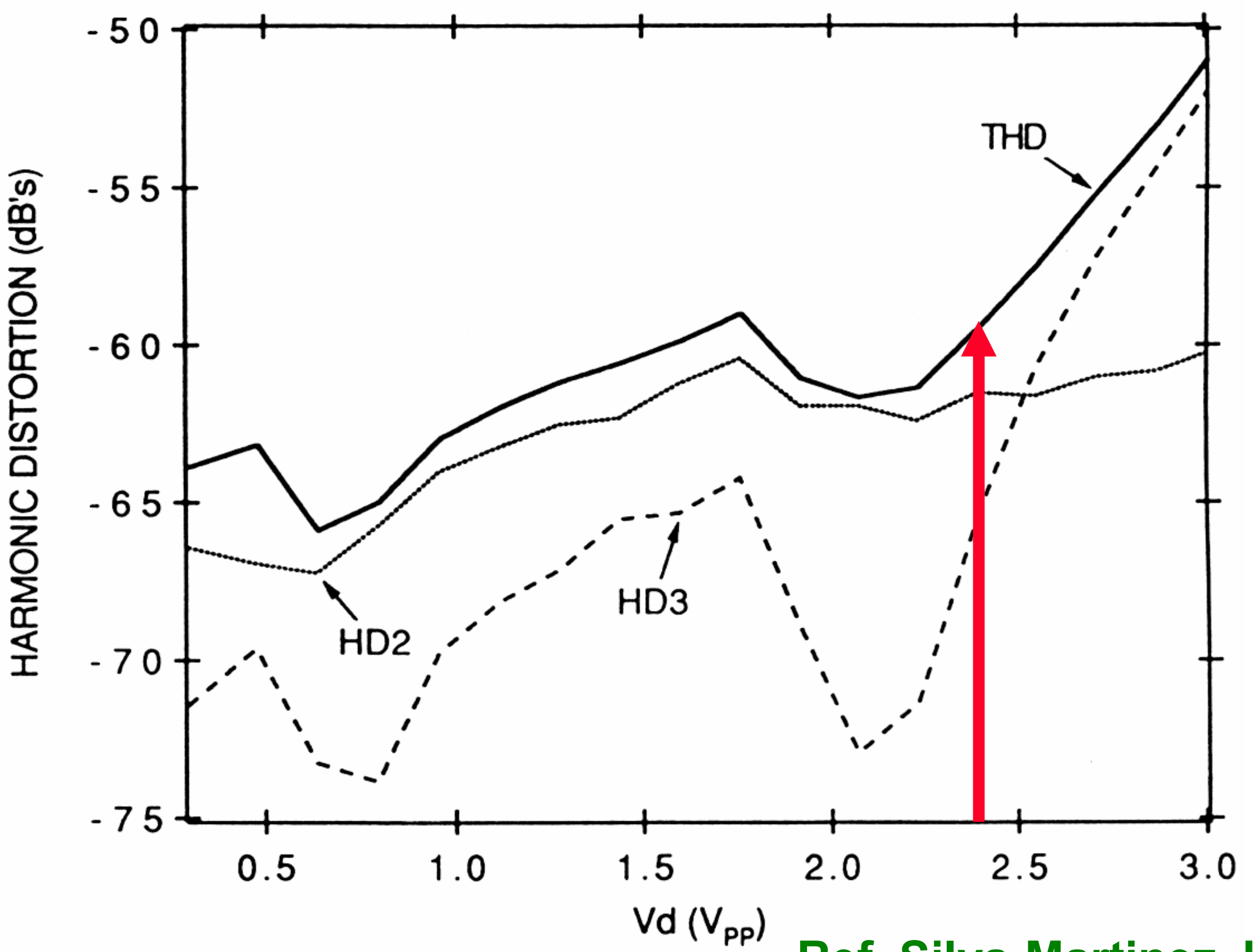


Ref. Silva-Martinez JSSC July 91,946-955

Comparison (simulations)



Measured THD for transconductor



THD ≈

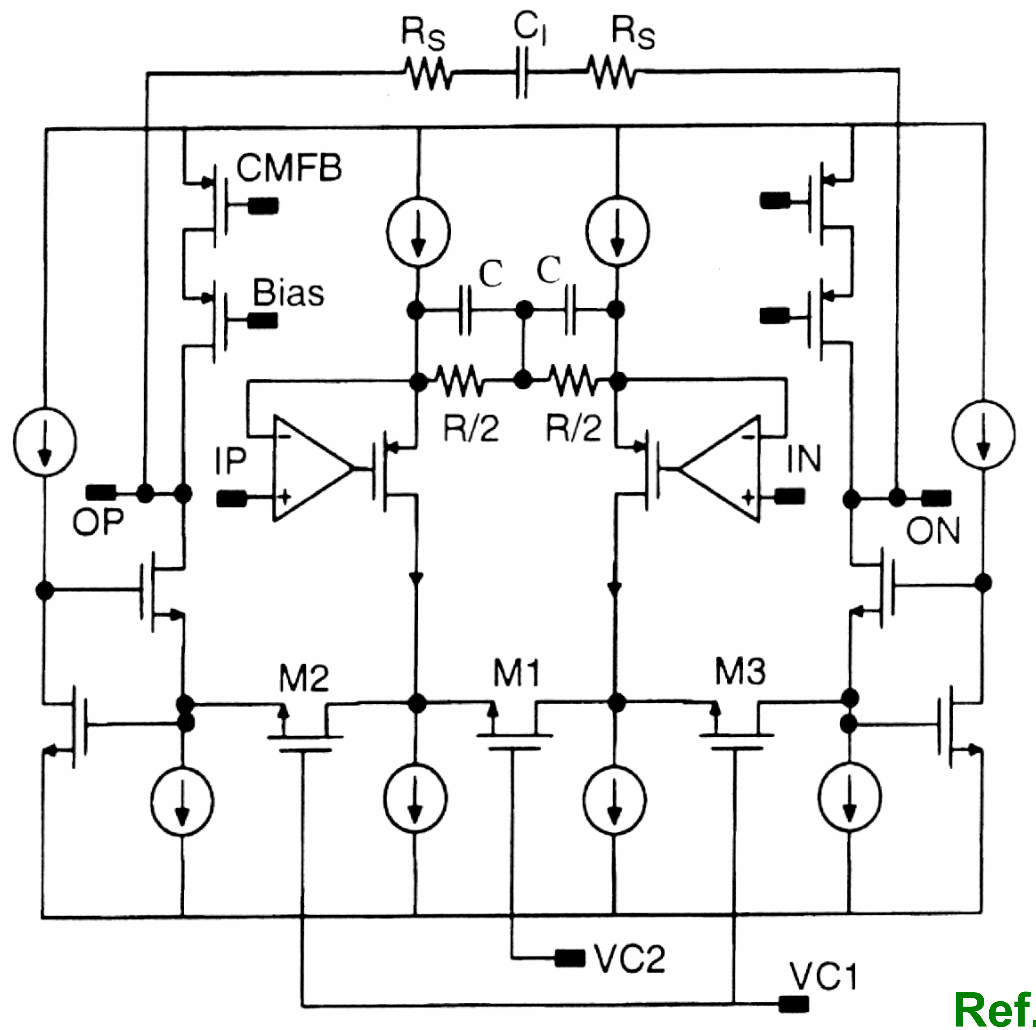
- 60 dB

2.4 V_{ptp}

Input Voltage

Ref. Silva-Martinez JSSC July 91,946-955

Linear transconductor with opamps



Ref. Chang JSSC March 97,388-397

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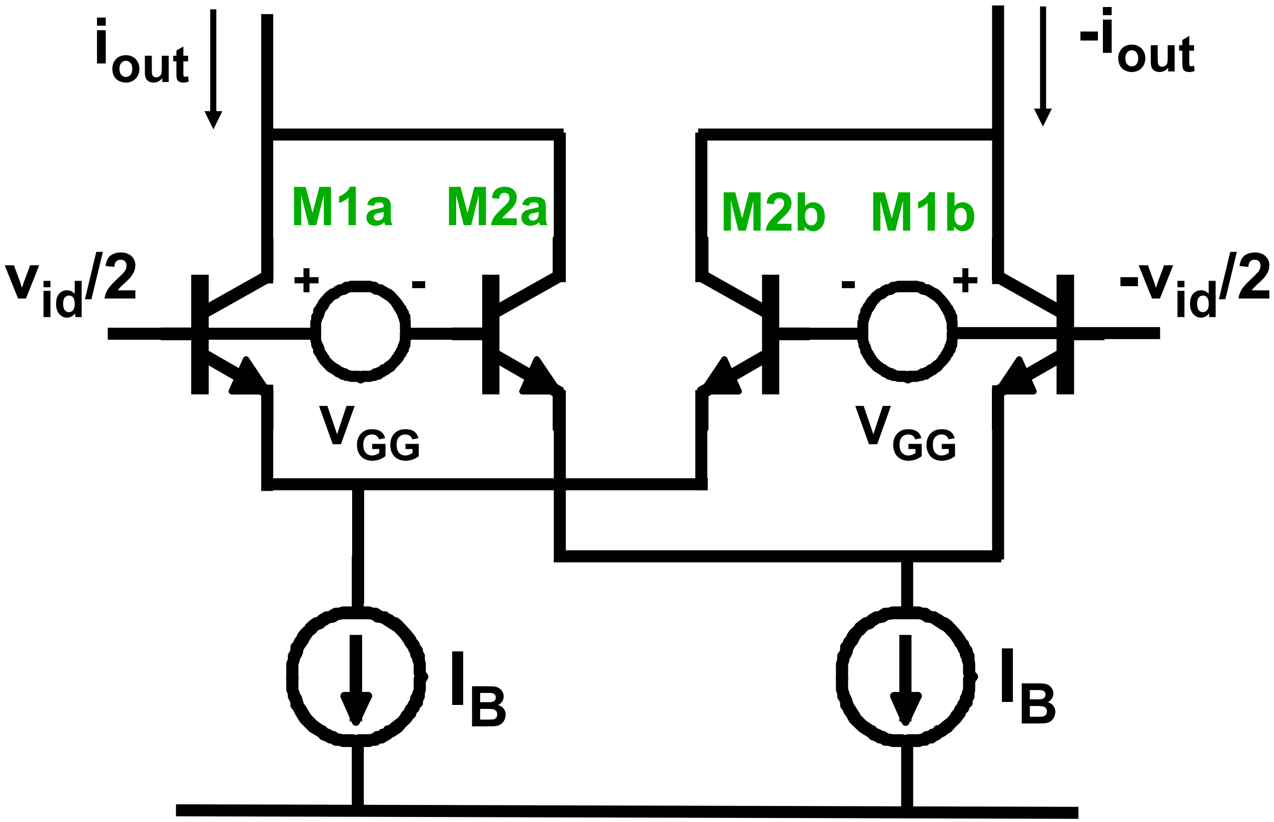
Parallel differential pairs with offset Voltages

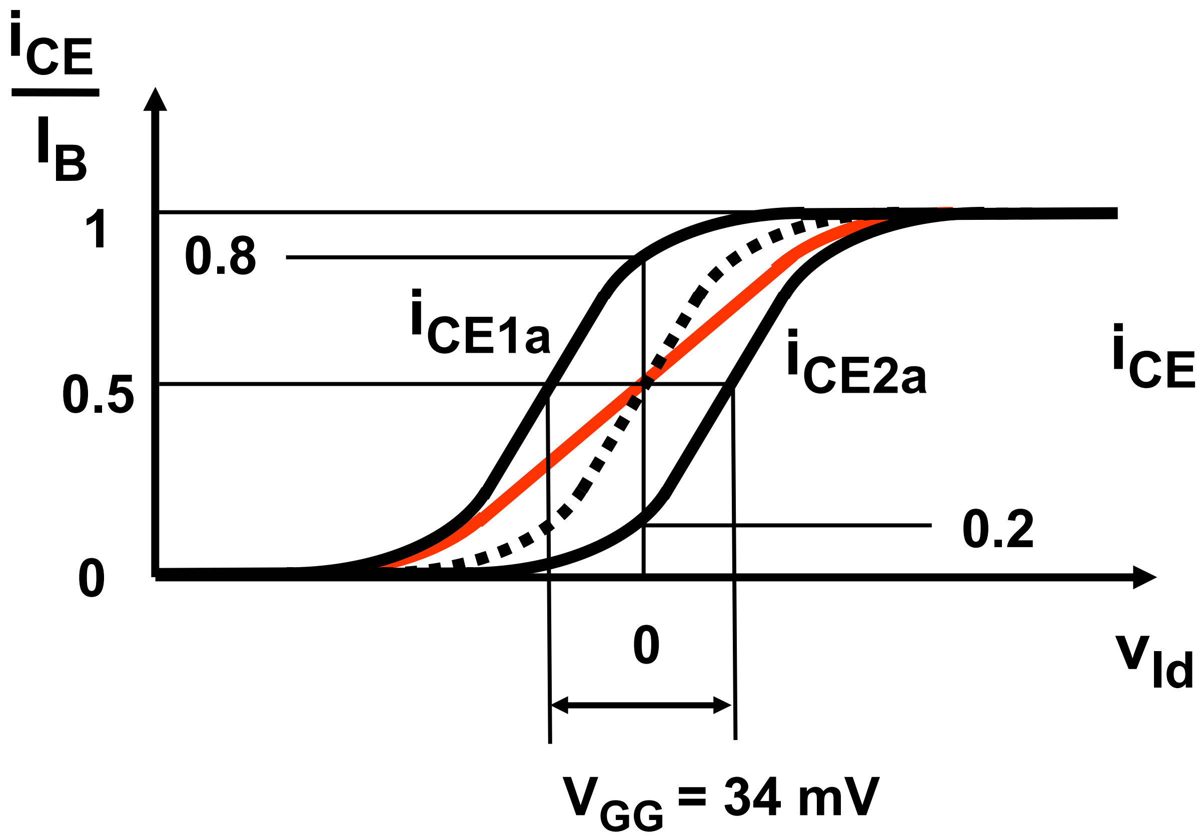


$V_{GG} \approx 1.3\ kT/q$

$\approx 34\ mV$

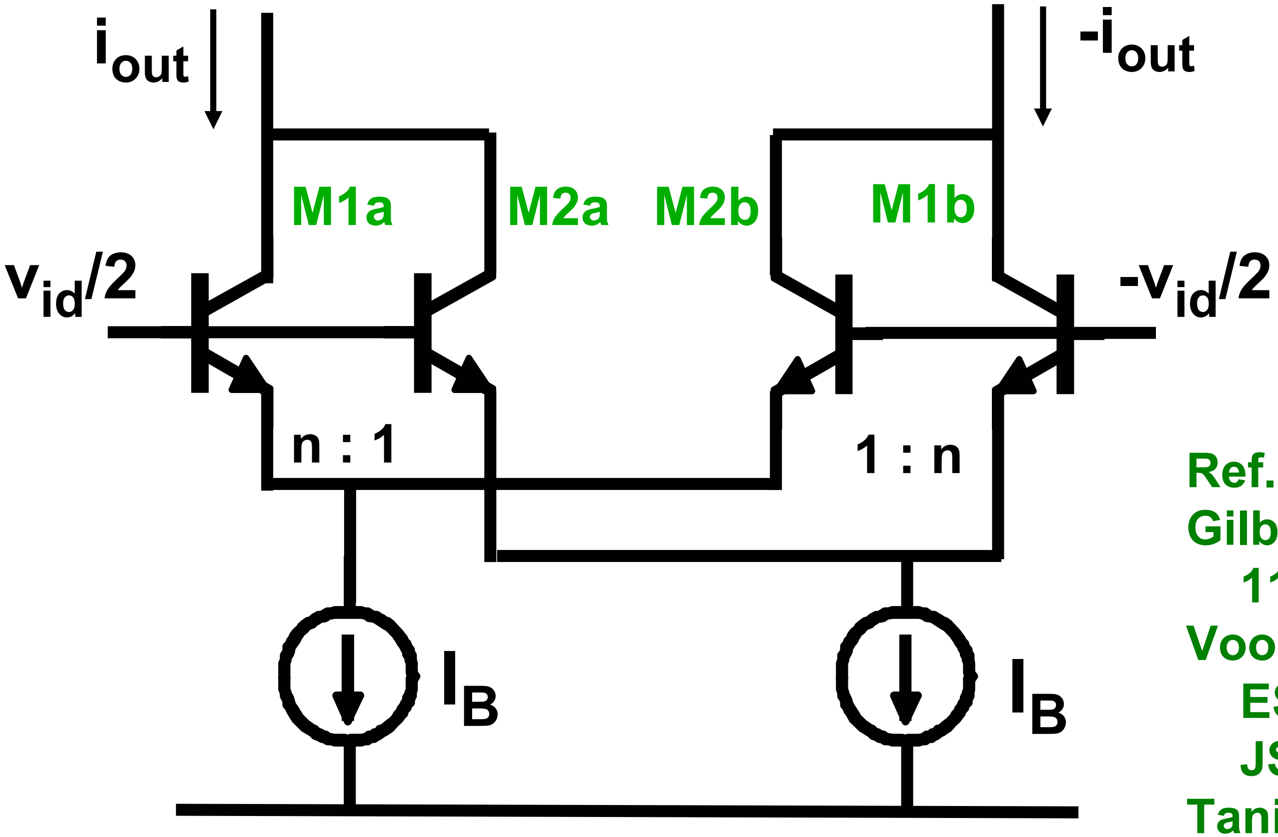
Ref. Gilbert, JSSC
Dec. 82, 1179-1191
Voorman ECCTD 83
Tanimoto, .. JSSC
July 91, 937-945

Transfer characteristics of parallel diff. pairs



$$i_{CE} = \frac{I_B}{1 + \exp(-qv_{Id}/kT)}$$

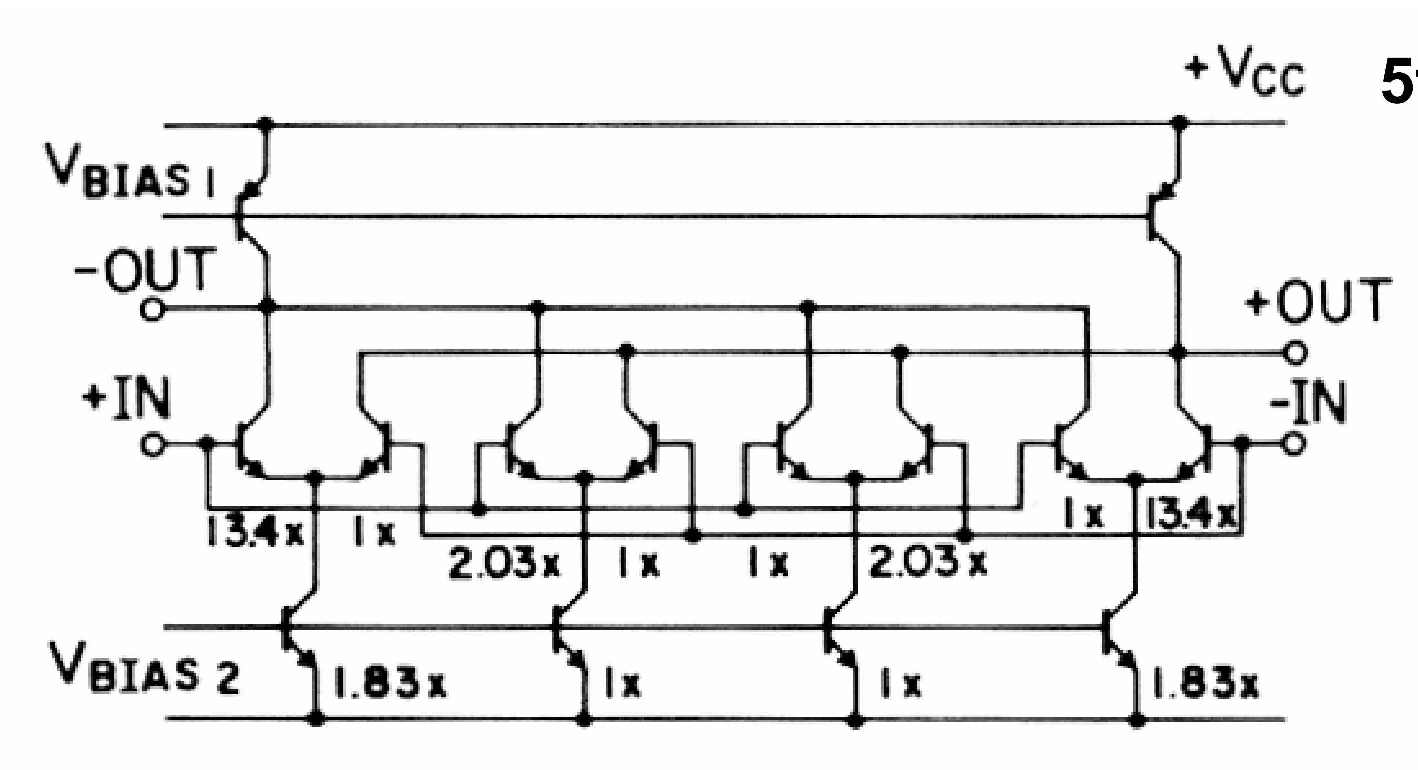
Parallel diff.pairs with different transistor sizes



Bipolar : n ≈ 4

Ref. in bipolar :
Gilbert, JSSC, Dec. 82, 1179-1191
Voorman, ECCTD 83
ESSCIRC 85
JSSC, Aug.00, 1097-1108
Tanimoto, .. JSSC July 91, 937-945
De Veirman, JSSC March 92, 324-331

Paralleling four differential pairs

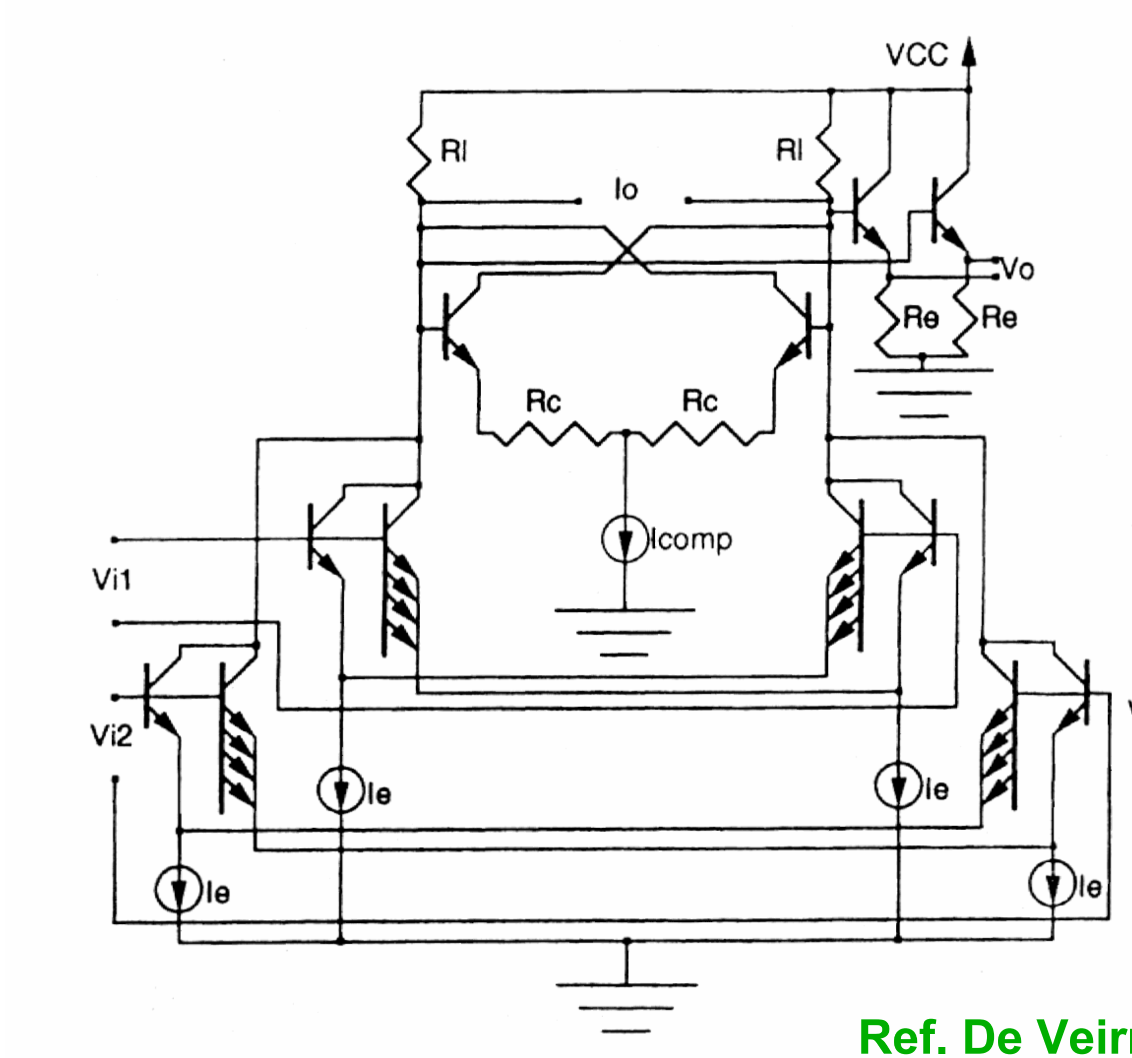


5th order filter
… 9 kHz

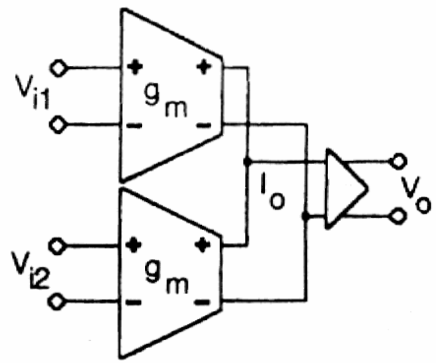
Input range 160 mV_{ptp} (1% THD)

Ref. Tanimoto,.. JSSC July 91, 937-945

Dual-input transconductor



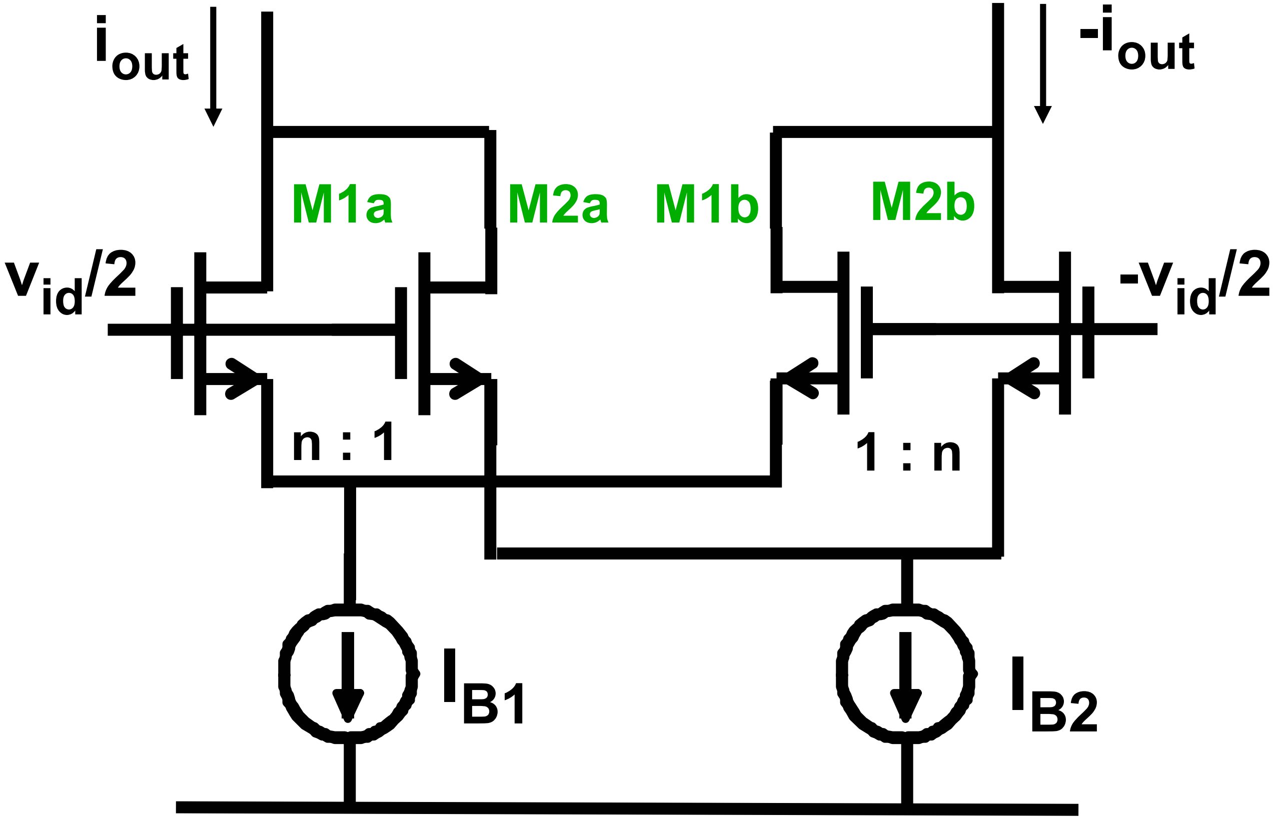
7th order filter
2 … 10 MHz



Input range
96 mV_{ptp} (1% THD)

Ref. De Veirman, JSSC, March 92, 324-331

Parallel diff.pairs with different transistor sizes



Parameters :

$\alpha = I_{B2} / I_{B1}$

$v = V_{GST1} / V_{GST2}$

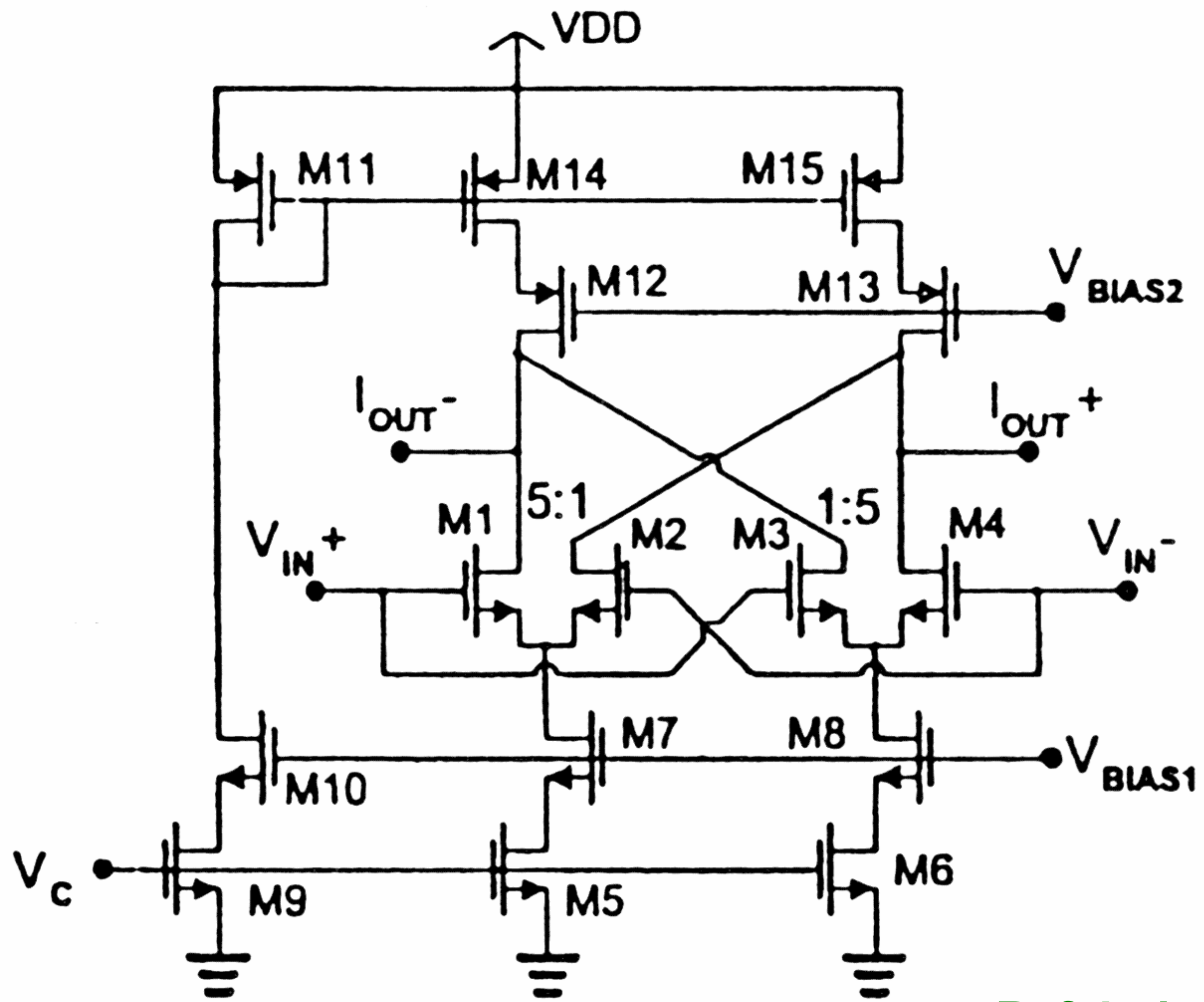
$V_{GST} = V_{GS} - V_T$

$n = \alpha\, v^2$

MOST : $n \approx 5$

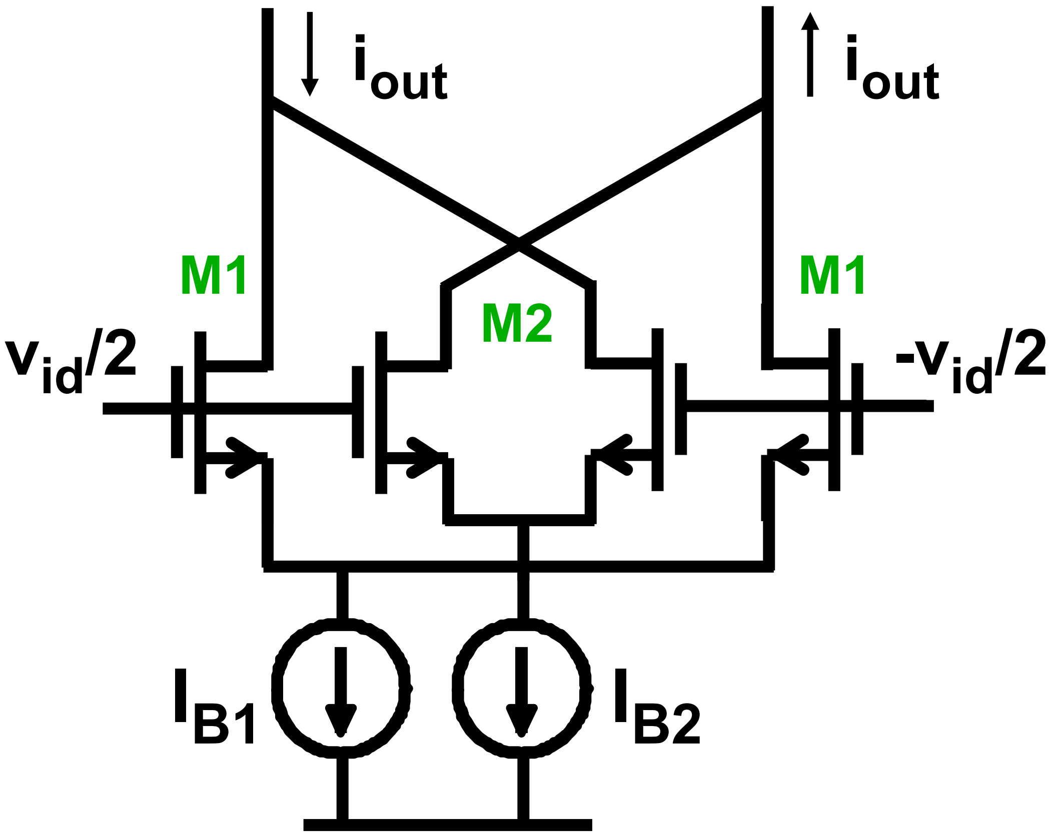
Ref. in CMOS :
Nedungadi, CAS
Oct 84, 891-894
Voorman, JSSC
Aug.00, 1097-1108
Luh, ESSCIRC 00

Cross-coupling for linearity and swing



Ref. Luh, USC, ESSCIRC 2000, 72-75

Multiplier or Amp. with distortion cancellation



Parameters :

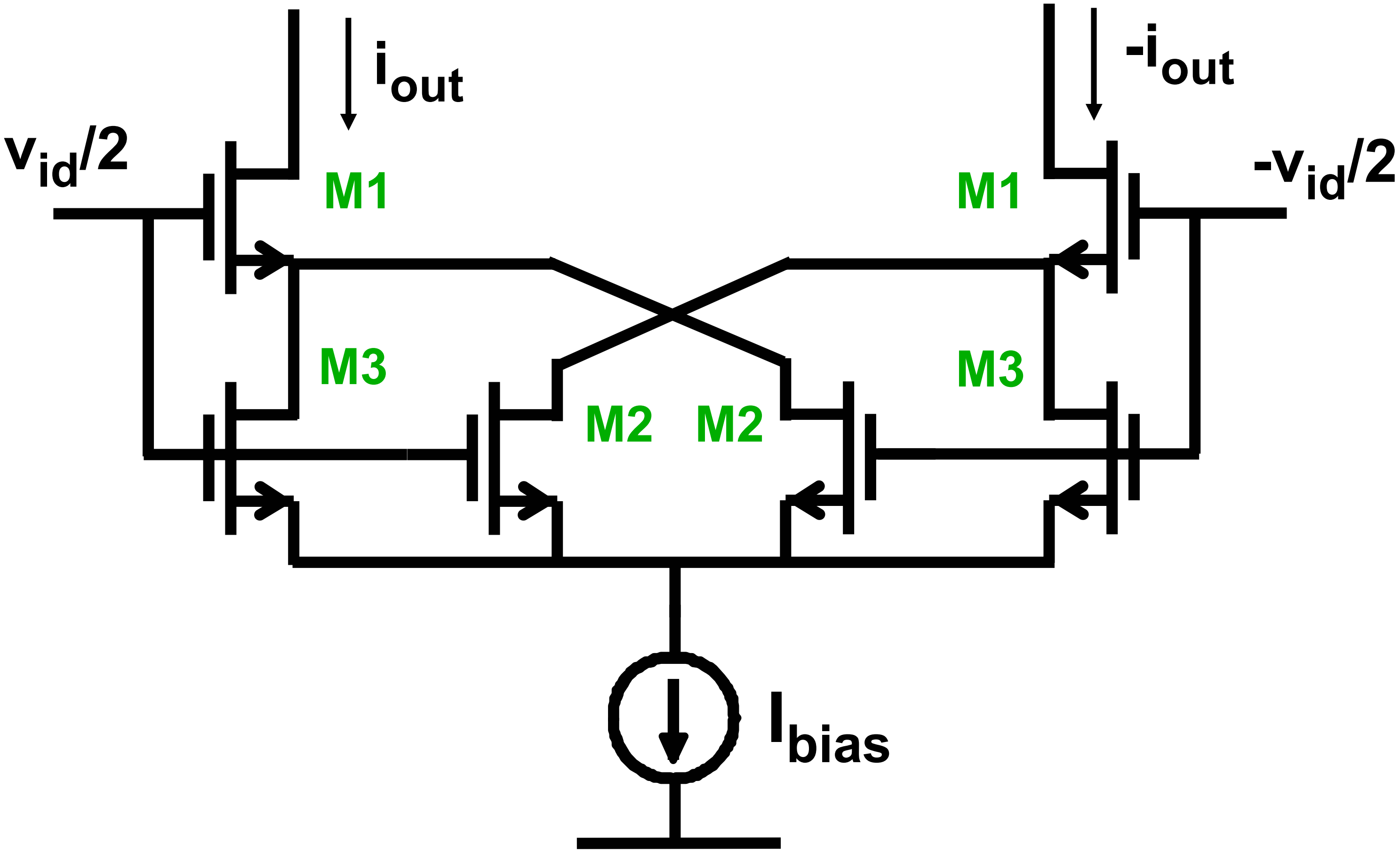
$\alpha = I_{B2} / I_{B1}$

$v = V_{GST1} / V_{GST2}$

$V_{GST} = V_{GS} - V_T$

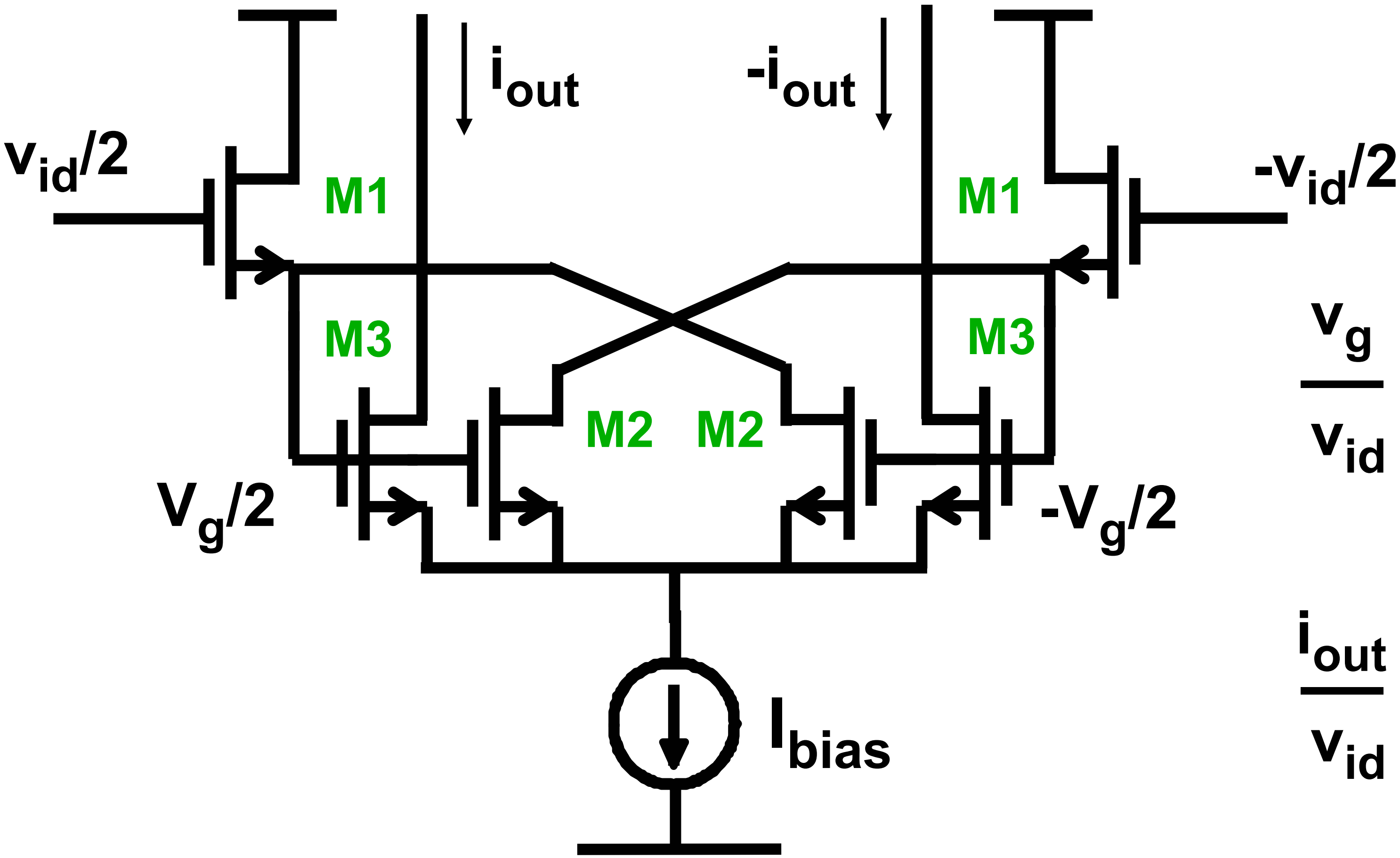
Ref. Gilbert, JSSC Dec. 68, 365-373

Cross-coupling and source resistors



Ref. Prodanov, ESSCIRC 2001, 488-491

Cross-coupling and source followers



$$\frac{v_g}{v_{id}} = \frac{1}{1 - \frac{g_{m2}}{g_{m1}}}$$

$$\frac{i_{out}}{v_{id}} = \frac{g_{m3}}{1 - \frac{g_{m2}}{g_{m1}}}$$

Ref. Van Engelen, JSSC Dec.99, 1753-1764

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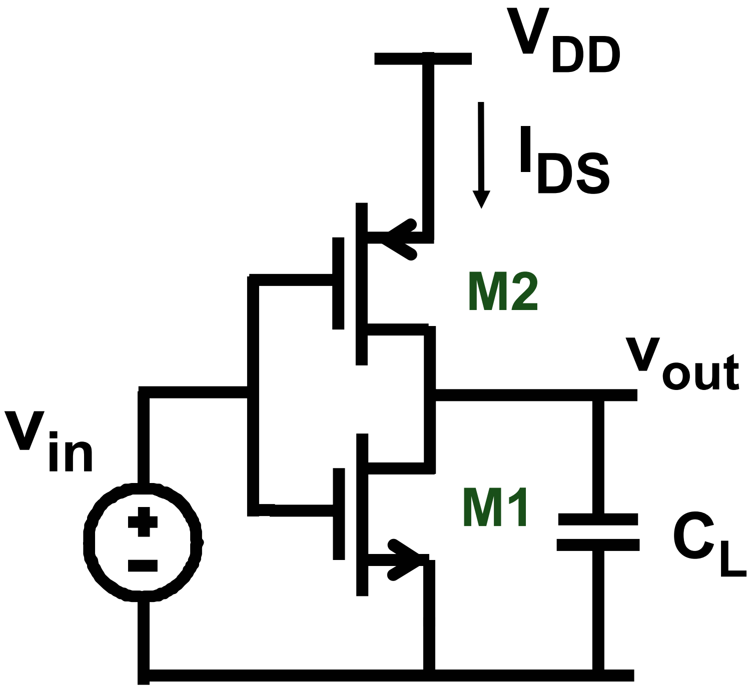
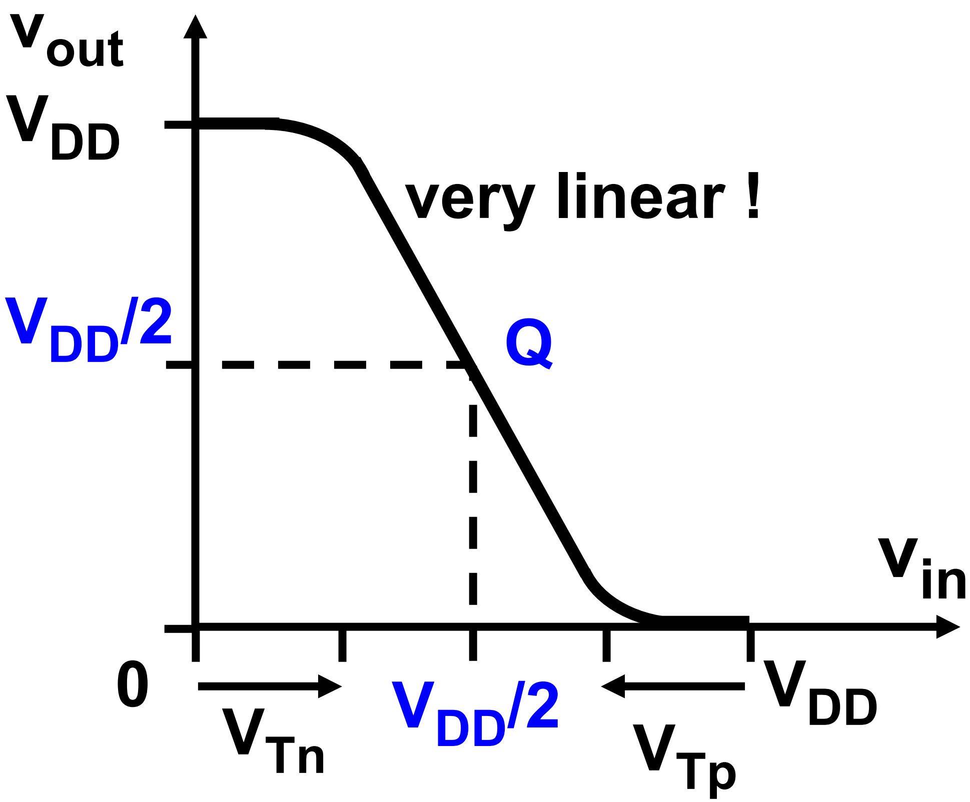
    - use of transconductors
    - local feedback
    - parallel differential pairs
    - others
  - Tuning
- Comparison

Linearity CMOS amplifier

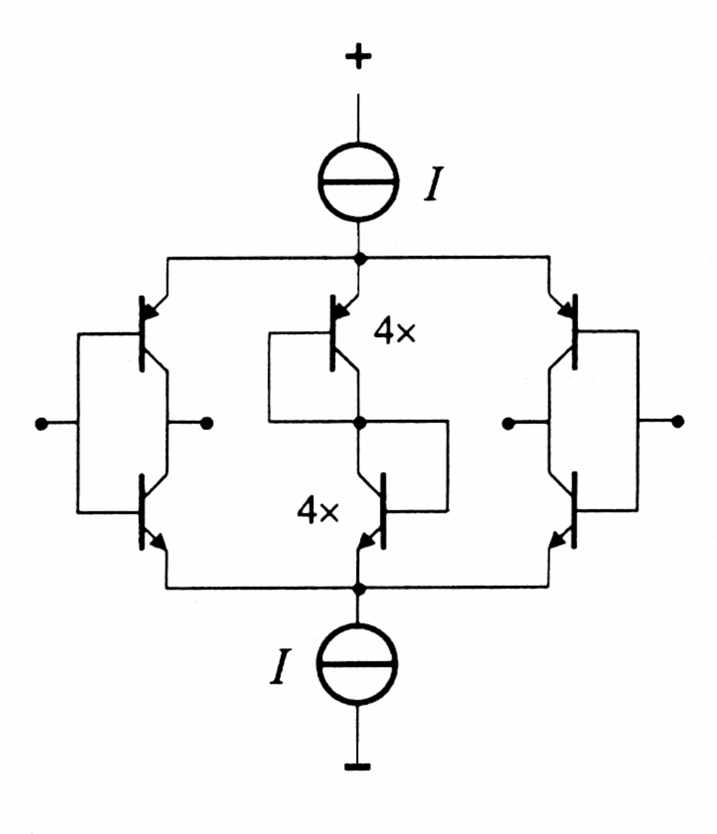


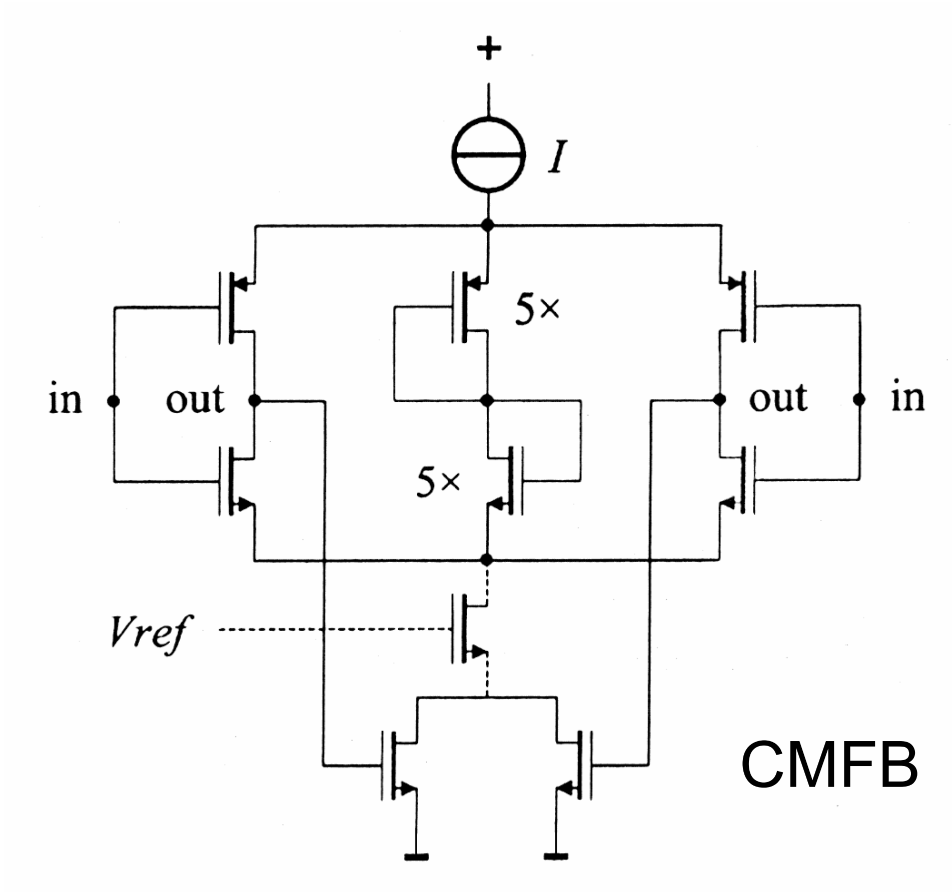


if $K'_n \frac{W_n}{L_n} = K'_p \frac{W_p}{L_p}$

$V_{in} = V_{out} = \frac{V_{DD}}{2}$

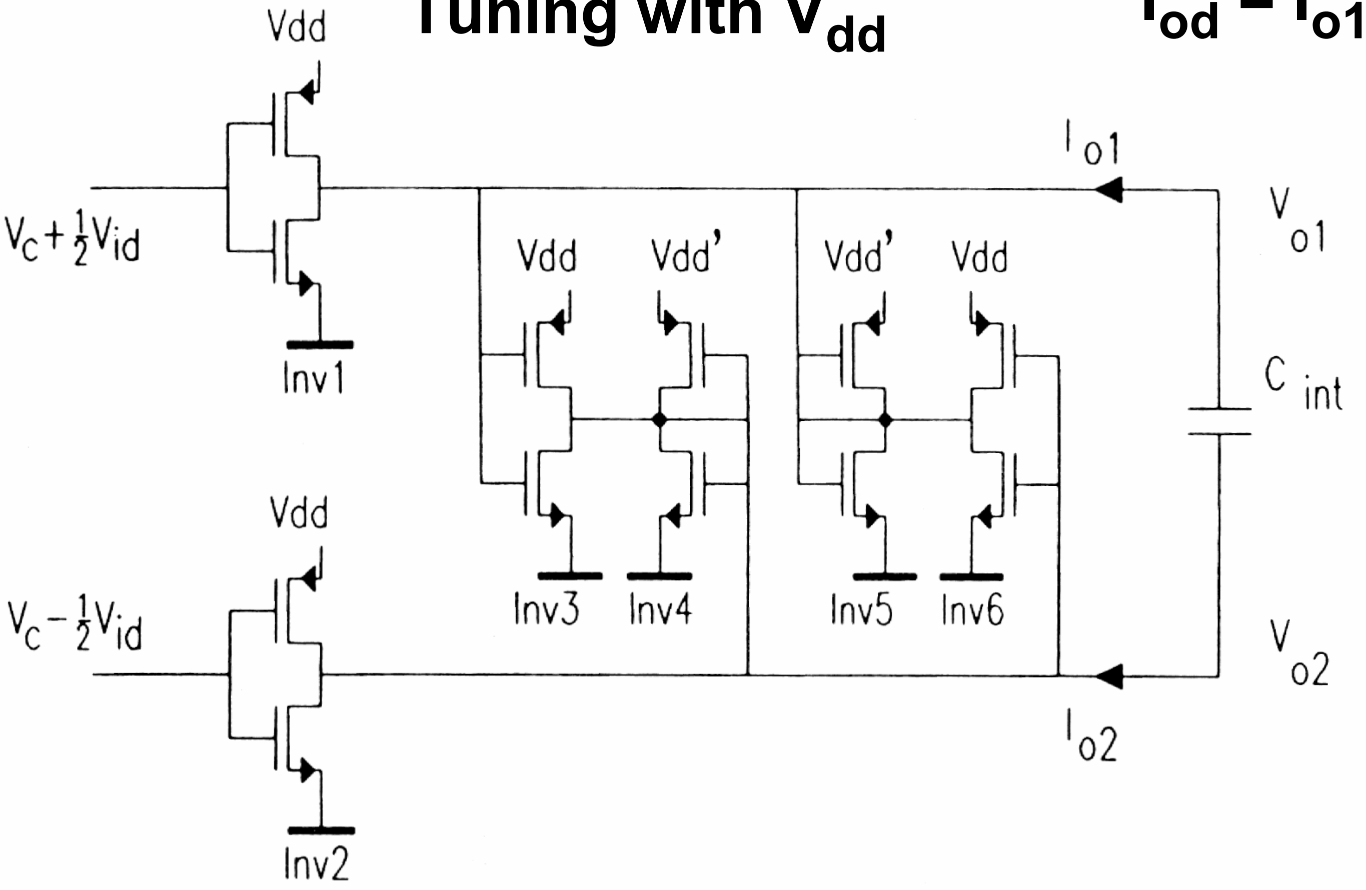
Linearized transconductors





Ref. Voorman, JSSC, Aug.2000, 1097-1108

Transconductor for High Frequencies (2 nodes)



Tuning with V_{dd}

$$I_{od} = I_{o1} - I_{o2} = g_{md} V_{id}$$

$$R_{DM1} = \frac{1}{g_{m5}-g_{m6}}$$

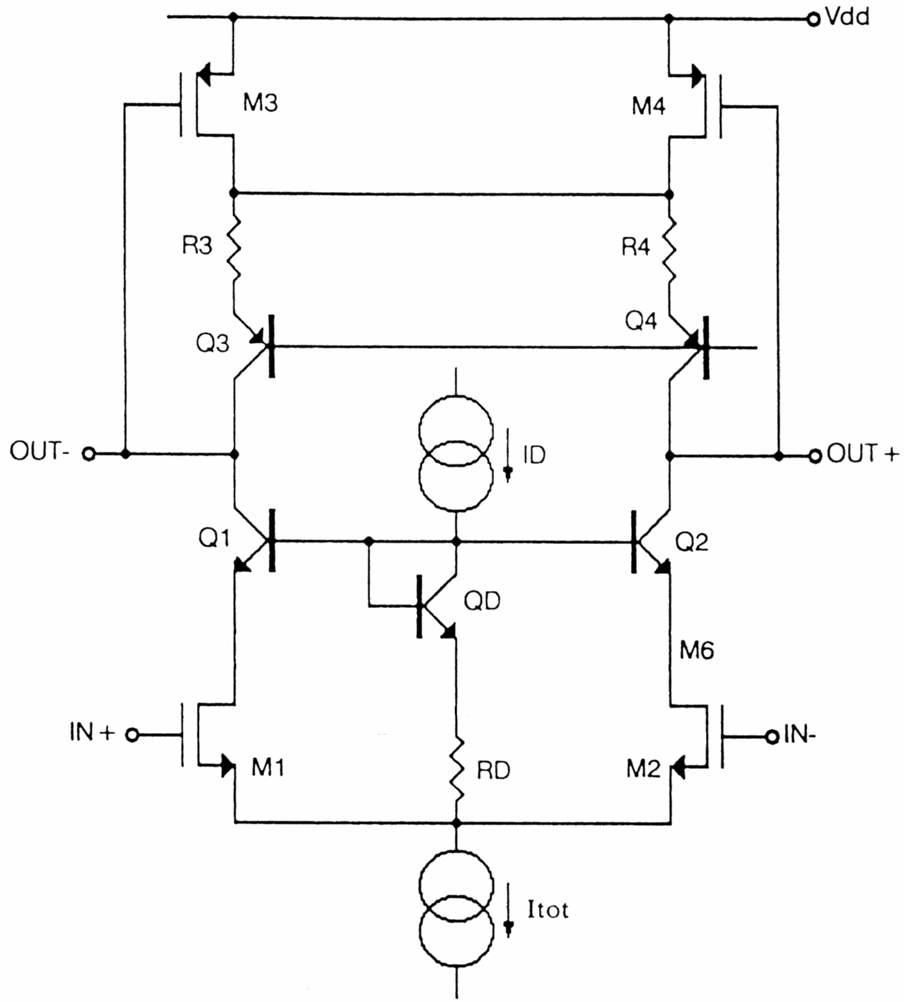
$$R_{DM2} = \frac{1}{g_{m4}-g_{m3}}$$

$$R_{CM1} = \frac{1}{g_{m5}+g_{m6}}$$

$$R_{CM2} = \frac{1}{g_{m4}+g_{m3}}$$

Ref. Nauta JSSC Febr.92,142-146

Transconductors with linear MOSTs



$V_{DS1} = R_D I_D \approx 0.2\ V$

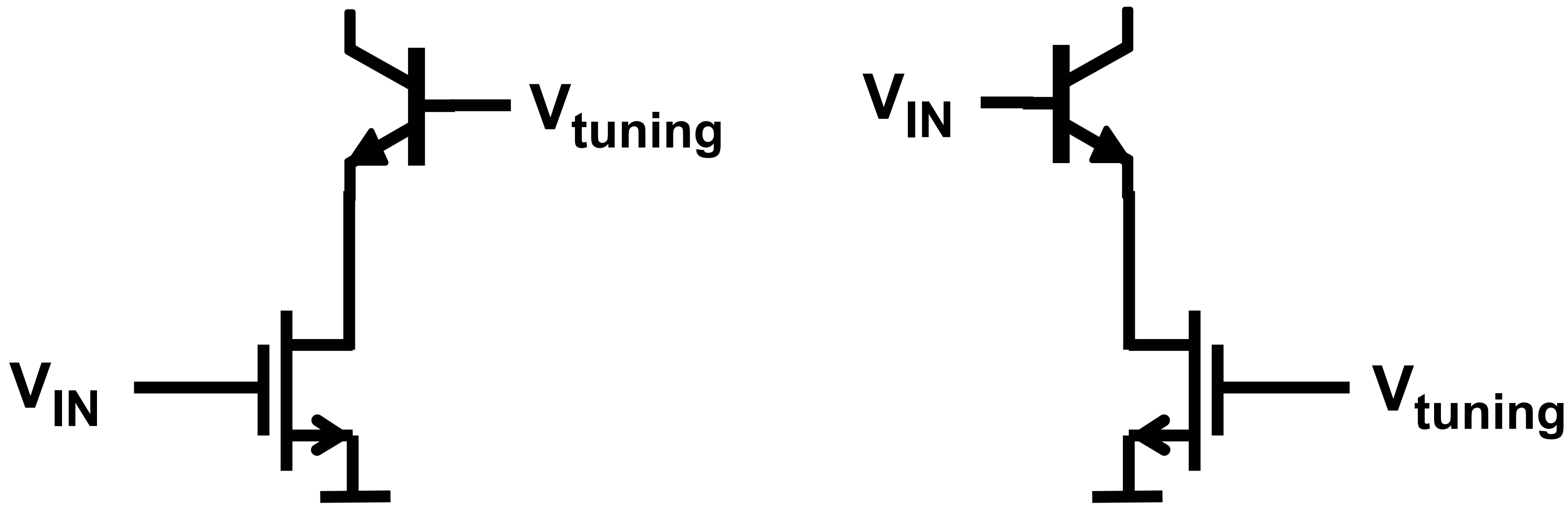
$I_{DS1} = \beta_1 V_{DS1}(V_{GS1} - V_T)$

$g_{m1} = \beta_1 V_{DS1}$ is constant

over wide range !

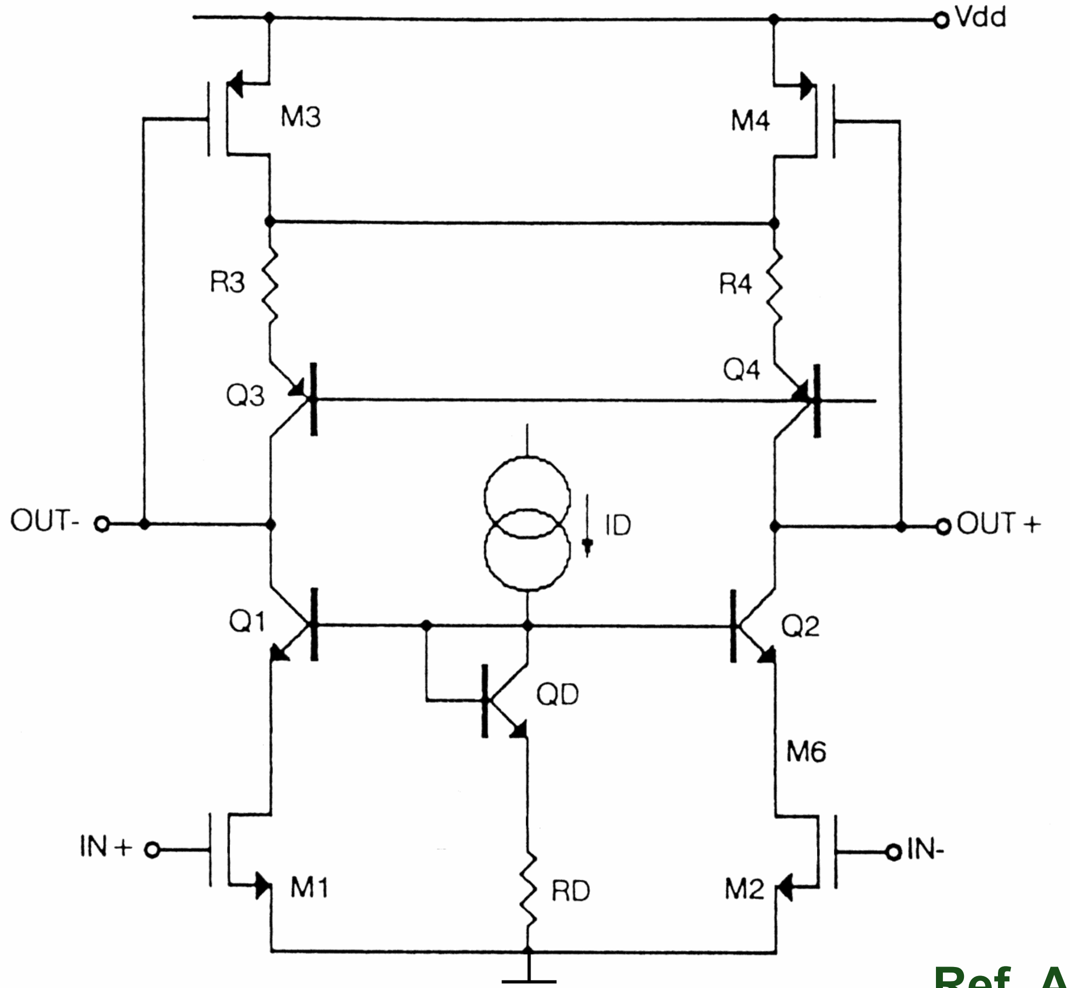
Alini, JSSC, Dec.92, pp.1905-1915

□ Alternative solutions



Larger tuning range	**Smaller tuning range**
Controls V_{DS}	**Controls V_{GS} -V_T**
$V_{DSmin} \approx 0$	**V_{GSTmin} limited by linearity**
V_{tuning} down to 0	**V_{tuning} from V_T up**

Pseudodifferential transc. with linear MOSTs

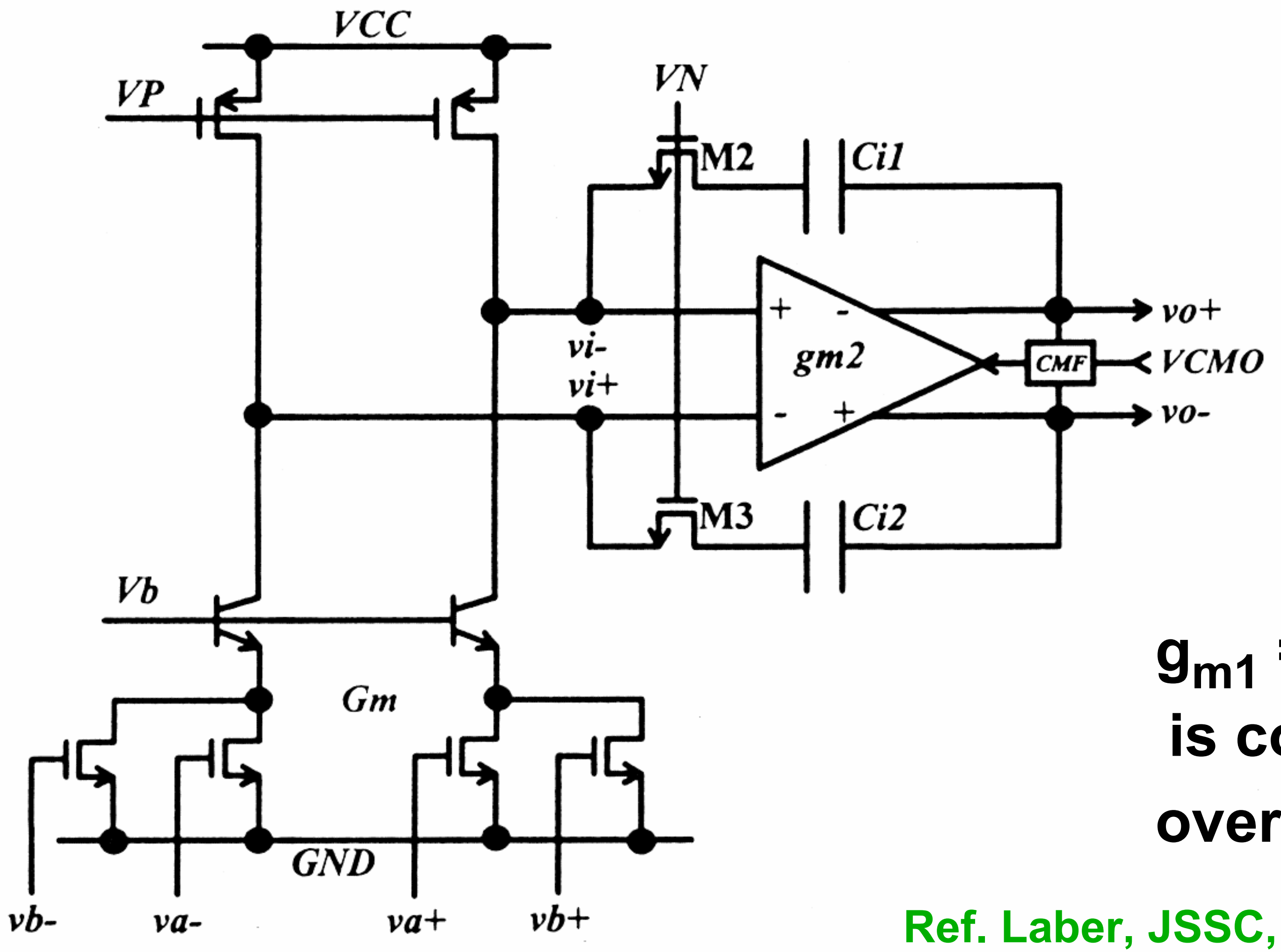


Biasing imposed by previous circuit !

No rejection of CM signals (CMRR = 0 dB)

Ref. Alini, JSSC, Dec.92, pp.1905-1915

Transconductors with linear MOSTs



$g_{m1} = \beta_1 V_{DS1}$

is constant

over wide range !

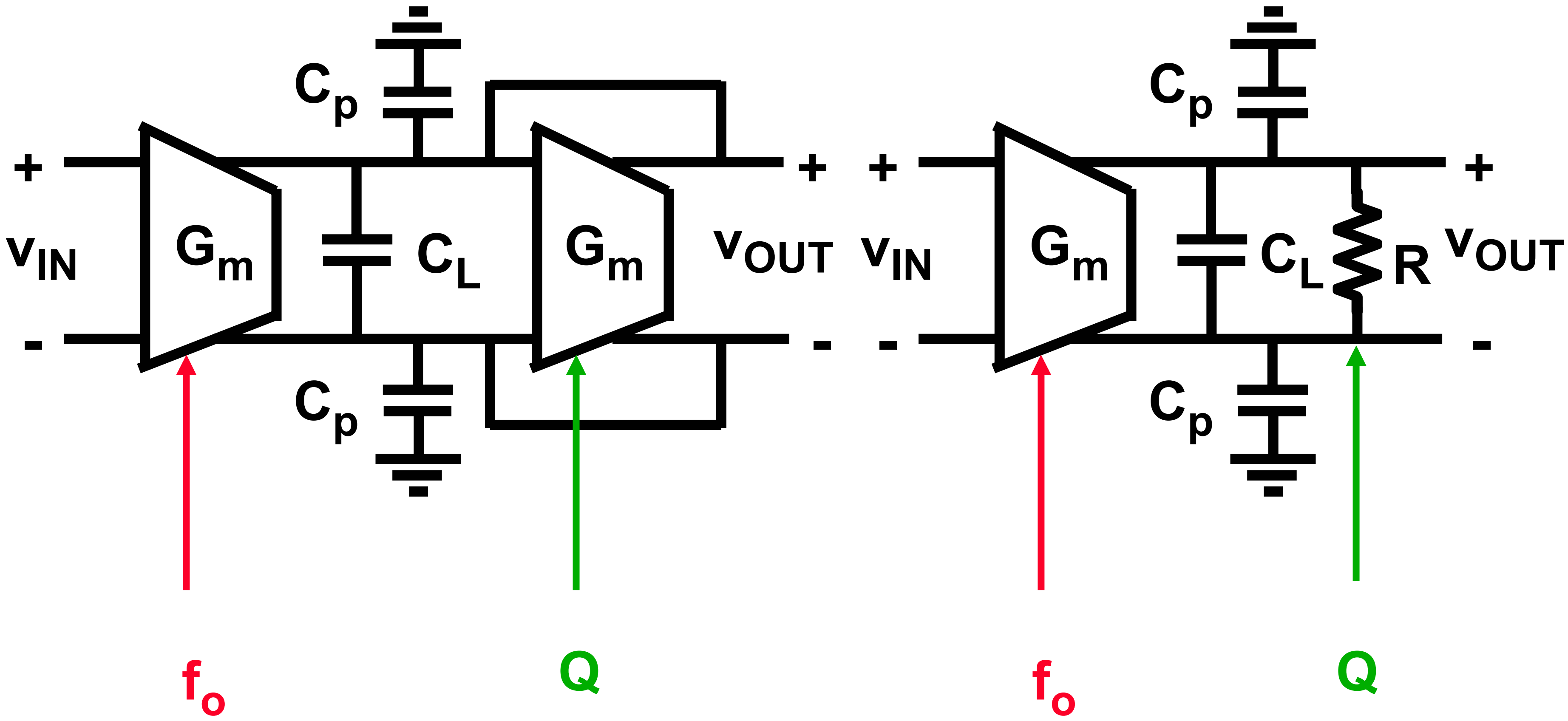
Ref. Laber, JSSC, April 93, 462-470

Table of contents

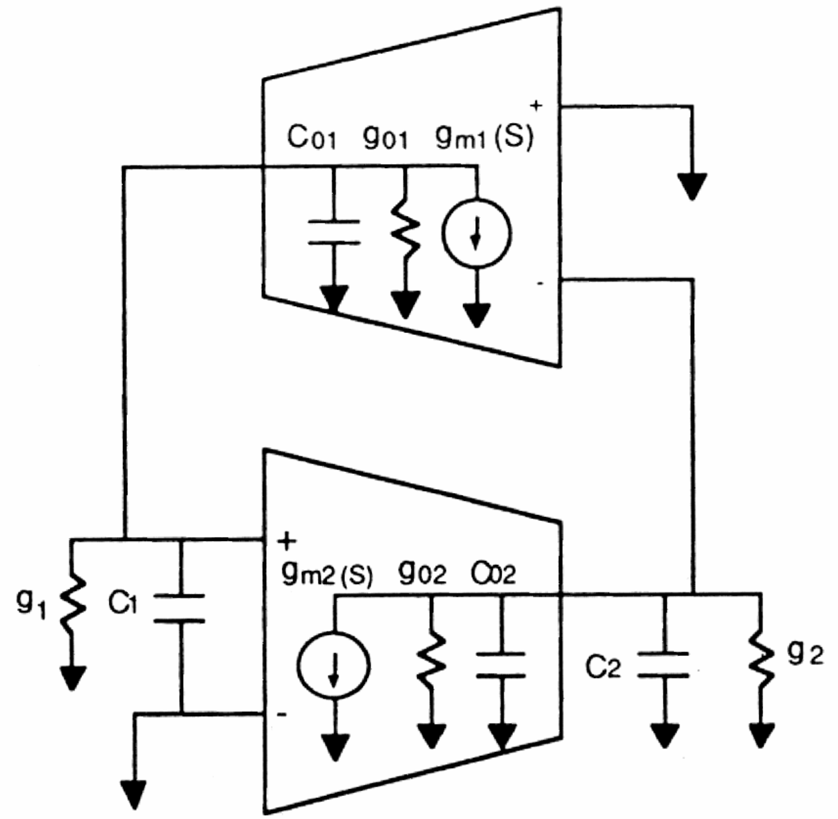
- Active RC filters
- MOSFET-C filters
- GmC filters
  - Transconductors
  - Tuning
- Comparison

Ref.: Silva-Martinez, Dehaene, ..

Gm-R-C versus Gm-C filters



Gm-R-C filters



$$f_o \approx \frac{1}{2\pi}\sqrt{\frac{g_{m1}g_{m2}}{C_1C_2}}$$

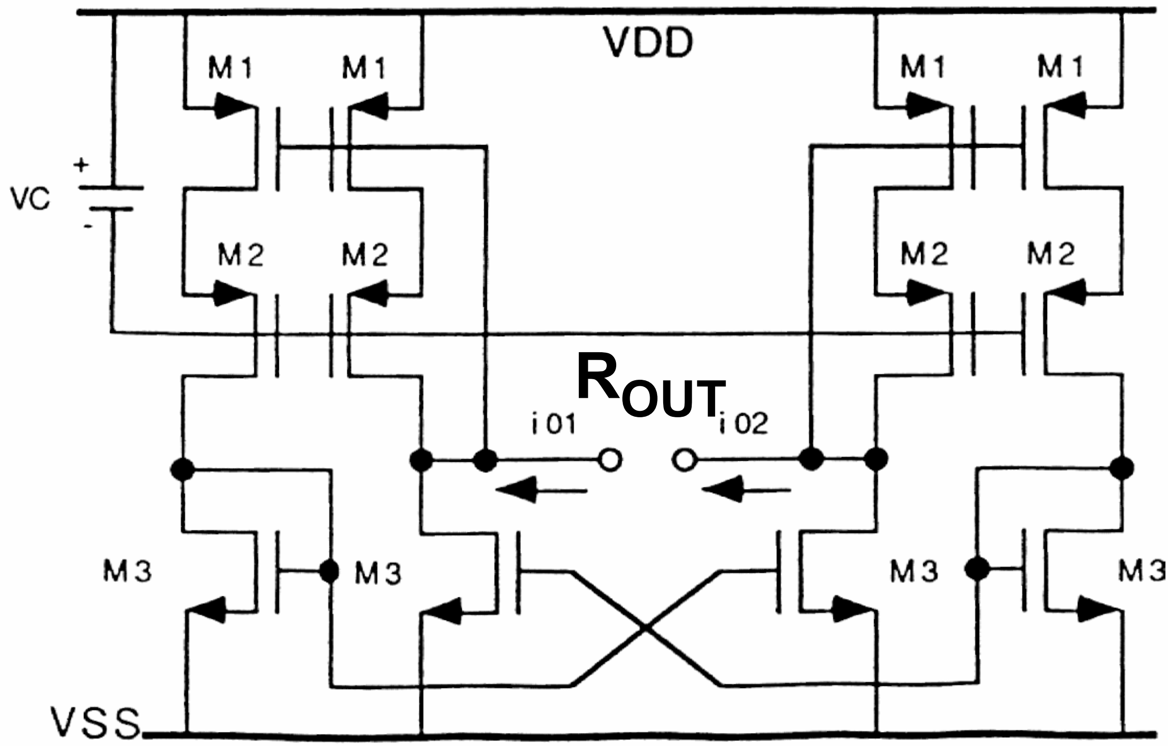
if $f_o << f_{par}$

$$Q \approx \frac{g_{m2}}{g_2+g_{o2}}$$

if $g_1 \approx 0$ (cascodes)

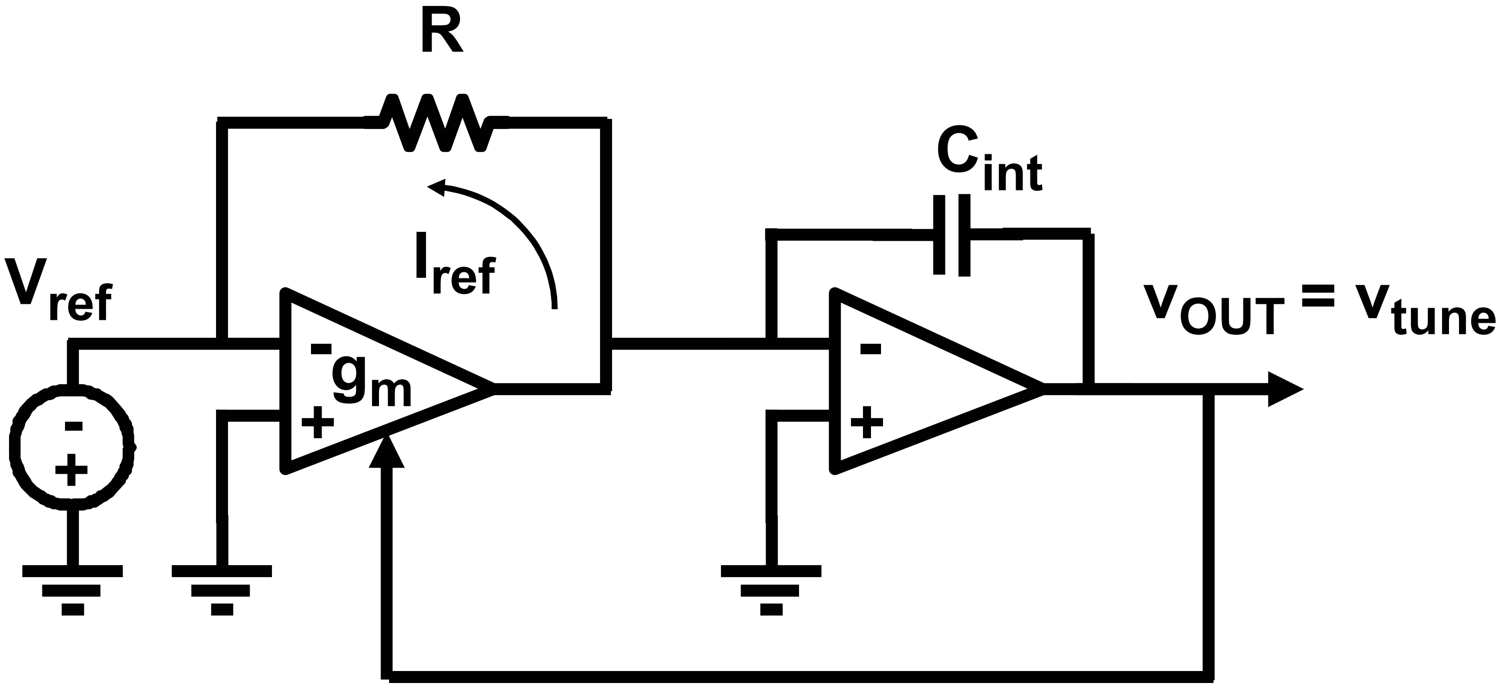
Ref. Silva-Martinez JSSC July 91,946-955

Tunable R to tune Q



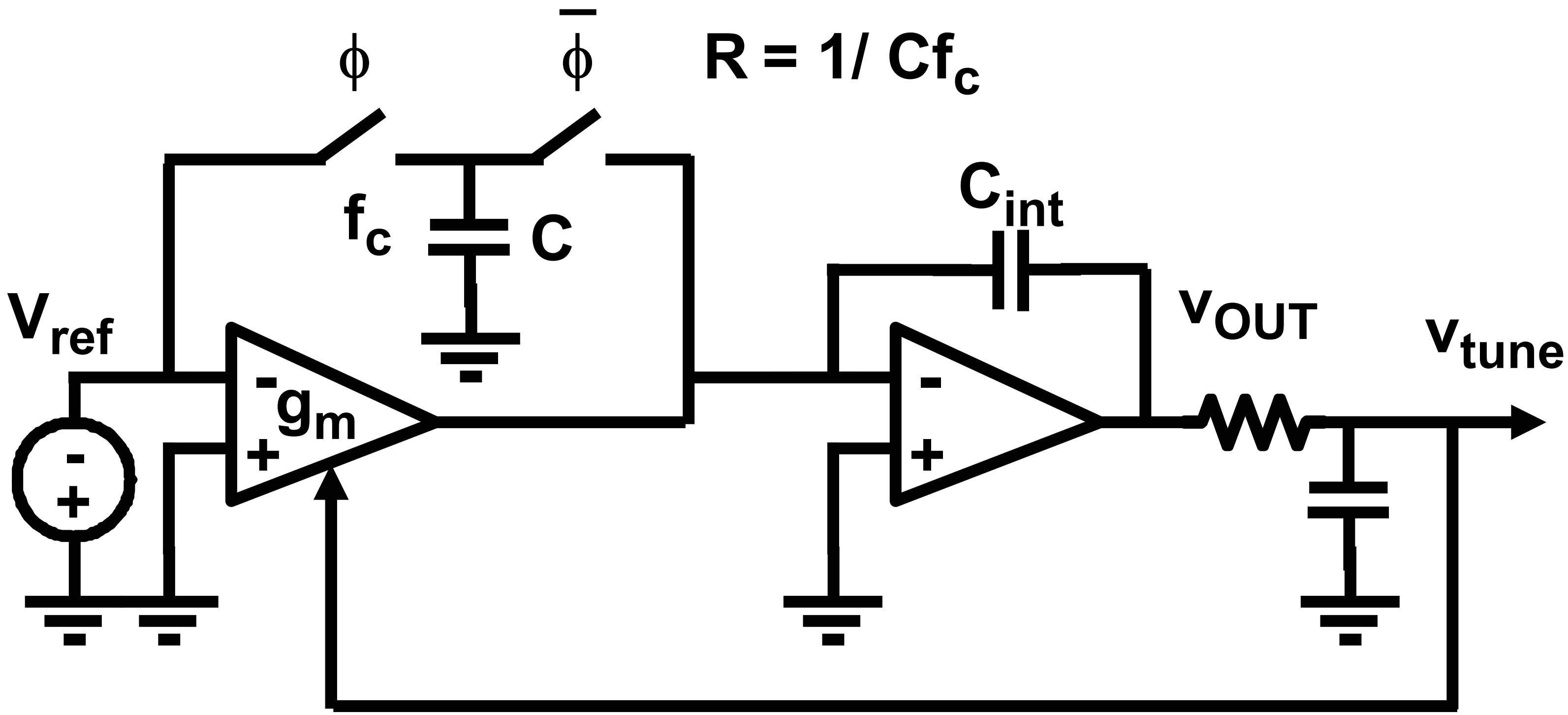
$$R_{OUT} \approx \frac{1}{KP_1 \frac{W_1}{L_1} (V_C - V_{GS2})}$$

Tuning systems : transconductance tuning



$$\left.\begin{array}{l} I_{ref} = V_{ref} / R \\ \\ I_{ref} = g_m V_{ref} \end{array}\right\} \quad g_m = 1/R$$

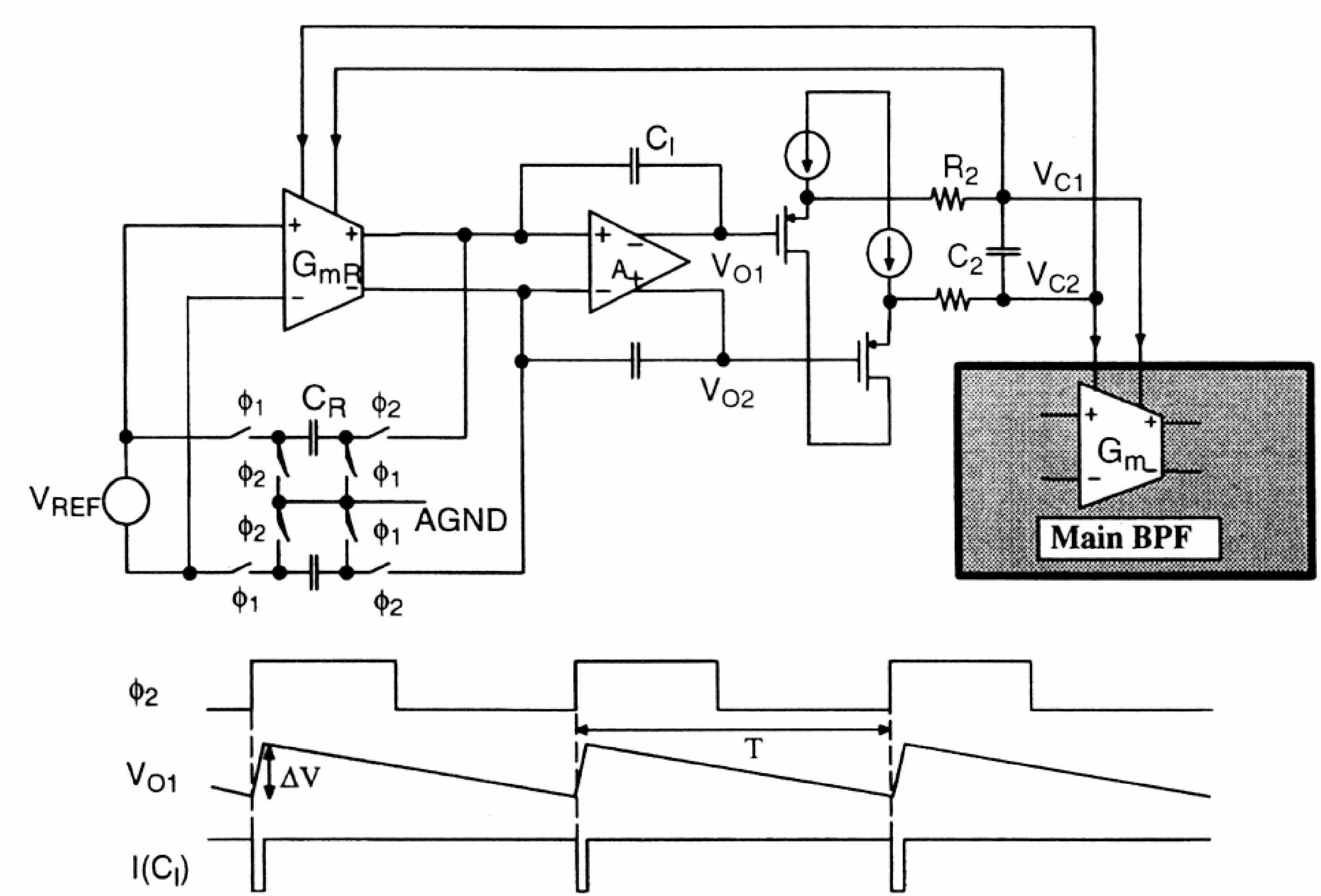
Tuning systems : frequency tuning



$$\left.\begin{array}{l} I_{ref} = Cf_c\,V_{ref} \\ I_{ref} = g_m V_{ref} \end{array}\right\} g_m = Cf_c$$

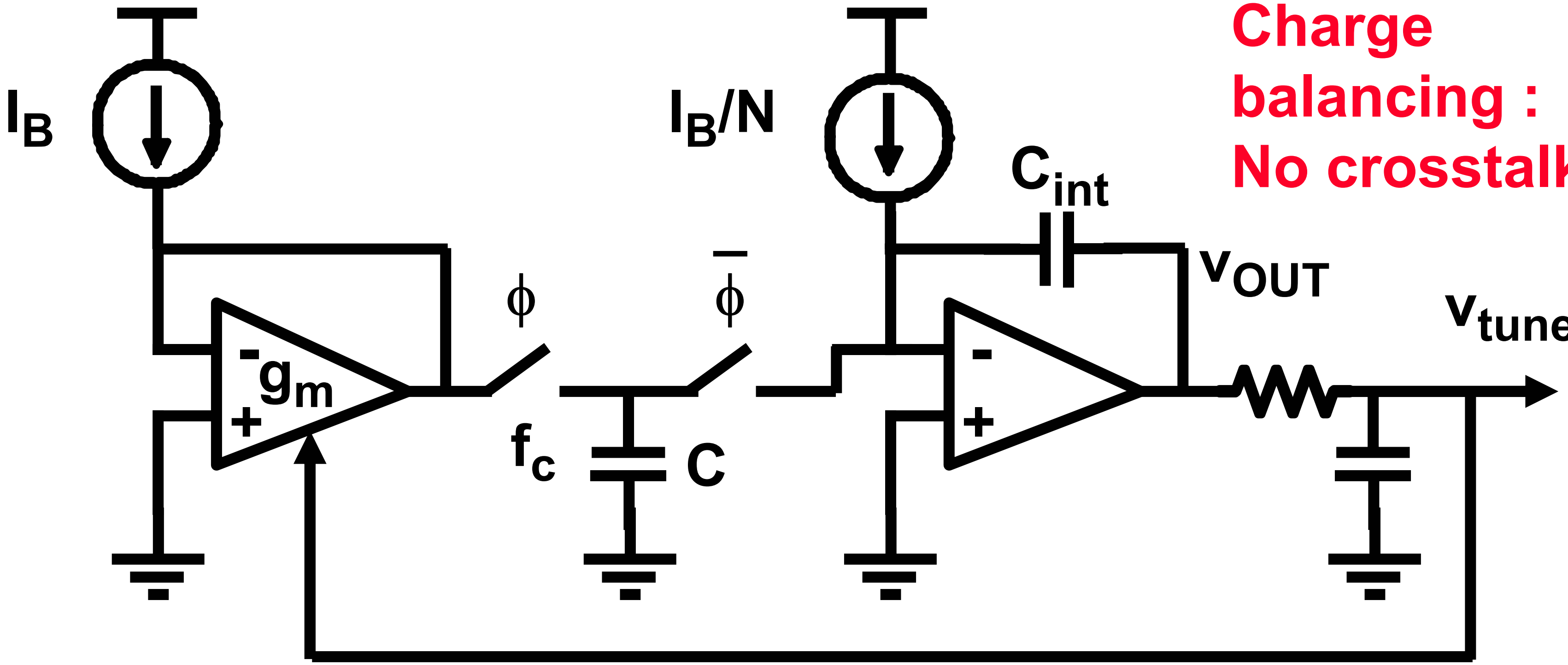
Ref. Viswanathan, JSSC Aug.82, 775-778
Silva, JSSC Dec. 92, 1843-1853

Fully-differential tuning system realization

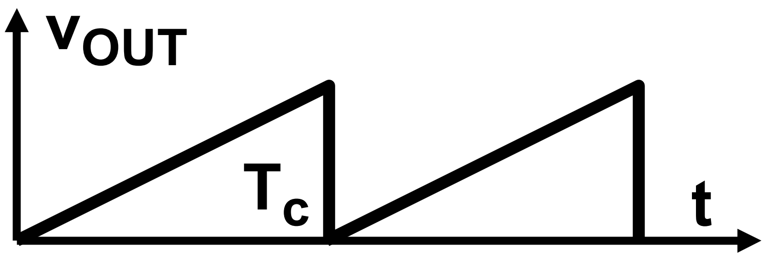


Ref. Chang, JSSC March 1997, 388-397

Tuning systems : frequency tuning with low f_c



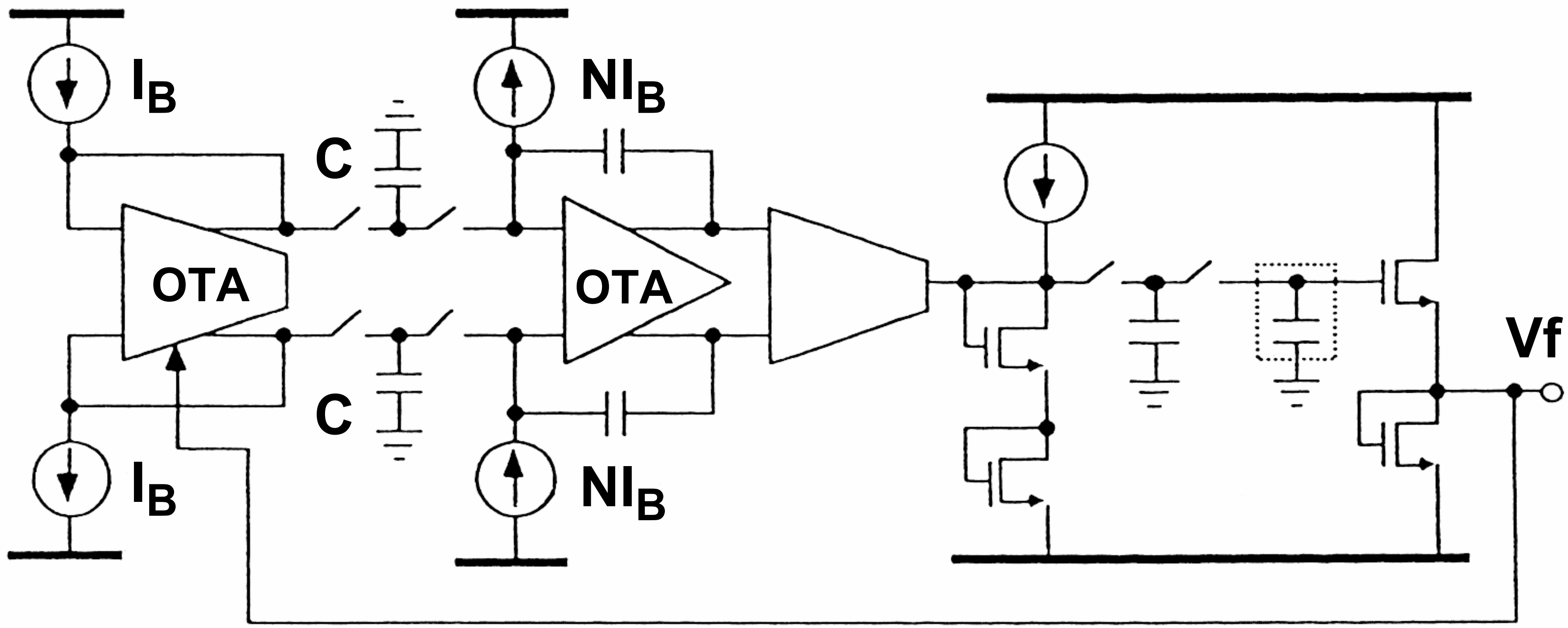
Charge balancing : No crosstalk



$$\left.\begin{array}{l} Q_{gm} = C\, I_B/g_m \\ Q_{IBN} = I_B/N\ T_c \end{array}\right\} \frac{g_m}{C} = Nf_c$$

Ref. Silva

Fully-differential frequency tuning system



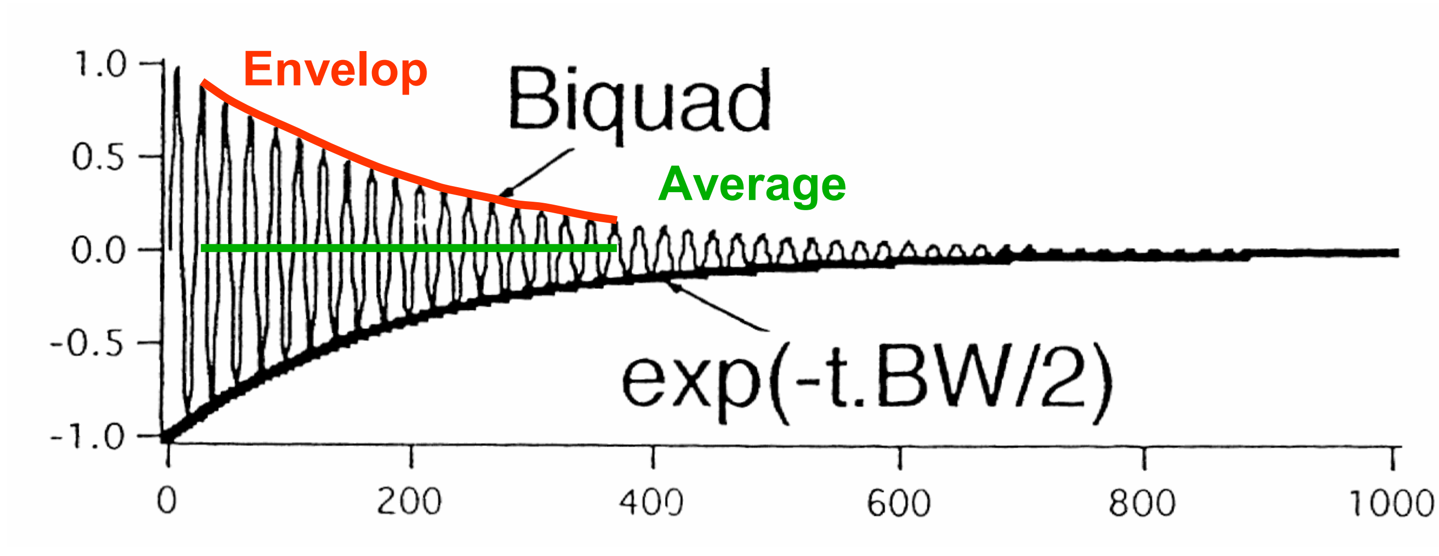
$$\frac{g_m}{C} = Nf_c$$

Ref. Silva, JSSC Dec. 92, 1843-1853

Tuning systems : Q tuning

Unity-pulse response Biquad :

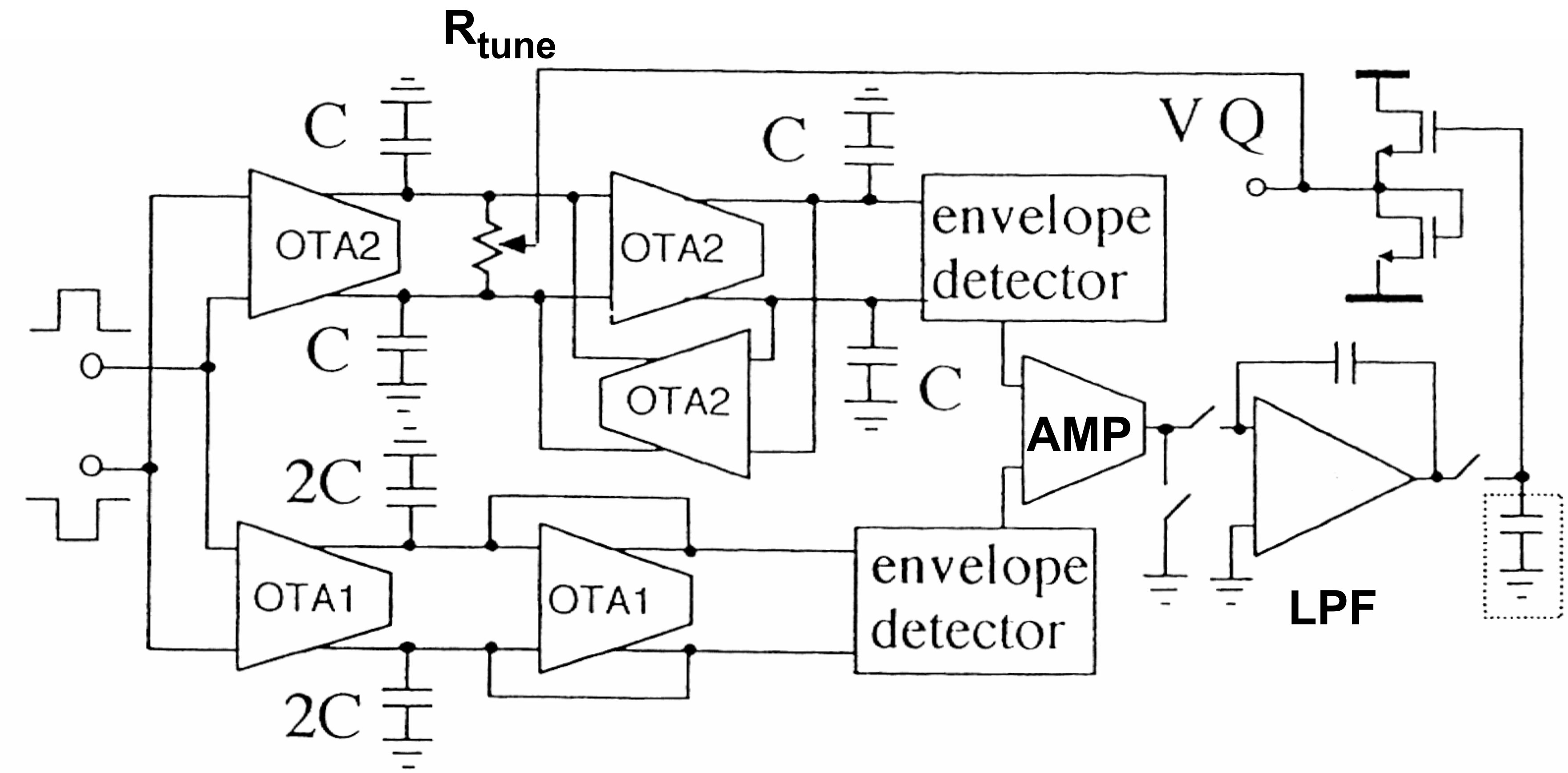
$$H(t) = \frac{1}{\sqrt{1 - \frac{1}{4Q^2}}} \exp\left(-\frac{t.BW}{2}\right) \sin\left(\sqrt{1 - \frac{1}{4Q^2}}\ \omega_o t + \theta\right)$$



No HF PLL or VCO !

Detection at f_c !

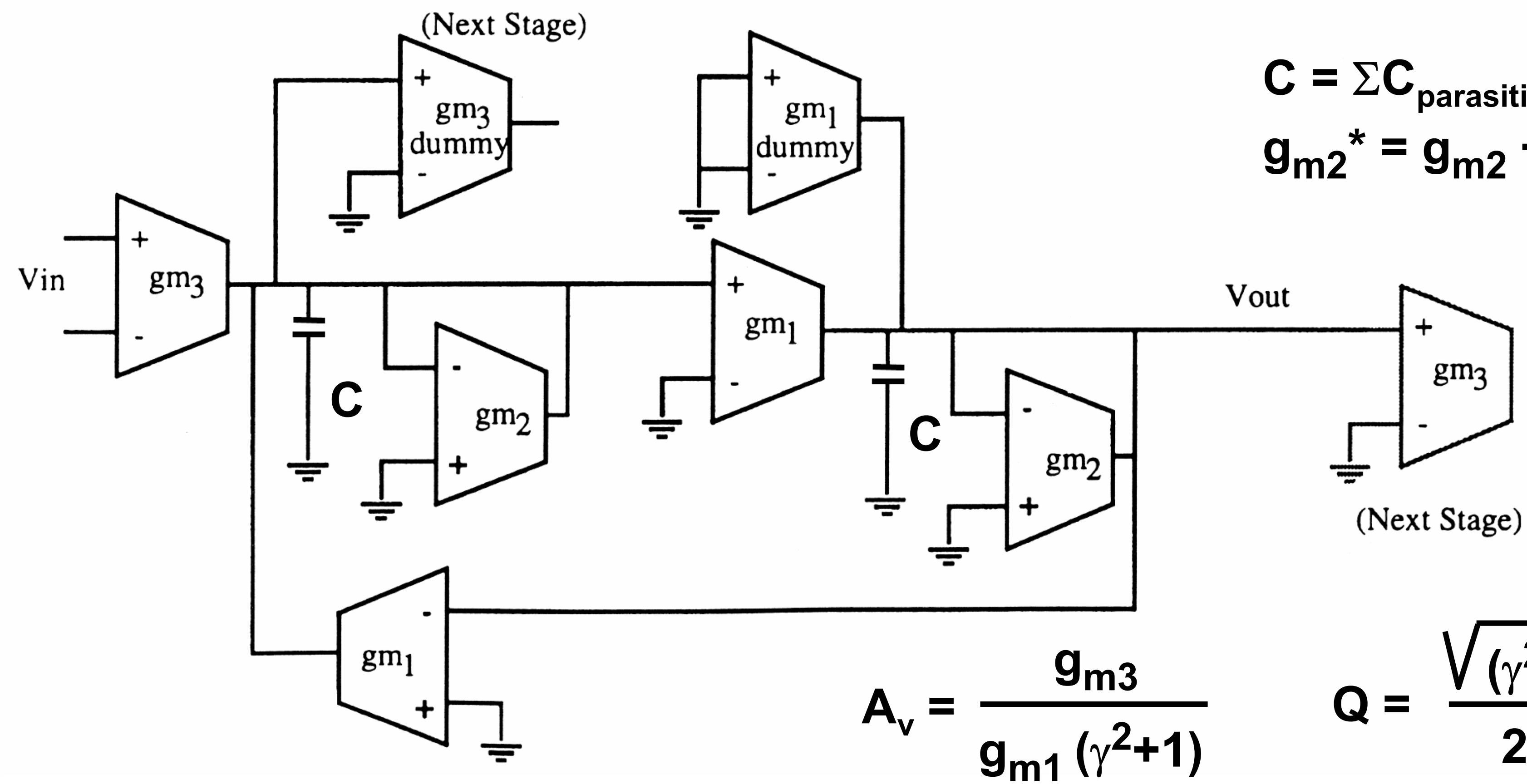
Q tuning with active resistor



Comparison of 10.7 MHz filters

	SC	OTA-C	Gm-RC
f_c (BW = 250 kHz)	10.7 MHz	12.5 MHz	10.7 MHz
Order filter	6	4	4
Vin @ IM3= 1%	0.24 V_{RMS}	0.32 V_{RMS}	0.71 V_{RMS}
DR @ IM3= 1%	34 dB	51 dB	68 dB
Power (± V)	500 mW(± 5)	360 mW(± 6)	220 mW(± 2.5)
Chip area	2 mm^2	7.8 mm^2	6 mm^2

Biquad for 7th-order Filter at 50 MHz



$C = \Sigma C_{parasitic}$

$g_{m2}^* = g_{m2} + \Sigma g_o$

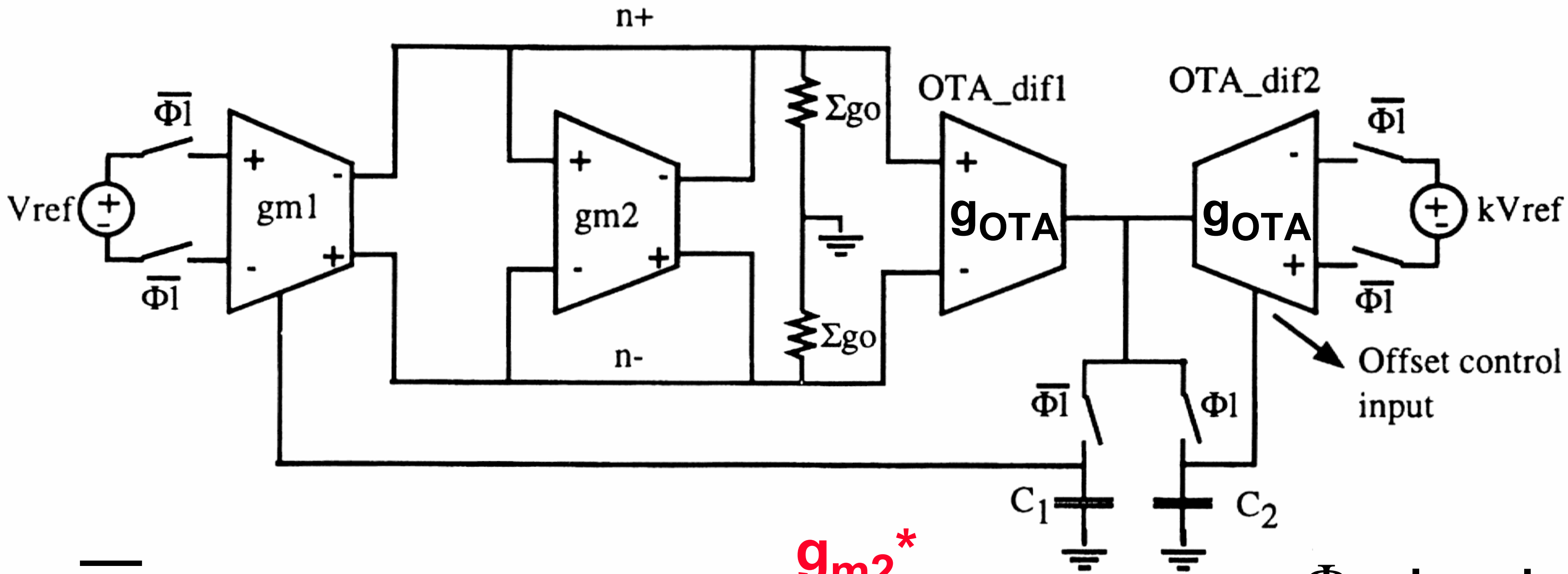
$$A_v = \frac{g_{m3}}{g_{m1}(\gamma^2+1)} \qquad Q = \frac{\sqrt{(\gamma^2+1)}}{2\gamma}$$

Biquad with matched nodes

$$f_o = \frac{1}{2\pi\,\tau}\,\frac{\sqrt{(\gamma^2+1)}}{\gamma} \qquad \tau = \frac{C}{g_{m2}^*} \qquad \gamma = \frac{g_{m2}^*}{g_{m1}}$$

Ref. Dehaene JSSC July 97, 977-988

Tuning system for Q : conductance ratio γ



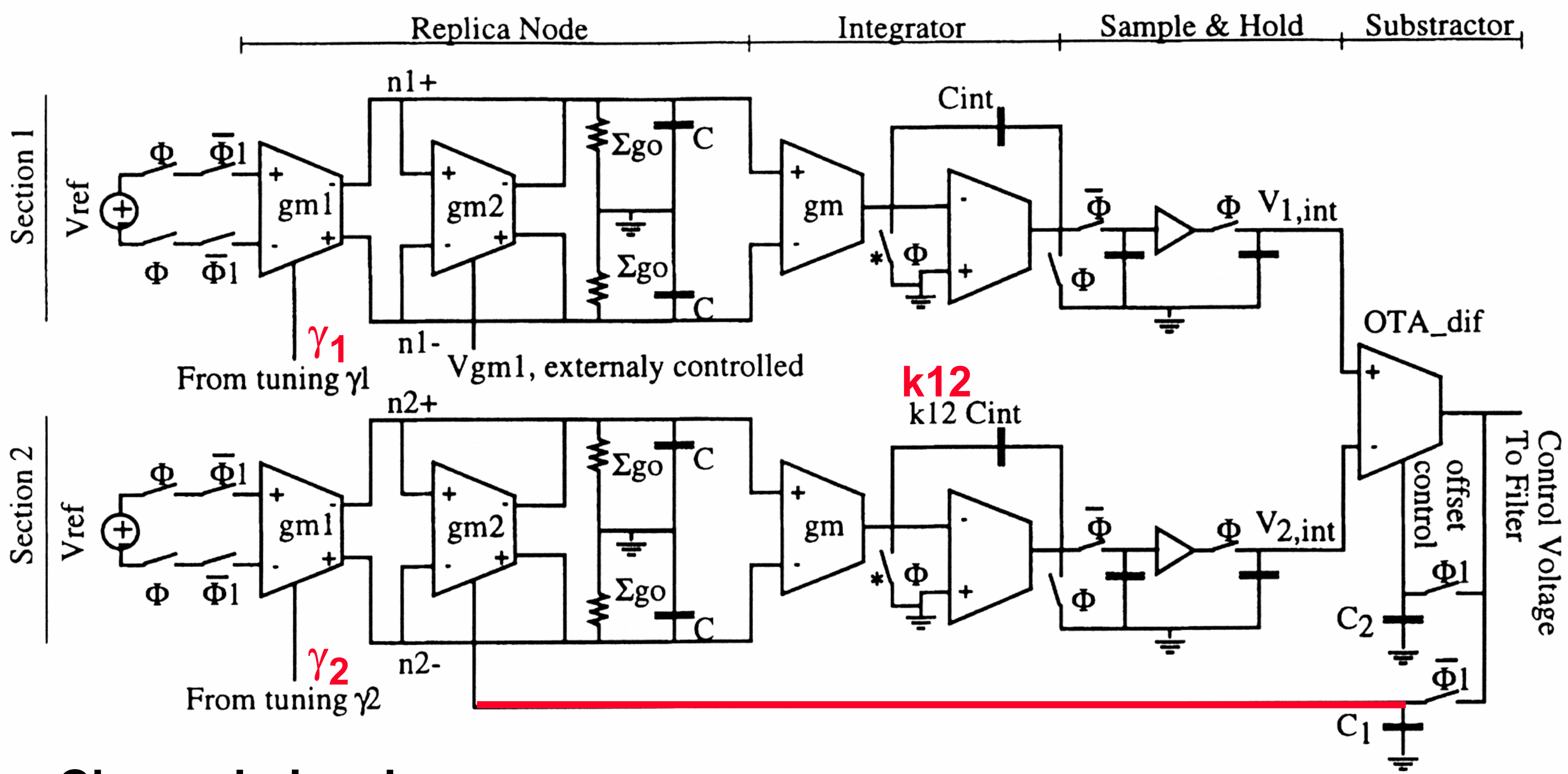
$\overline{\Phi_1}$ **closed : γ tuning mode** $\gamma = \dfrac{g_{m2}^*}{g_{m1}}$

$$V_{n+,n-} = \frac{g_{m1}}{g_{m2}^*} g_{OTA} V_{ref} = kV_{ref}\, g_{OTA} \Rightarrow \gamma = \frac{1}{k}$$

Φ_1 **closed :**
offset calibration mode for all OTA's (Vref set to 0)

Ref. Dehaene JSSC July 97, 977-988

Tuning system for the ratio of time constants



Charge balancing :

$V_{1,int} = V_{2,int}$ **or**

$$\frac{V_{ref}}{\gamma_1}\,\frac{g_m}{C_{int}}\,\tau_1 = \frac{V_{ref}}{\gamma_2}\,\frac{g_m}{k_{12}C_{int}}\,\tau_2 \Rightarrow \frac{\tau_2}{\tau_1} = k_{12}\,\frac{\gamma_2}{\gamma_1}$$

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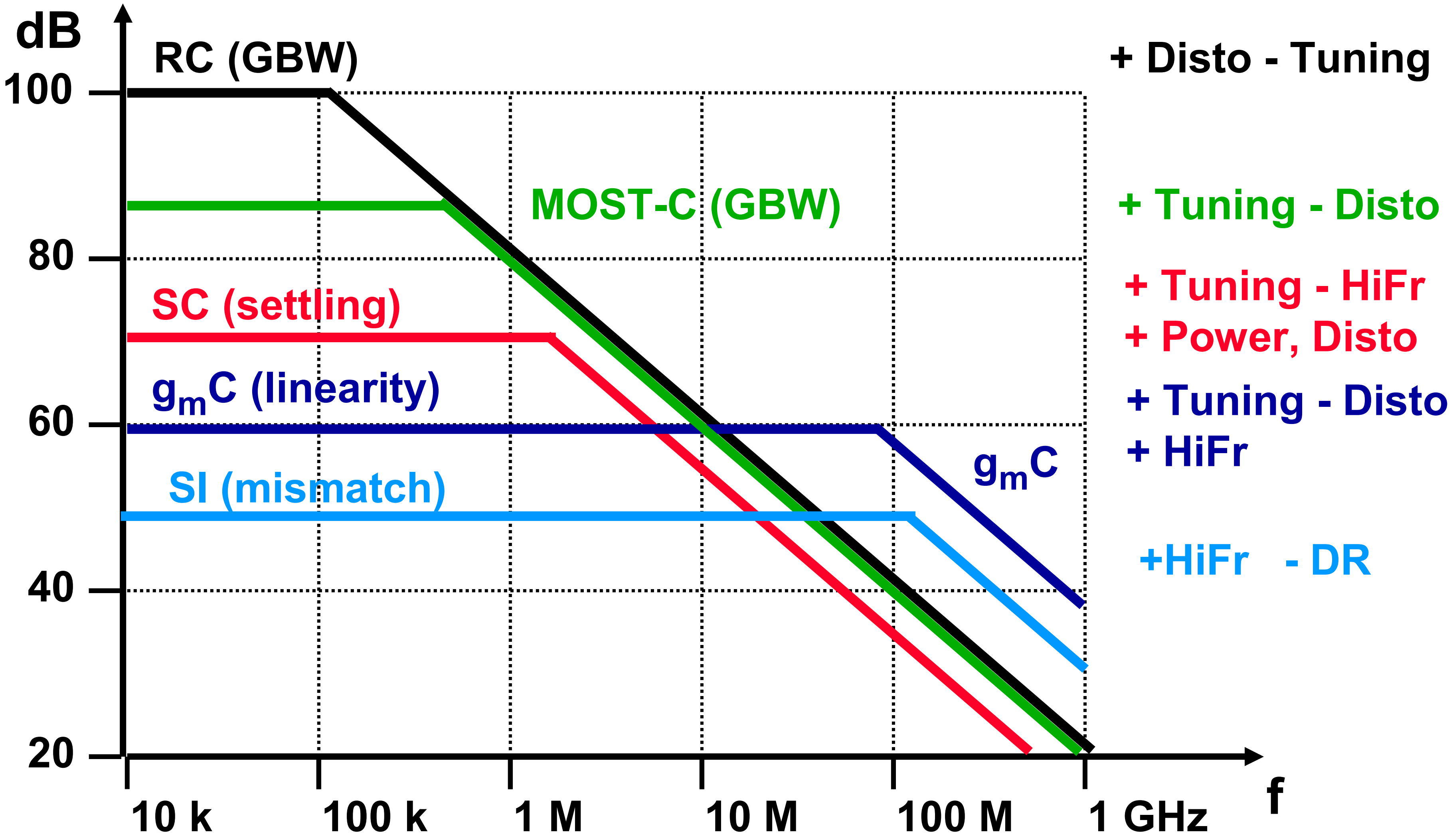
J. Silva-Martinez, Kluwer 1993,
W. Dehaene, JSSC, July 1997, 977-988

Signal to Noise + Distortion ratio



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