Class AB and driver amplifiers

Willy Sansen

KULeuven, ESAT-MICAS

Leuven, Belgium

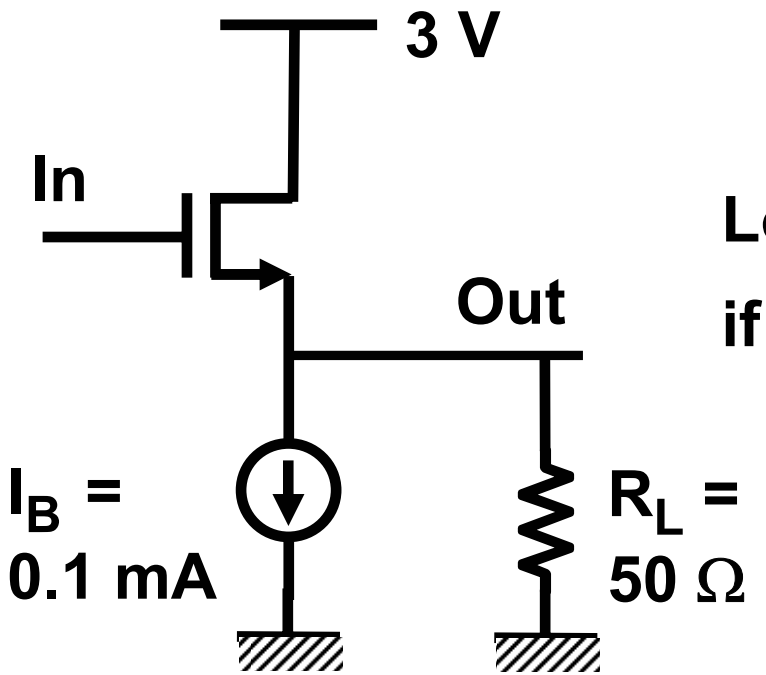
willy.sansen@esat.kuleuven.be

Outline

- **Problems of class AB drivers**
- **Cross-coupled quads**
- **Adaptive biasing**
- **I_Q control with translinear circuits, etc.**
- **Current feedback and other principles**
- **Low-Voltage realizations**

Ref.: W. Sansen : Analog Design Essentials, Springer 2006

CMOS Output stage problem



Low power consumption:

if $I_B = 0.1$ mA : $V_{out,\,peak} = 5\ mV_{peak}$

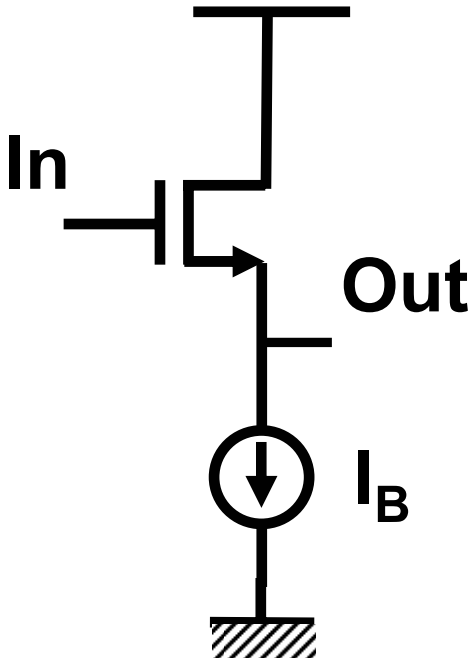
$I_{max} < I_B$

For $V_{out,\,peak} = 1\ V_{peak}$: $I_B = 20$ mA

High power consumption !

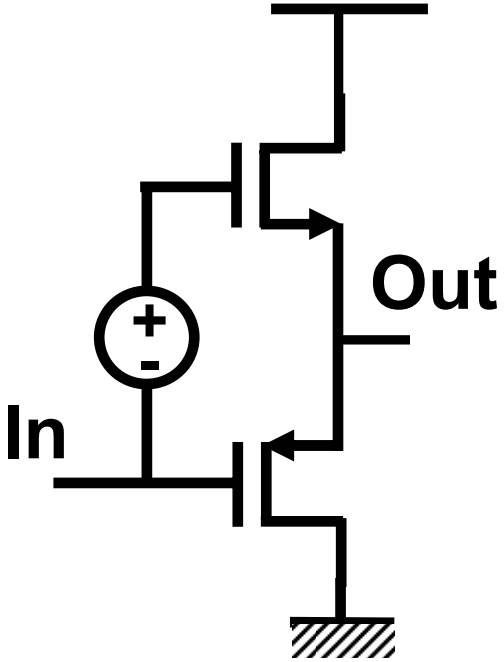
$V_{Out} = V_{In} - V_{GS}$

CMOS Output stages



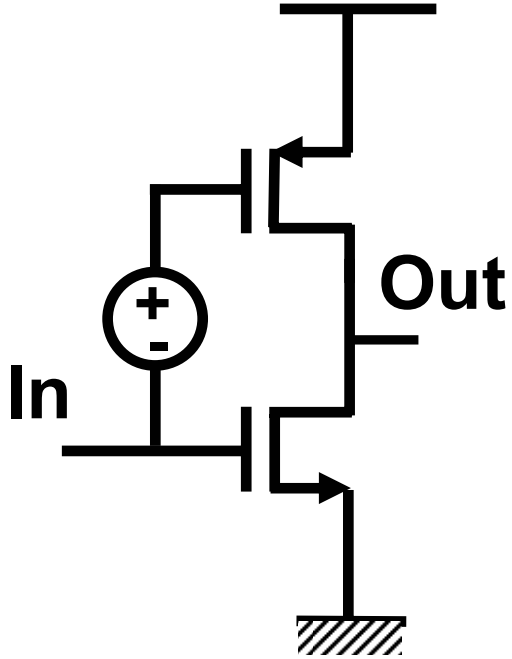
$I_{max} < I_B$

$V_{Out} = V_{In} - V_{GS}$



Push-Pull

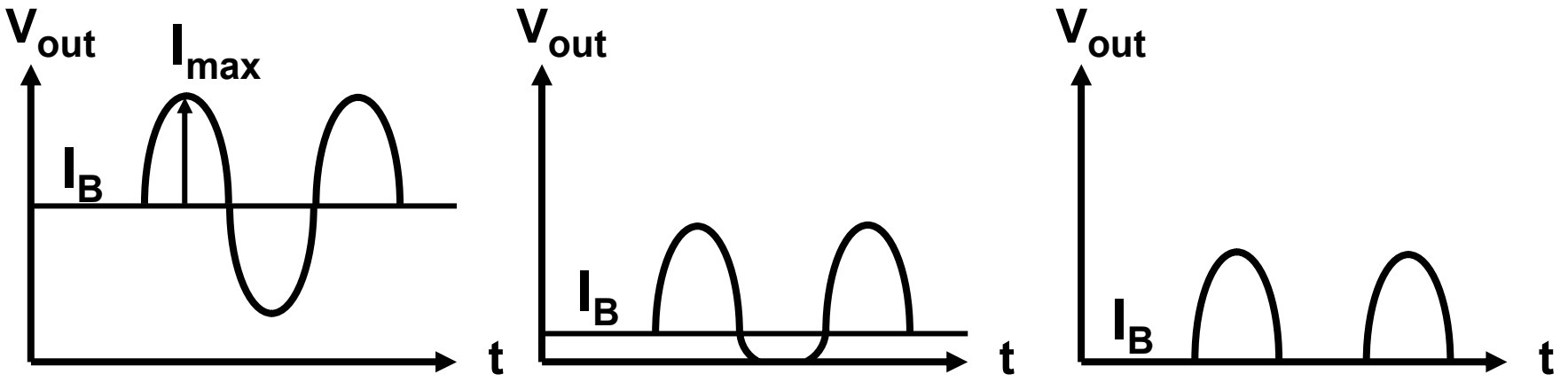
$V_{out,max} = V_{DD} - 2V_{GS}$



Amplifier

Rail-to-rail

Class A, AB, B, etc



$I_B > I_{max}$

Class A

High power !

$I_B < I_{max}$

Class AB

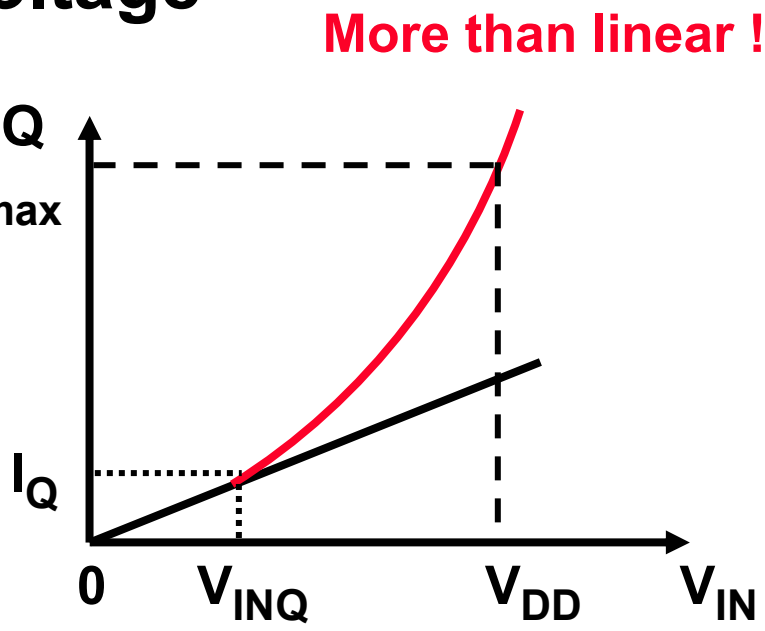
$I_B = 0$

Class B

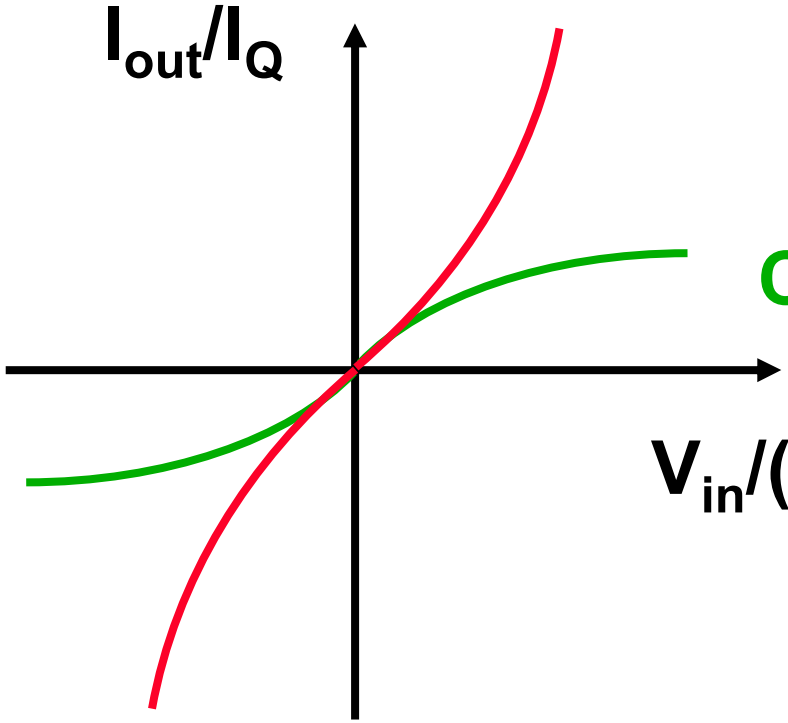
Distortion !

Requirements class -AB stages

- Rail-to-rail output swing
- Accurate control of quiescent current I_Q
  - Must be low
  - Independent of supply voltage
- Large drive capability I_{max}/I_Q
- Small area



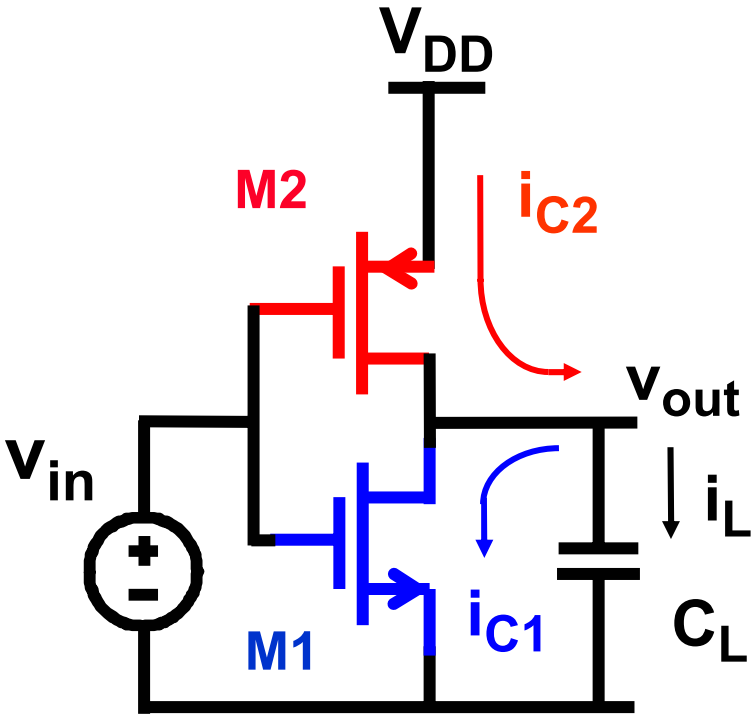
Class -AB stages

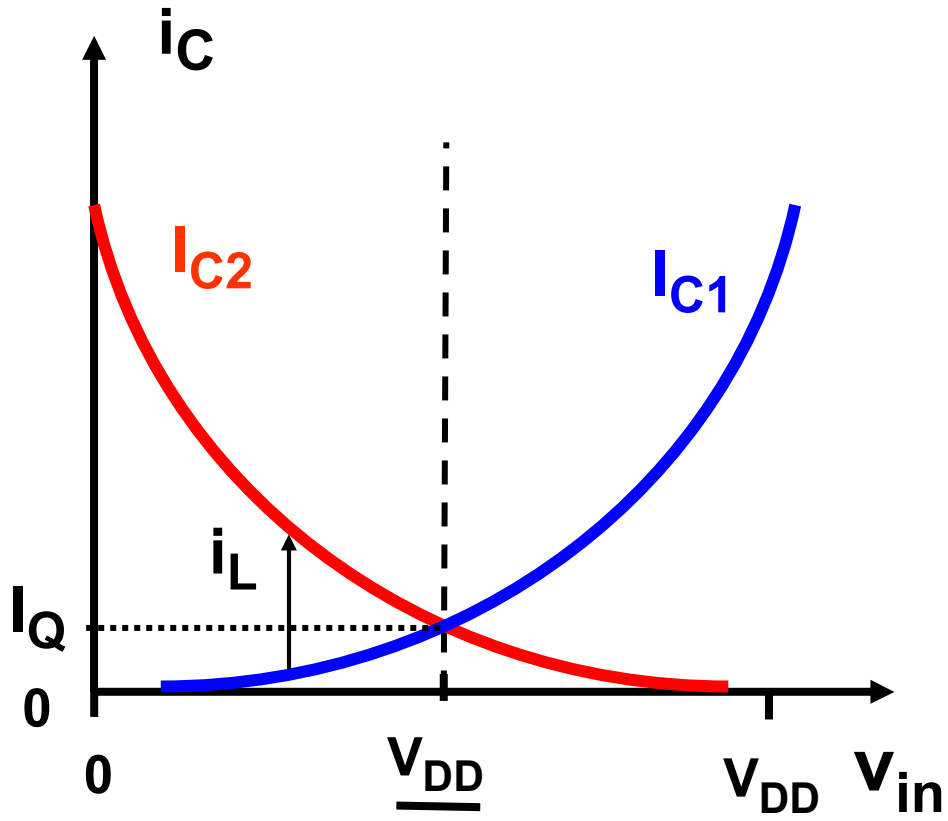


Class AB diff stage :
more than linear !
expanding !

Conventional diff. Stage :
limiter !

Simple CMOS class-AB amplifier



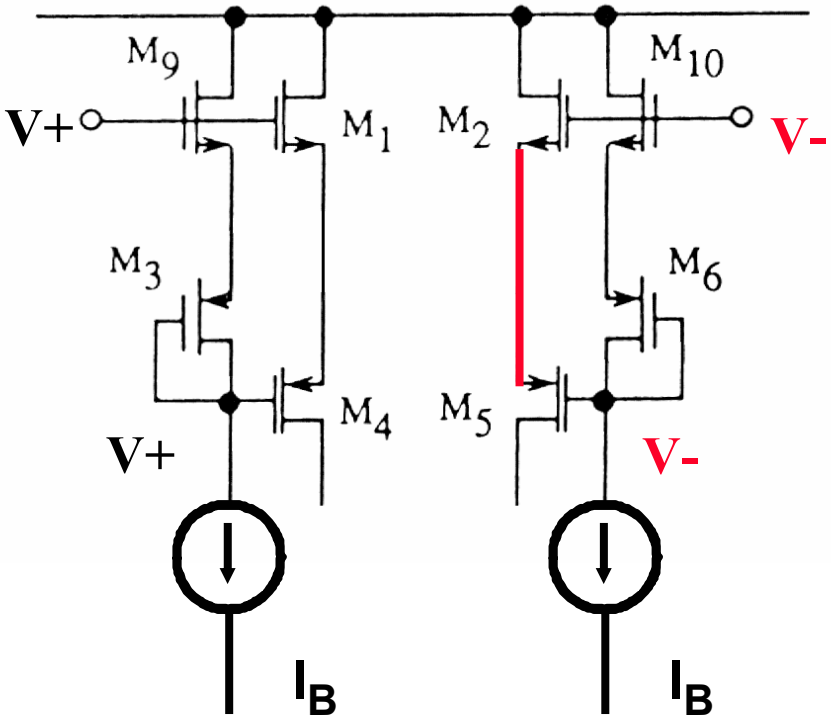


$$i_L = i_{C2} - i_{C1}$$

Outline

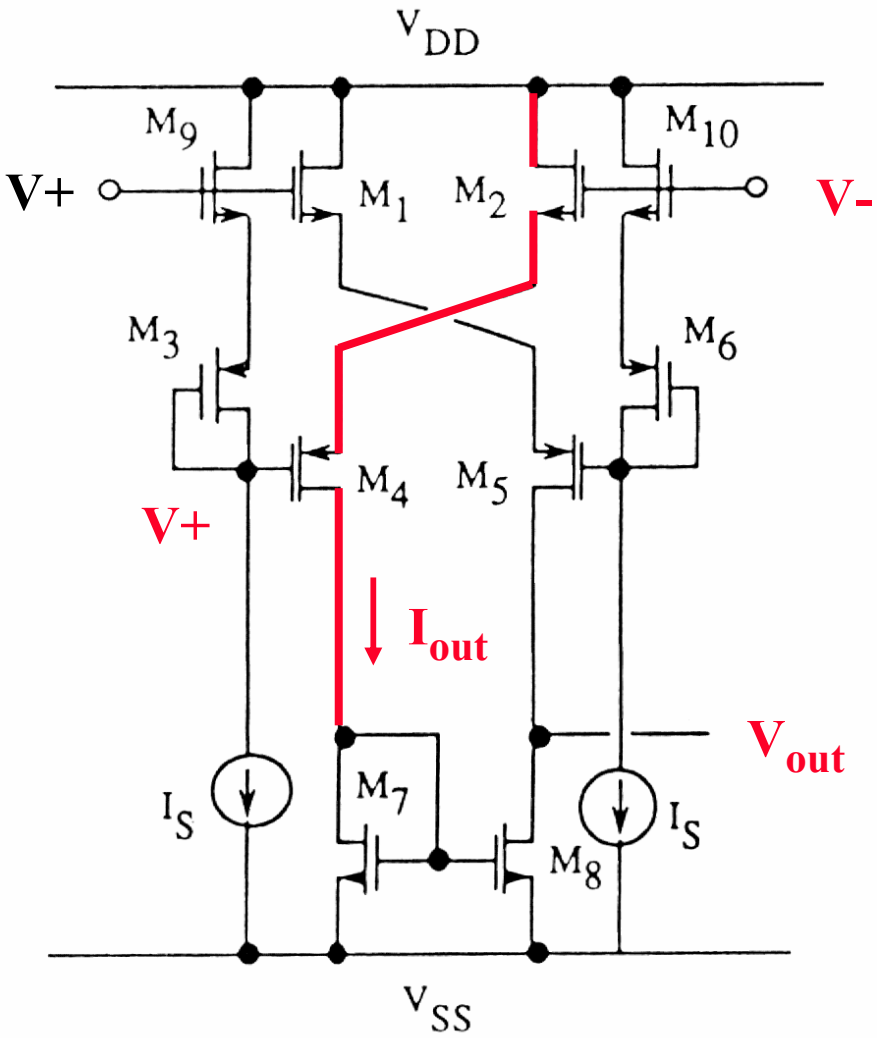
- Problems of class AB drivers
- Cross-coupled quads
- Adaptive biasing
- I_Q control with translinear circuits, etc.
- Current feedback and other principles
- Low-Voltage realizations

Cross-coupled quad

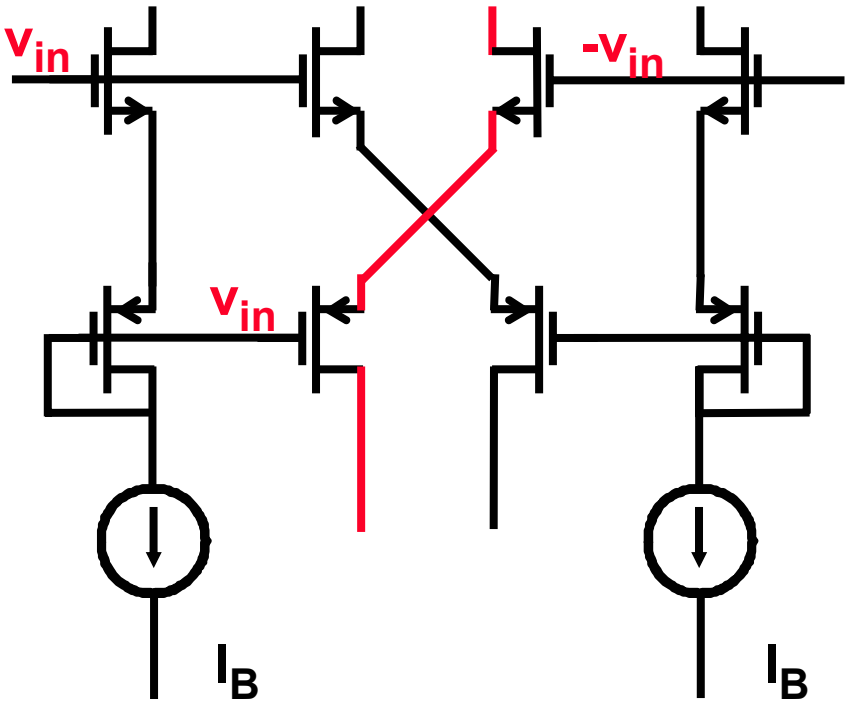


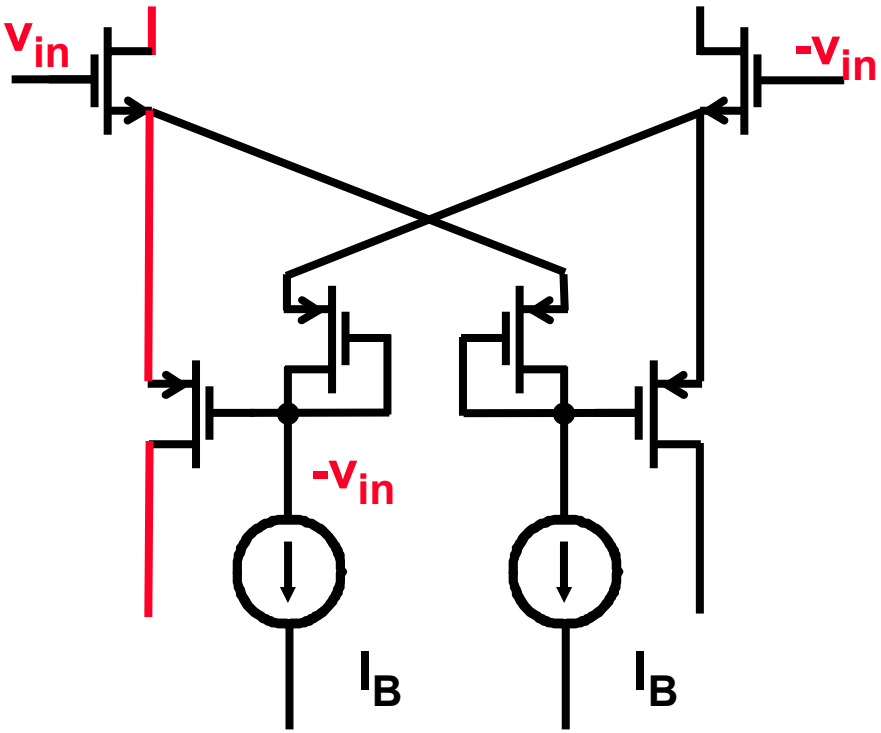
Two super-followers

Ref. Castello, JSSC Dec.85, 1122-1132



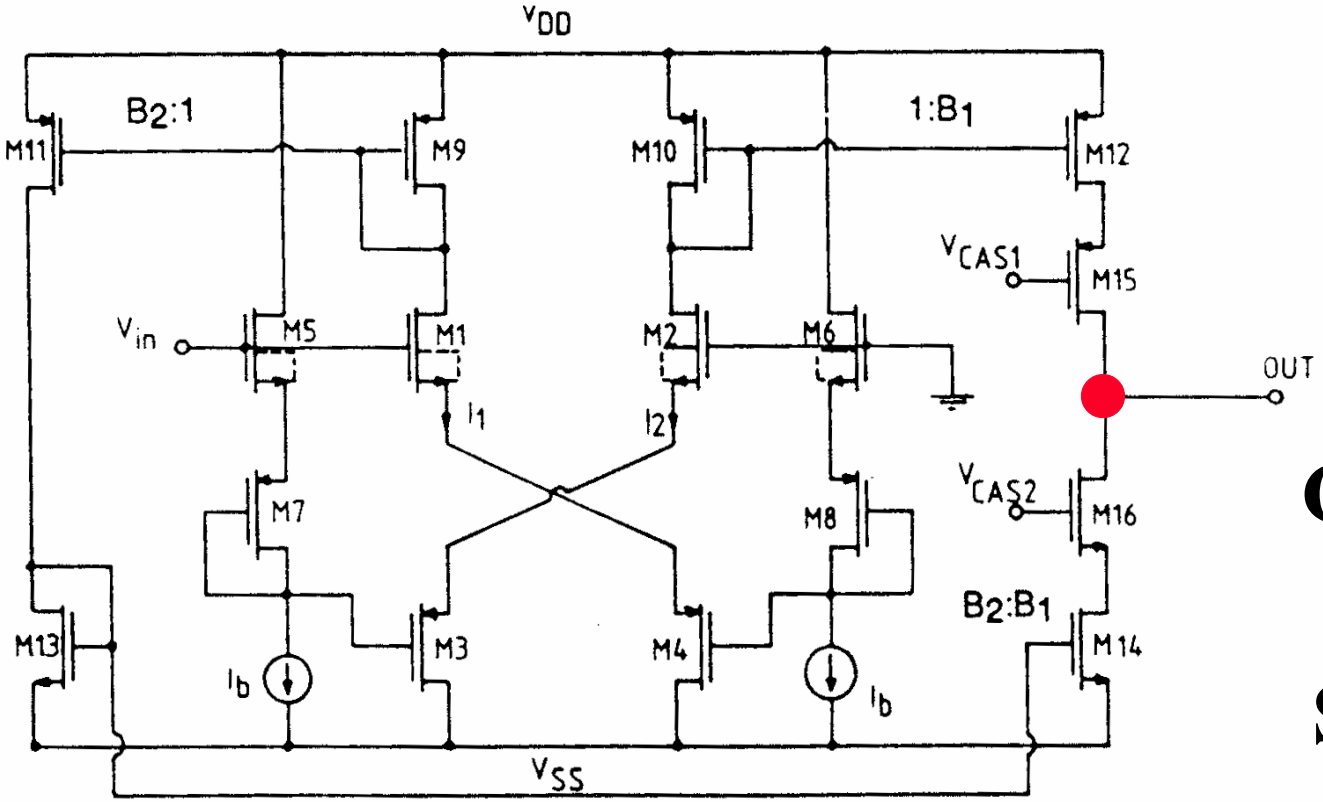
Other cross-coupled quads





Bipolar Ref. Hearn, JSSC Febr.71

Class AB Input structures

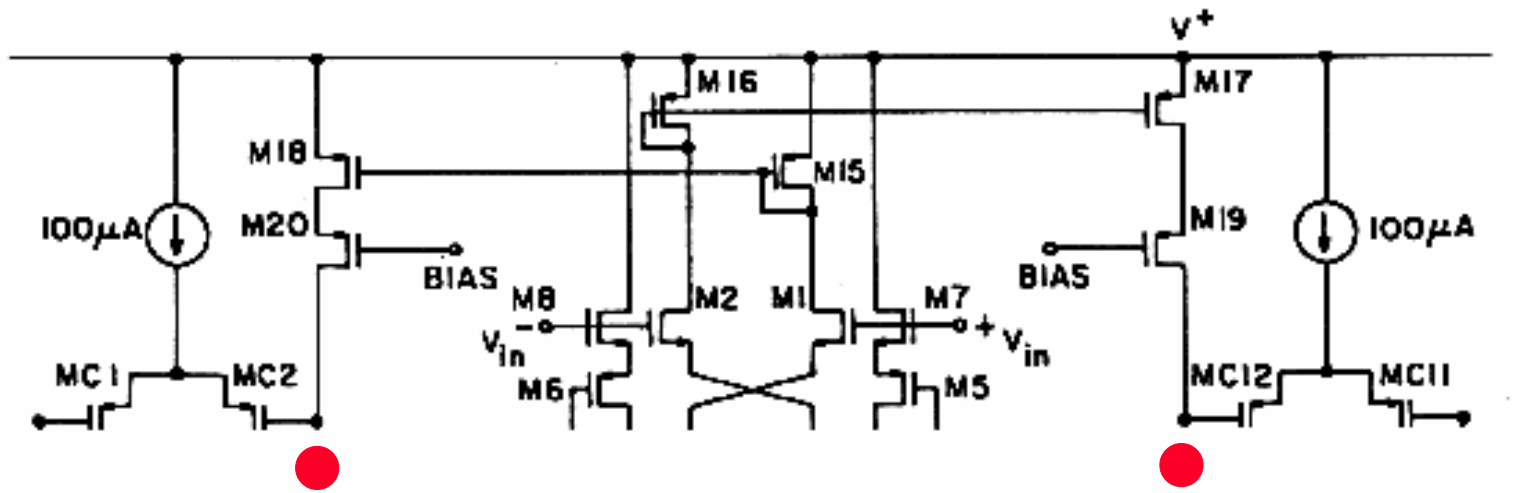


$$GBW = \frac{g_{m1}}{2\pi C_L}$$

$$SR \Uparrow\Uparrow$$

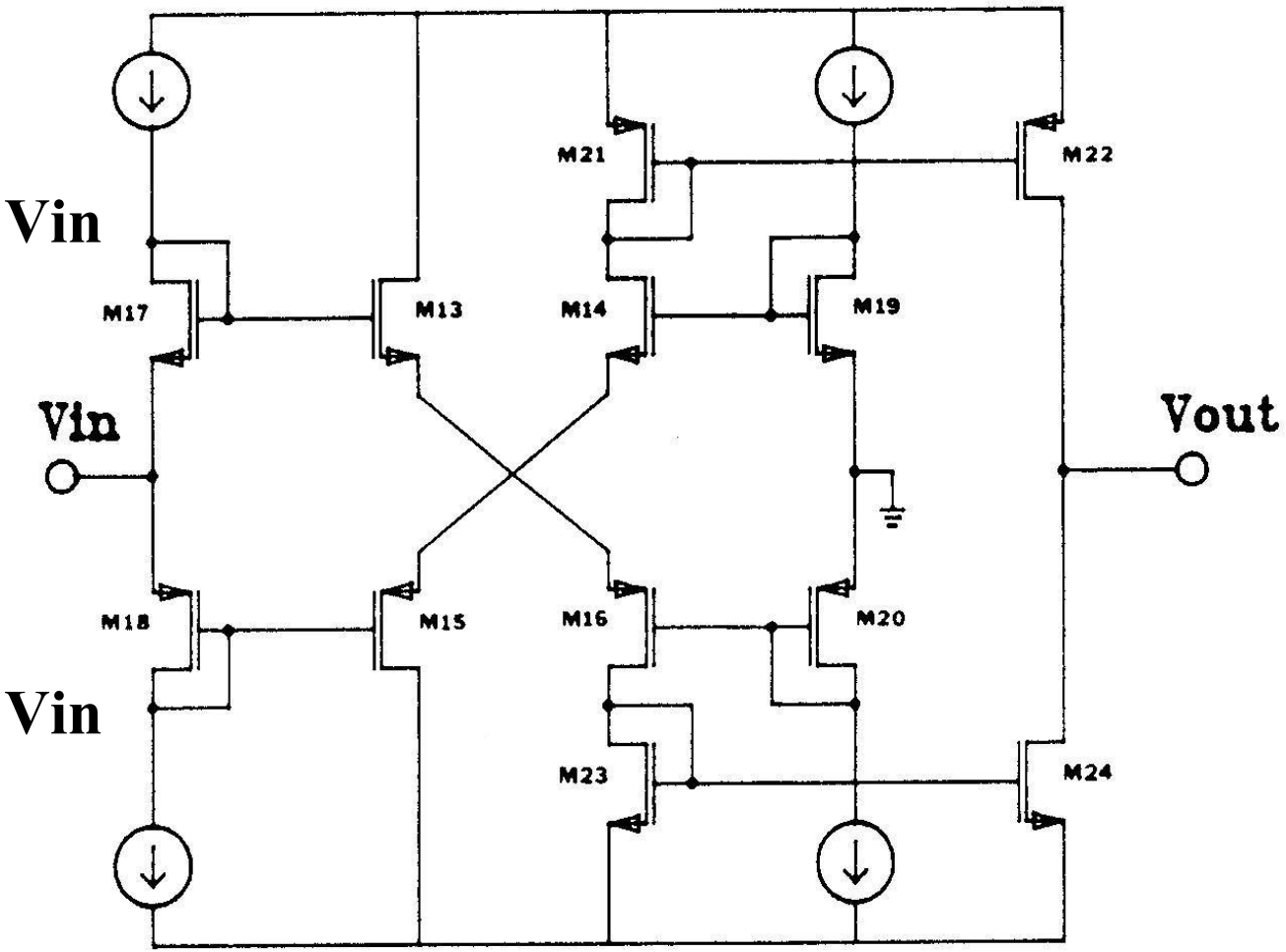
Ref. Halonen, 1987

Class AB fully differential amplifier



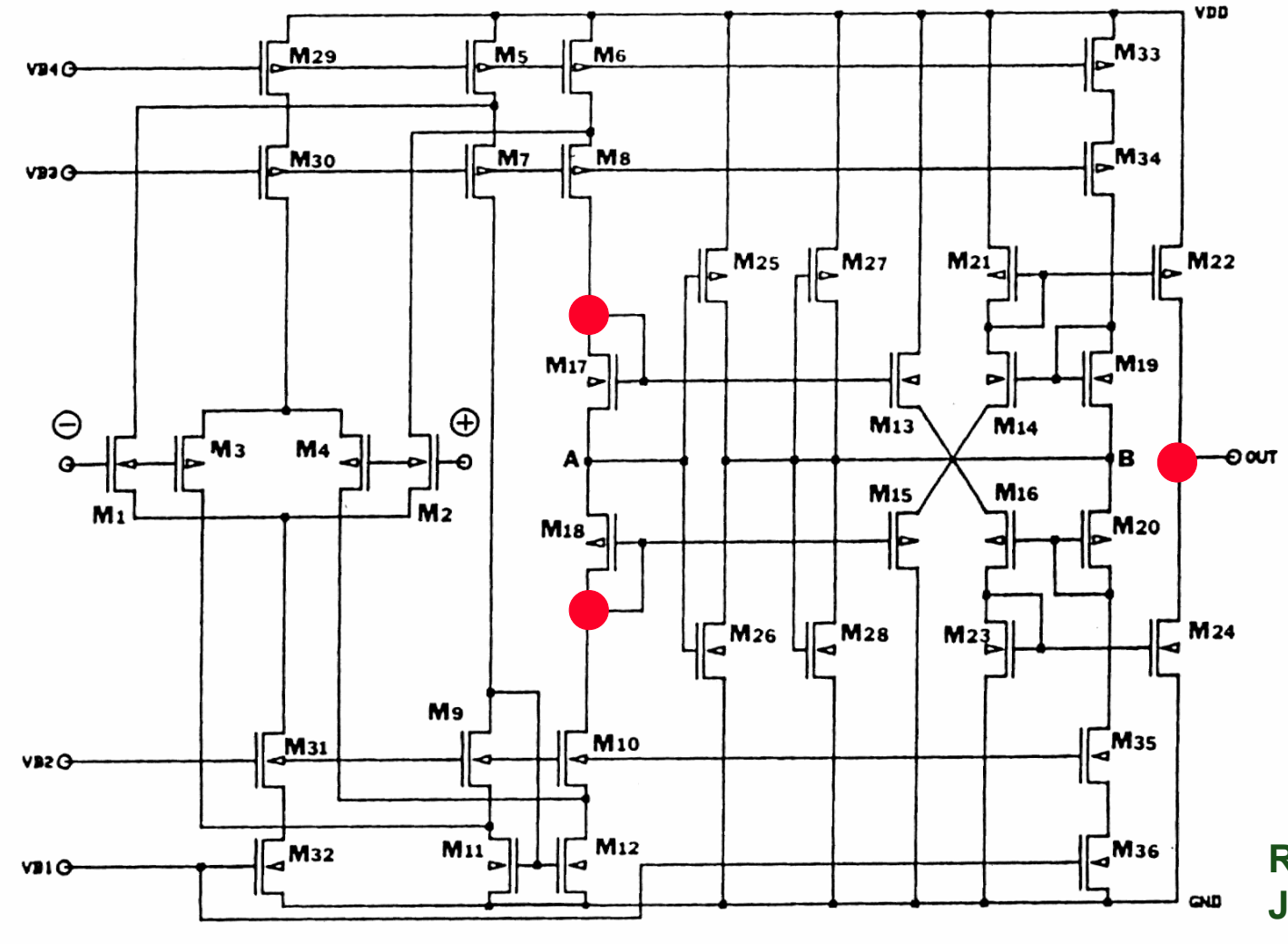
Ref.Lee,
JSSC
Dec.85,
1103-1113

Double-Push



Ref. Fischer, JSSC June 87, 330-340

Double-Push amp (Fischer)

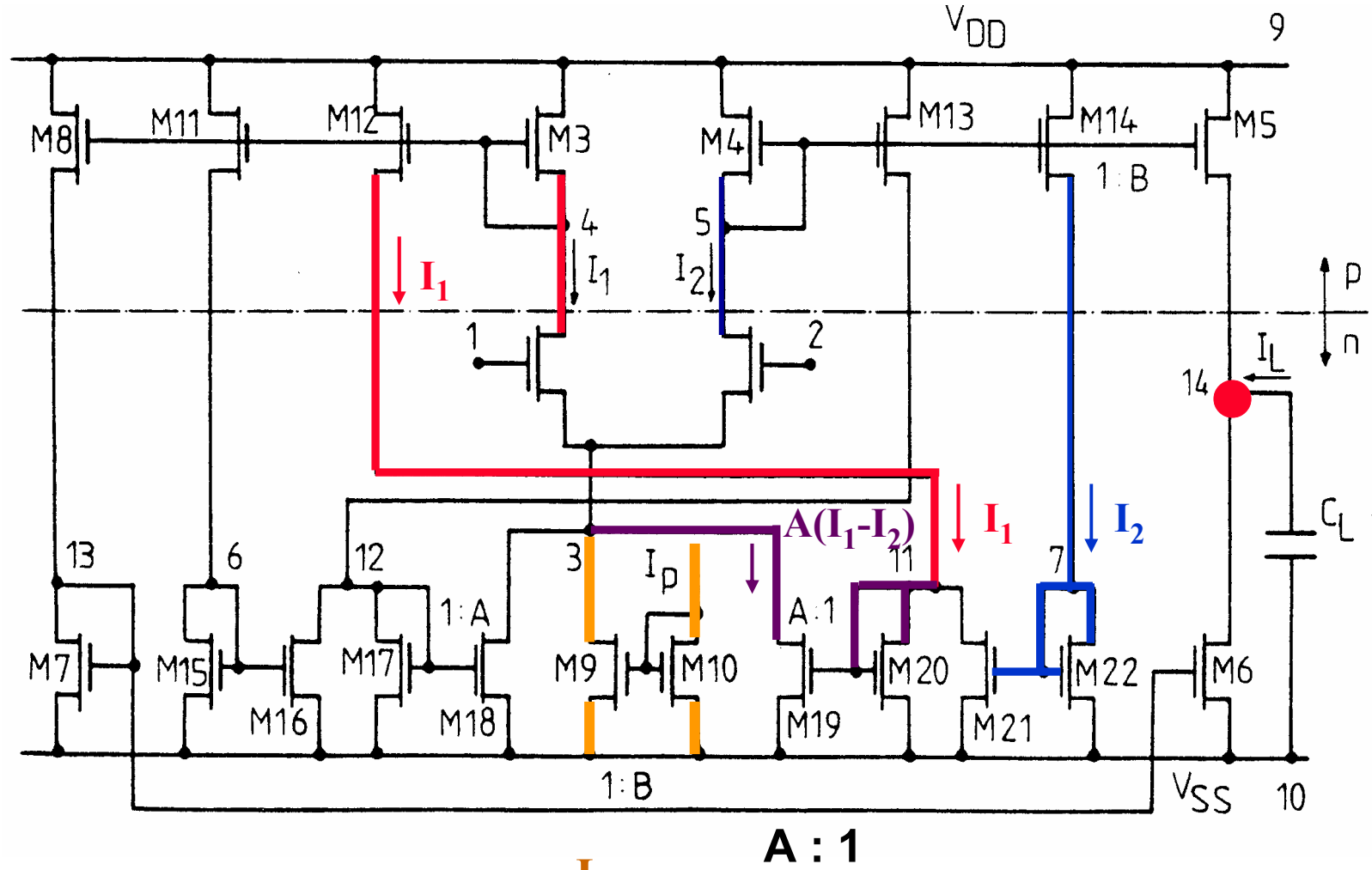


Ref. Fischer, JSSC
June 87, 330-340

Outline

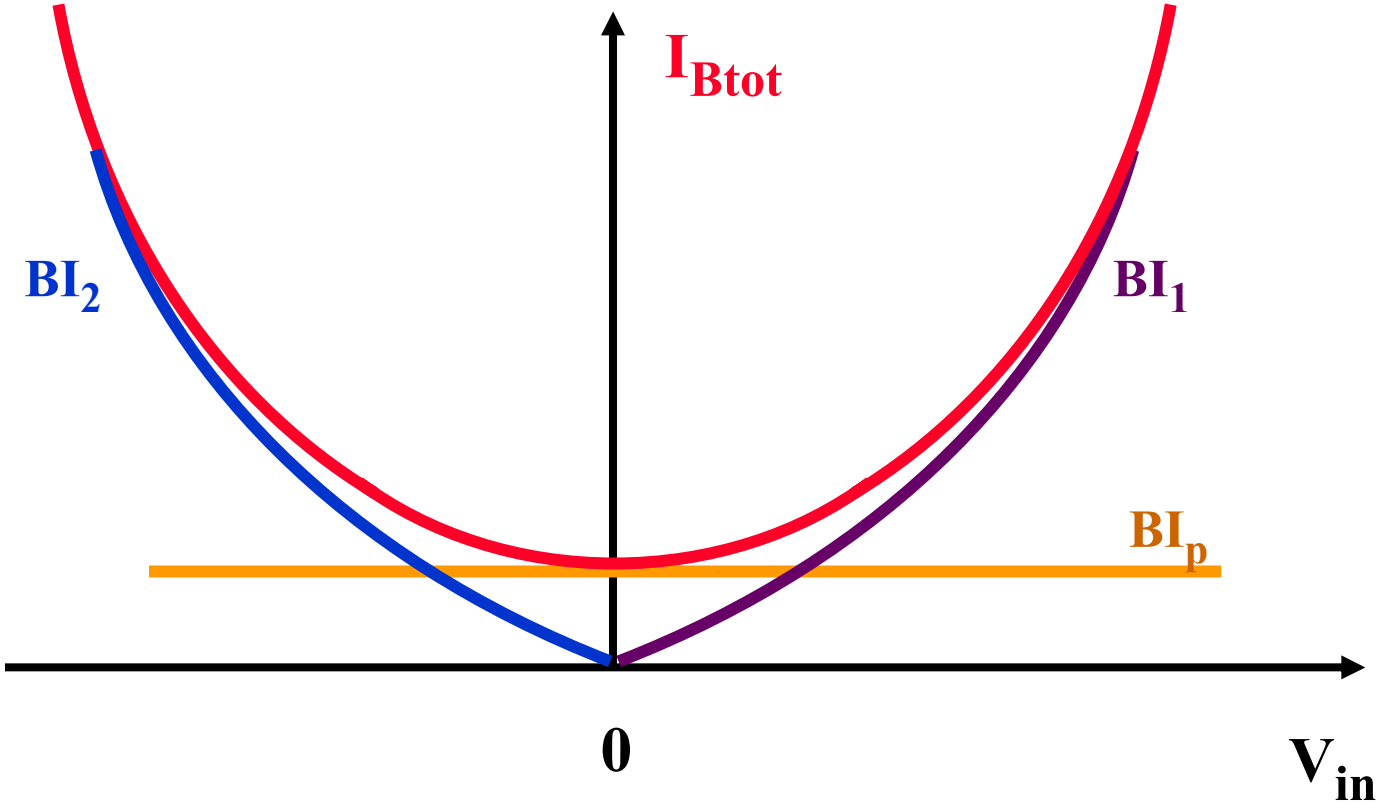
- Problems of class AB drivers
- Cross-coupled quads
- Adaptive biasing
- I_Q control with translinear circuits, etc.
- Current feedback and other principles
- Low-Voltage realizations

Adaptive Biasing Amplifier



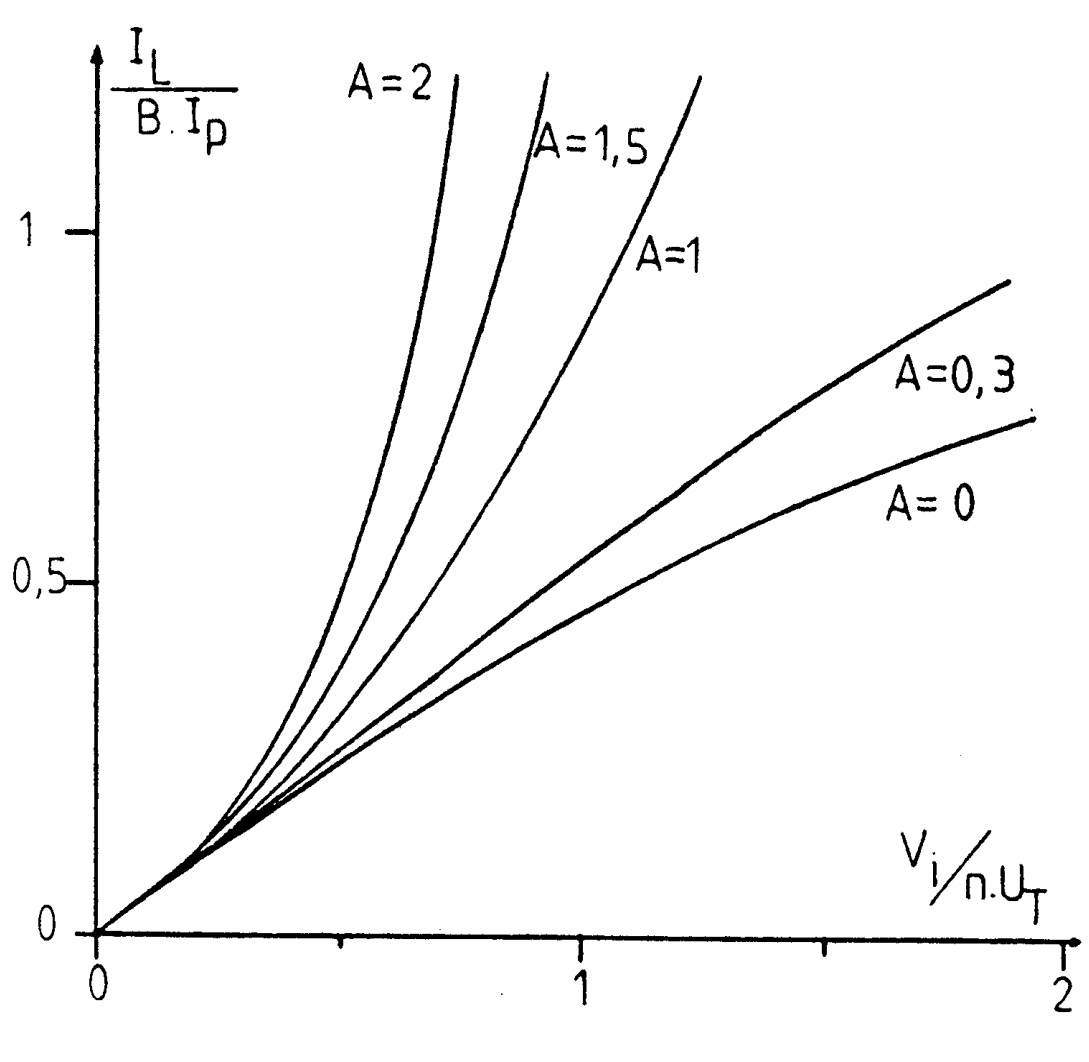
Ref. Degrauwe, JSSC June 82, 522-528

Adaptive Biasing Amplifier : biasing current



Ref. Degrauwe, JSSC June 82, 522-528

Adaptive Bias Amplifier: transfer curve



If $A.\alpha_{mis18\text{-}19} \geq 1$

⇩

UN-stable

e.g. if $\alpha_{mismatch}$ = 10%

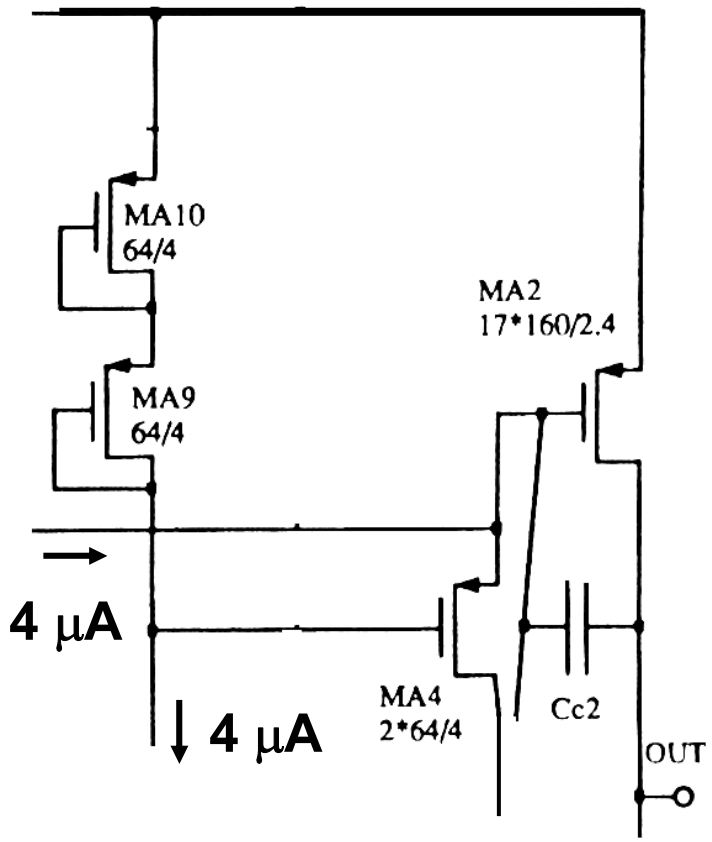
⇩

A << 10

Outline

- Problems of class AB drivers
- Cross-coupled quads
- Adaptive biasing
- I_Q control with translinear circuits, etc.
- Current feedback and other principles
- Low-Voltage realizations

Quiescent current control with translinear loop



Translinear loop :

$$V_{GS2} + V_{GS4} = V_{GS9} + V_{GS10}$$

$$V_{GS2} - V_T = \sqrt{\frac{I_{DS2}}{K'_p\, W/L_2}}$$

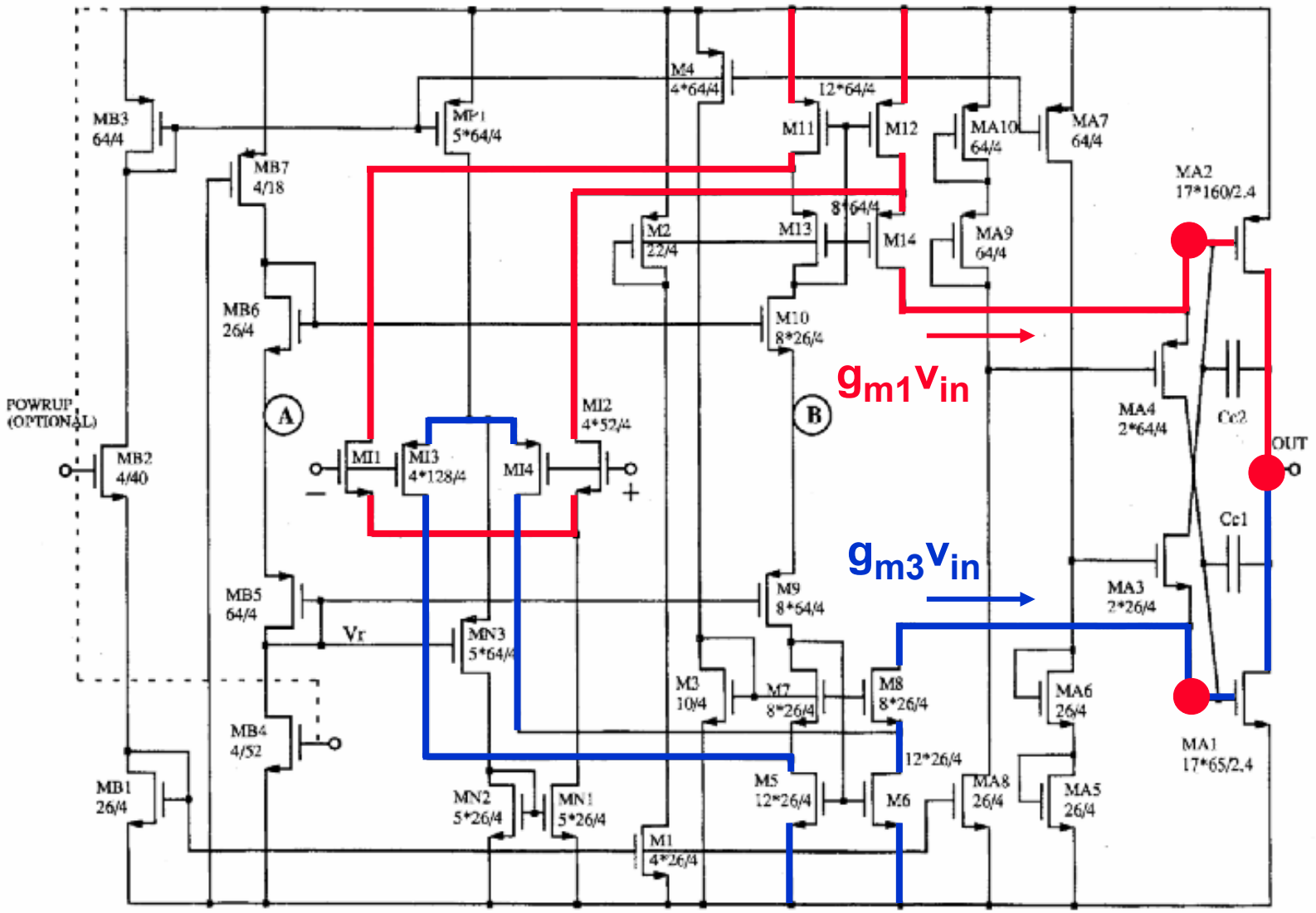
$$\sqrt{\frac{I_{DS2}}{W/L_2}} + \sqrt{\frac{I_{DS4}}{W/L_4}} = 2\sqrt{\frac{I_{DS9}}{W/L_9}}$$

$$\frac{I_{DS2}}{I_{DS9}} = \frac{W/L_2}{W/L_9}\left(2 - \frac{1}{\sqrt{2}}\right)^2 \approx 118$$

$W/L_4 = 2\ W/L_9$ & $W/L_2 = 70.8\ W/L_9$

$I_{DS2} \approx 473\ \mu A$ since $I_{DS9} \approx 4\ \mu A$

Ref. : Wu etal, JSSC Jan.1994, pp.63-66



14 MHz / 11pF

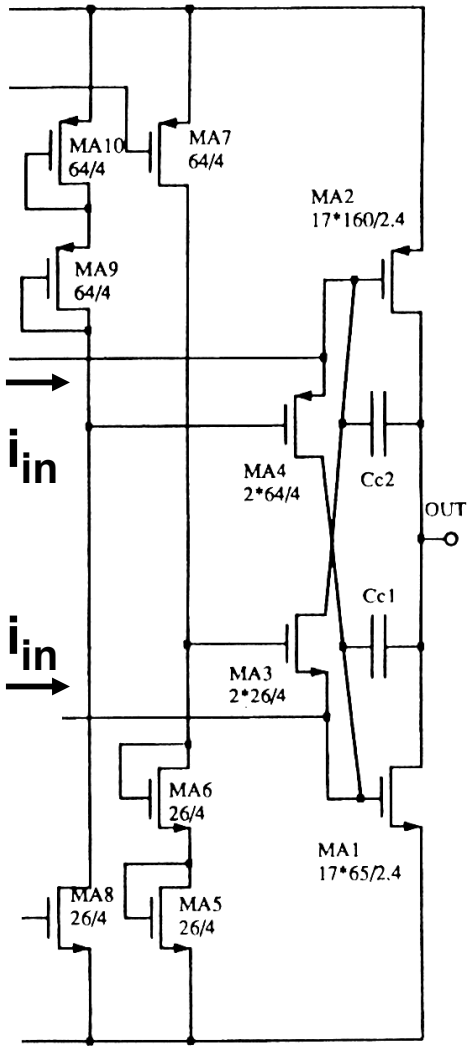
5.6 MHz / 100pF

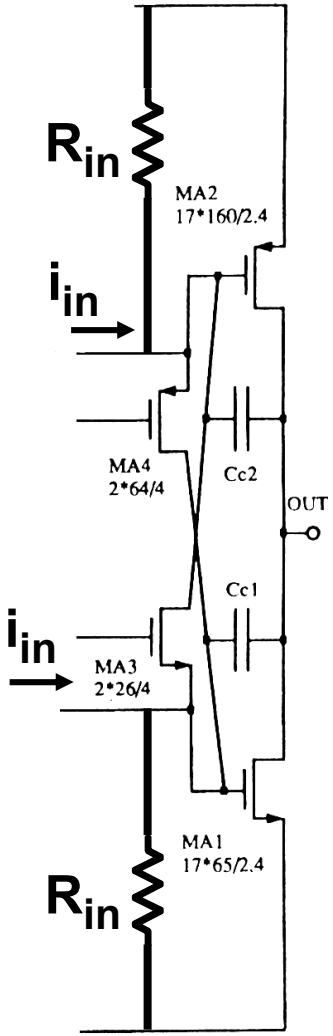
4 V/µs

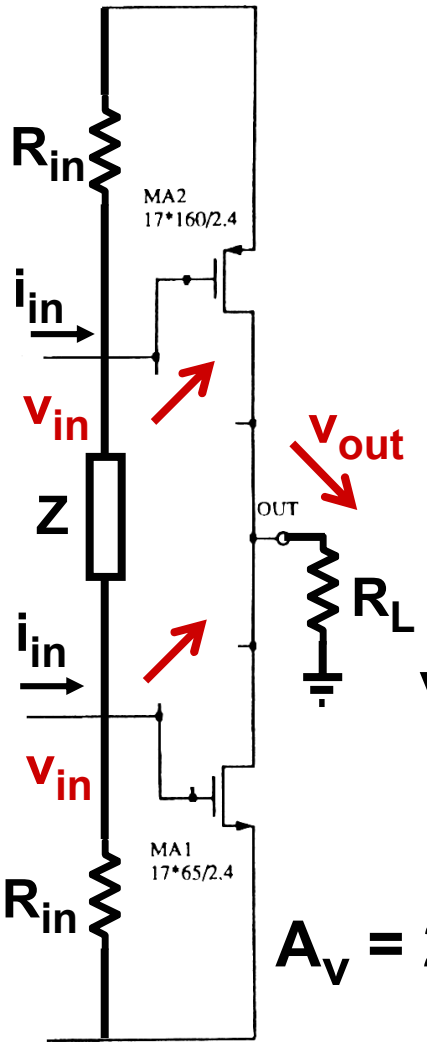
36 nV/√ Hz

5 V
0.4 mA

Output stage : gain







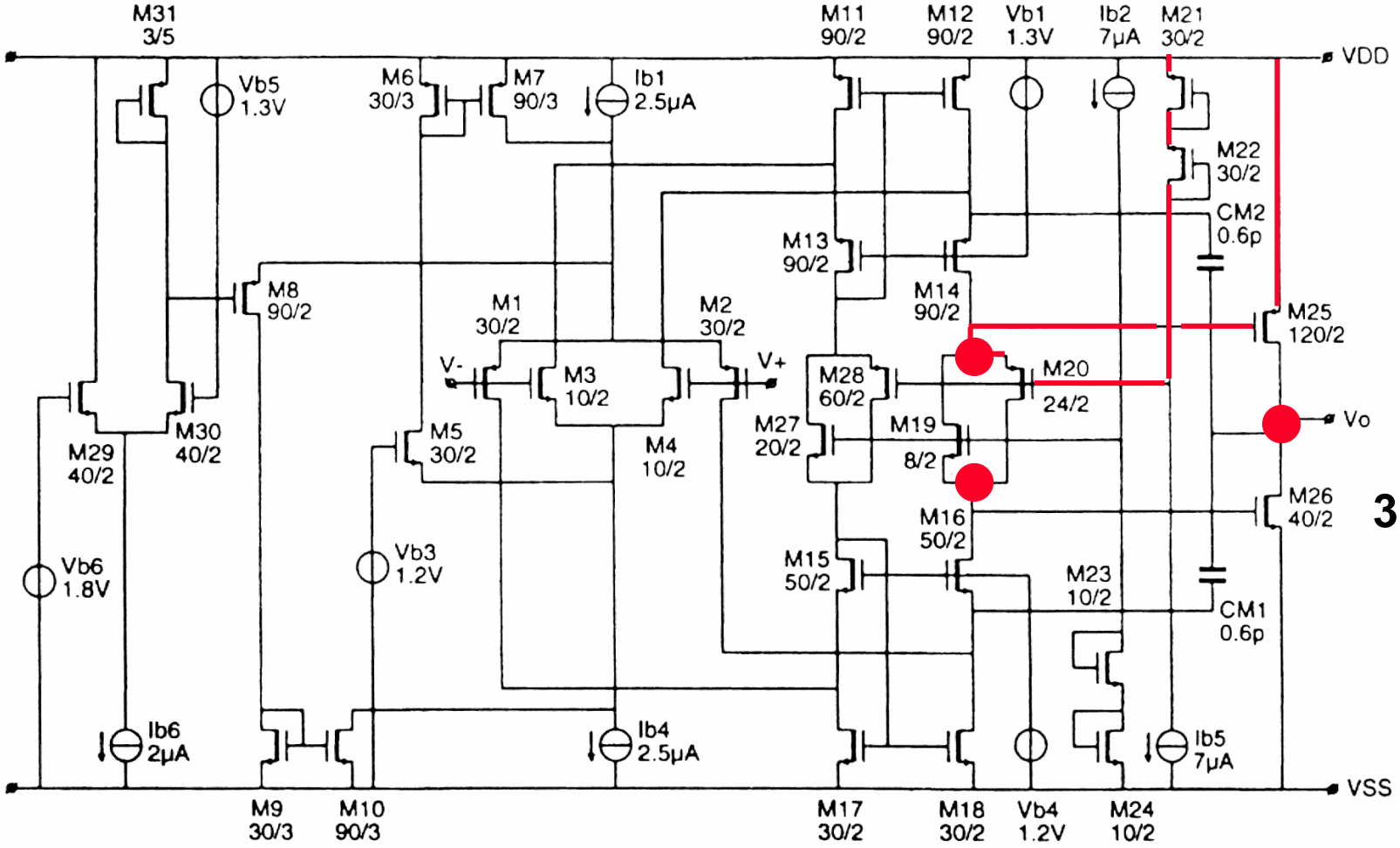
$$i_{in} = g_{m1} v_{+-}$$

$$\frac{v_{in}}{i_{in}} = R_{in}$$

$$\frac{v_{out}}{v_{in}} = 2 g_{mA1} R_L$$

$$A_v = 2 g_{m1} R_{in} g_{mA1} R_L$$

Class AB amplifier with translinear loop



6.4 MHz / 10 pF

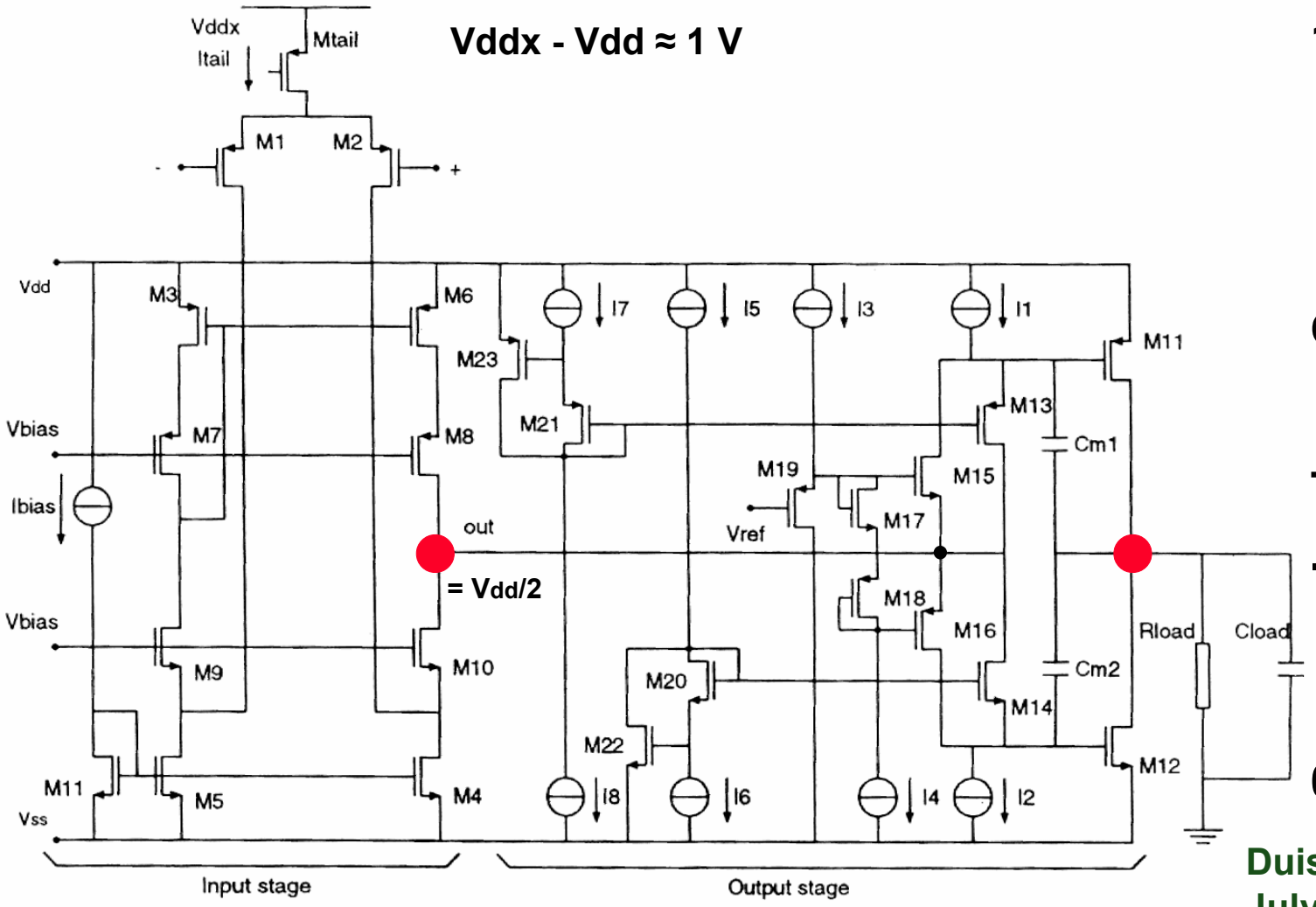
6.4 V/µs

31 nV/√ Hz

3.3 V
0.18 mA
3 mApk

Ref. Hogervorst, JSSC Dec 94, 1504-1512

Class-AB Opamp with voltage multiplier



Vddx - Vdd ≈ 1 V

1.8 - 3.3 V

0.75 mA

6.5 MHz

On 3 V :

2.8 V_{ptpt}

THD :

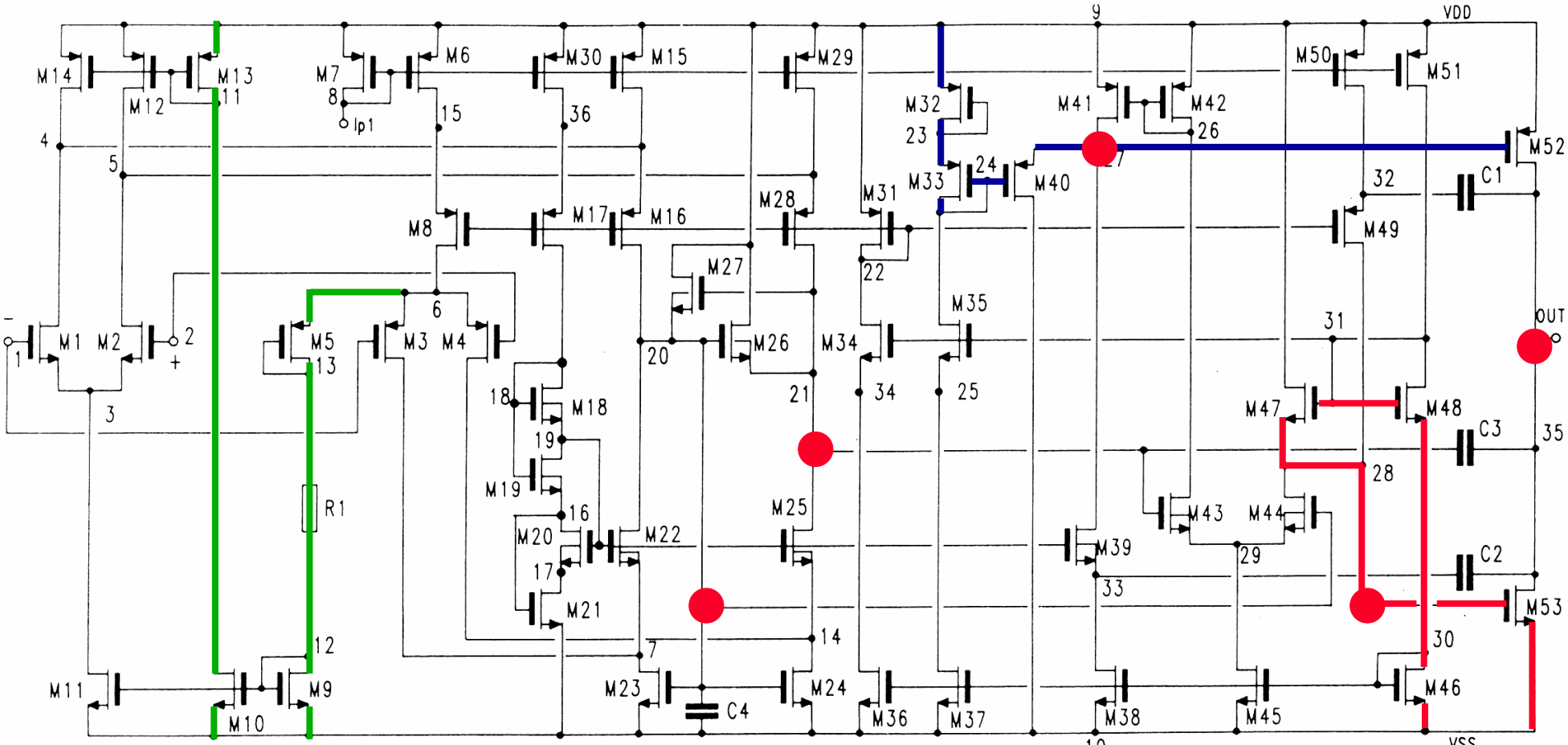
-90 dB /10kΩ

-81 dB/32 Ω

0.5 μm CMOS

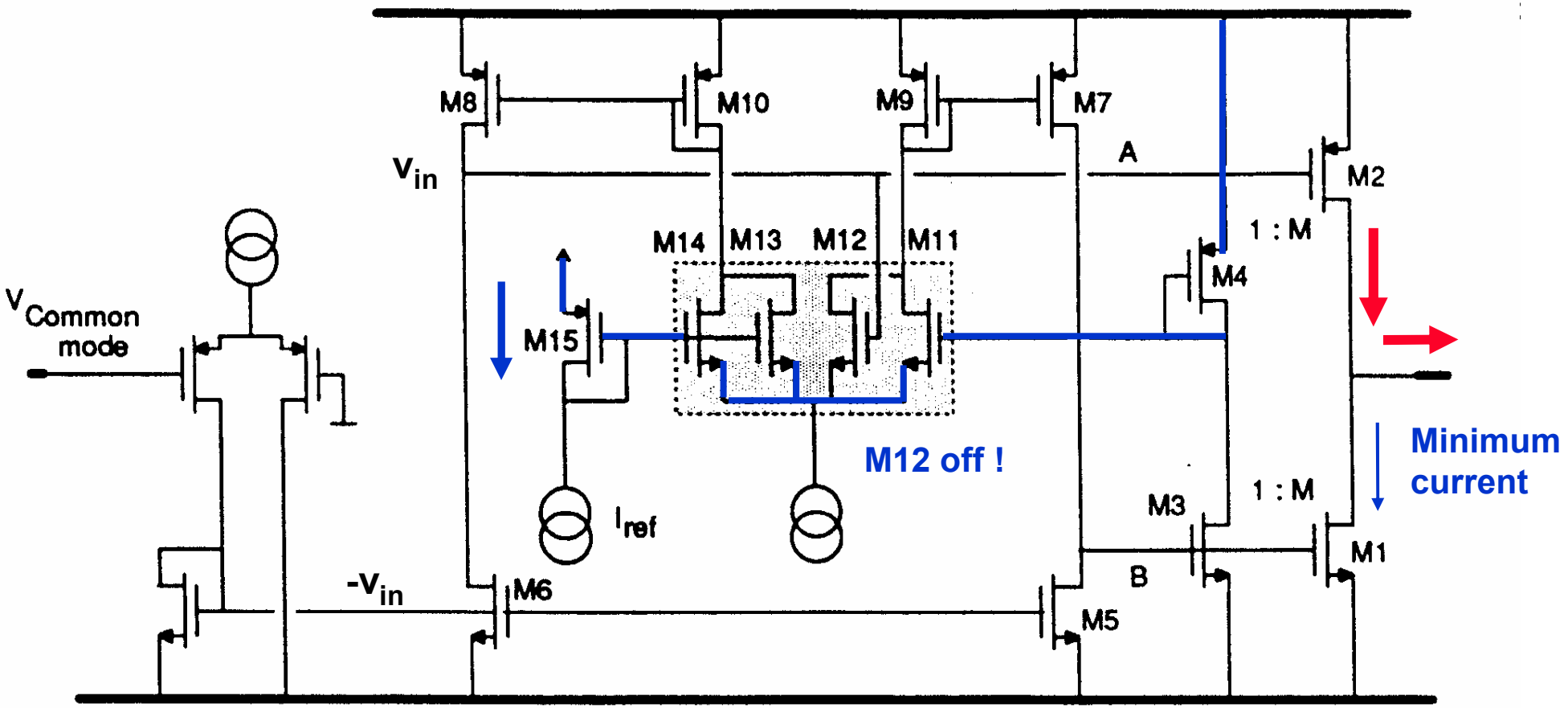
Duisters, .., JSSC July 98,pp.947-955

Three-stage Modified Current Mirror



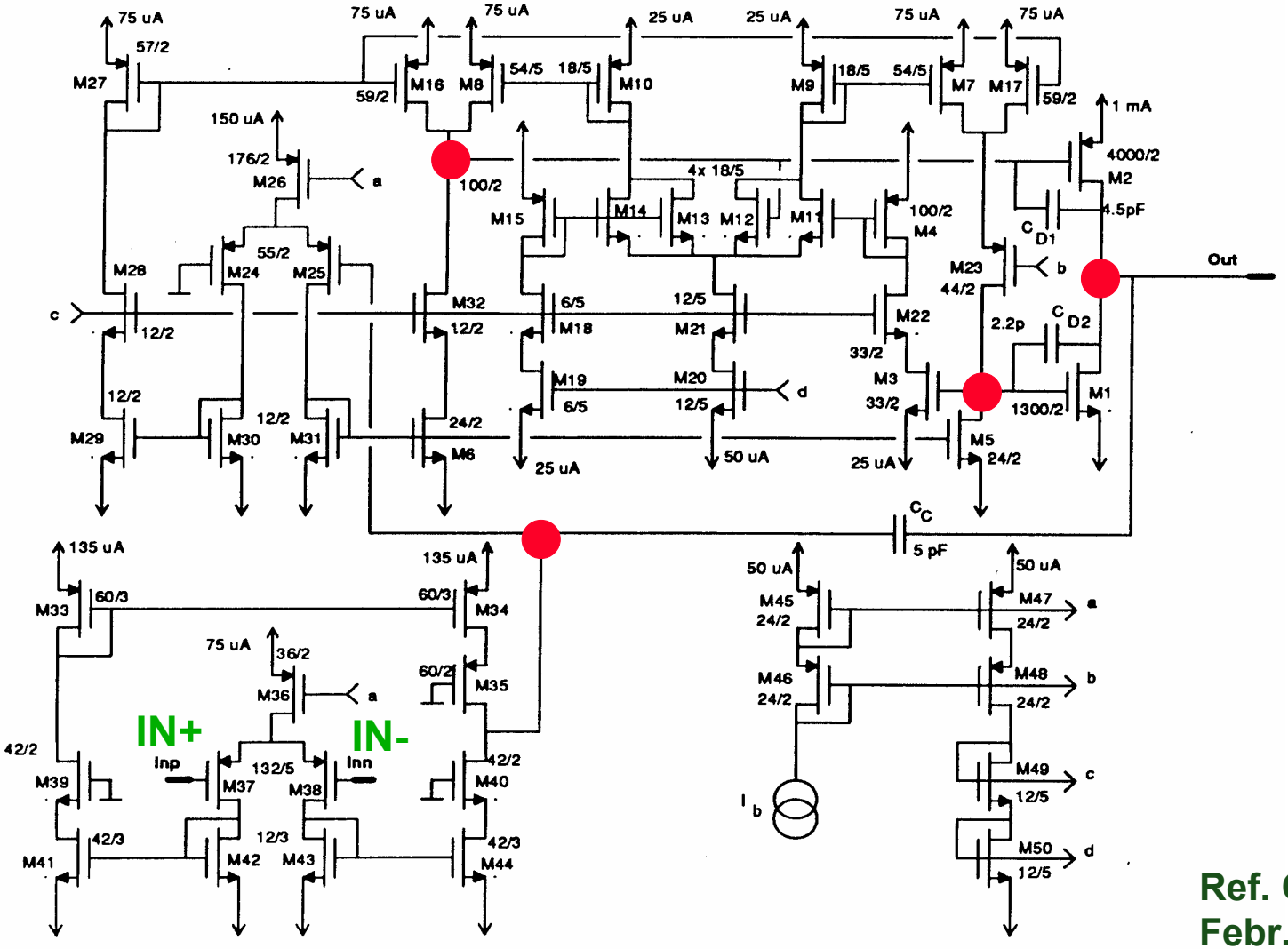
Pardoen, .., JSSC April 90, 501-504

Translinear I_Q Control



Ref. Op 't Eynde, JSSC Febr.90, 265-273

Translinear I_Q Control

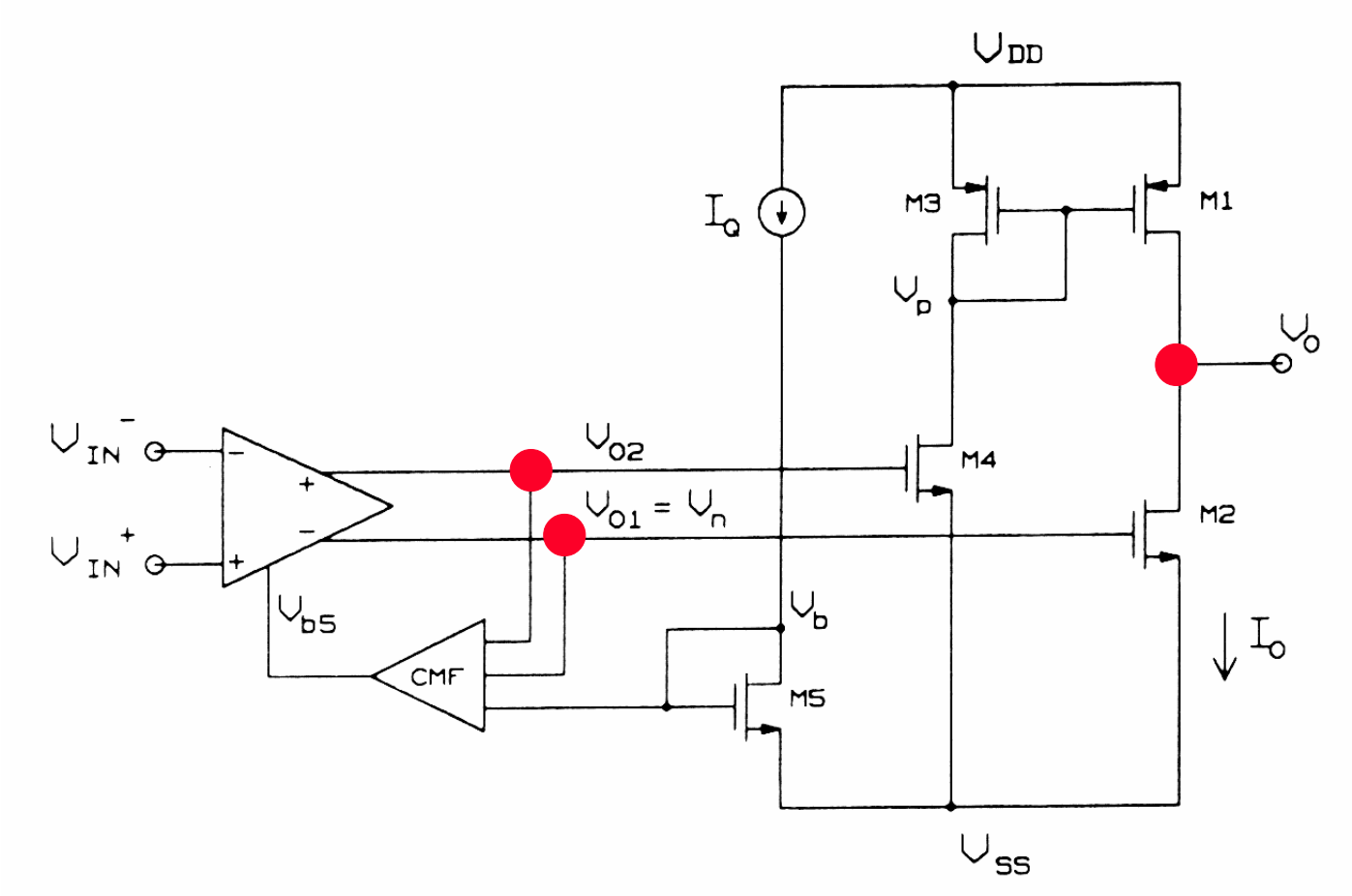


3 stage Class-AB Amplifier

I_Q control

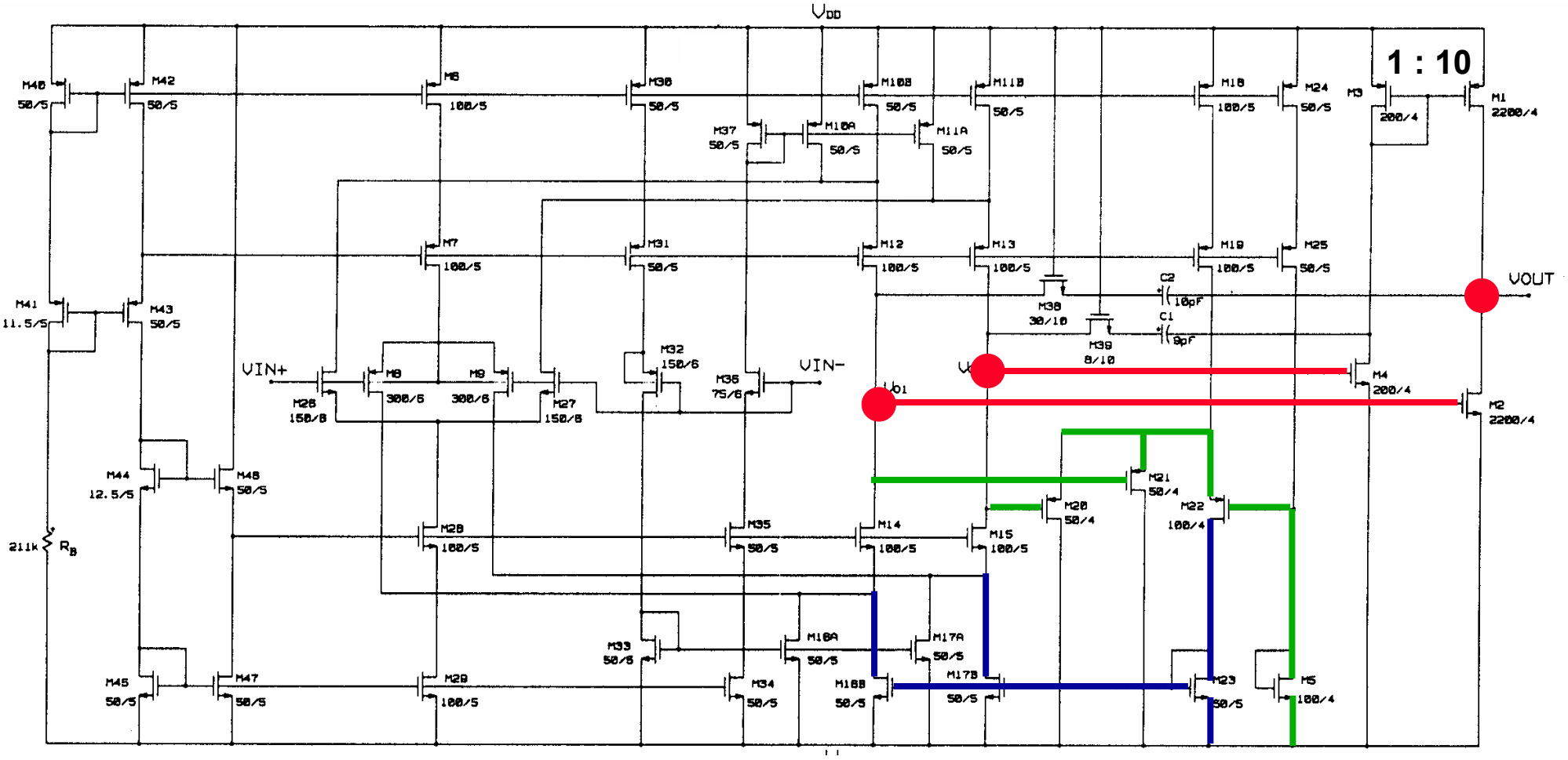
Ref. Op 't Eynde, JSSC Febr.90, 265-273

Class-AB amplifier with differential drive



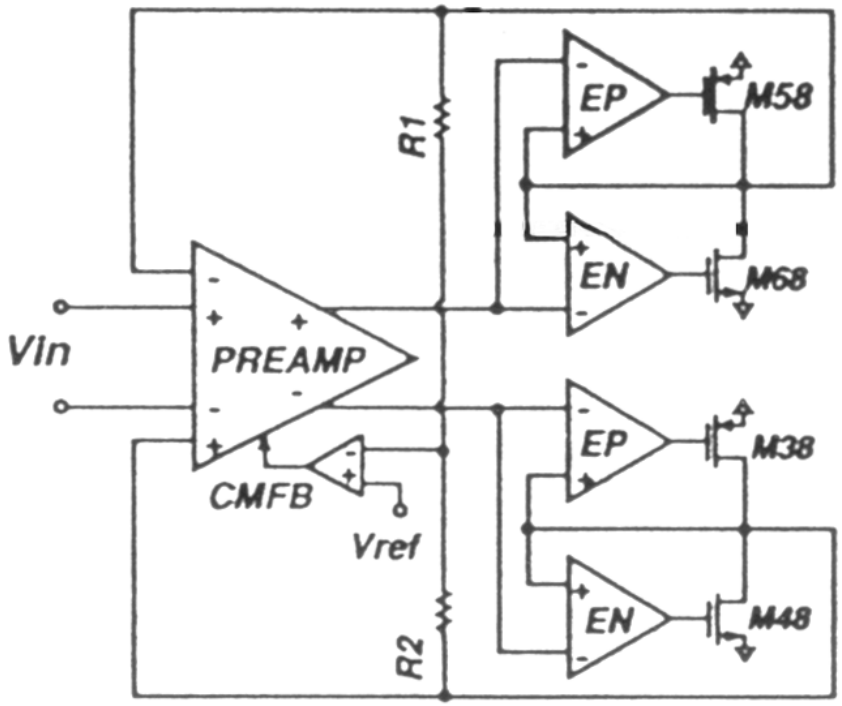
Ref. Babanezhad, JSSC Dec.88, 1414-1417

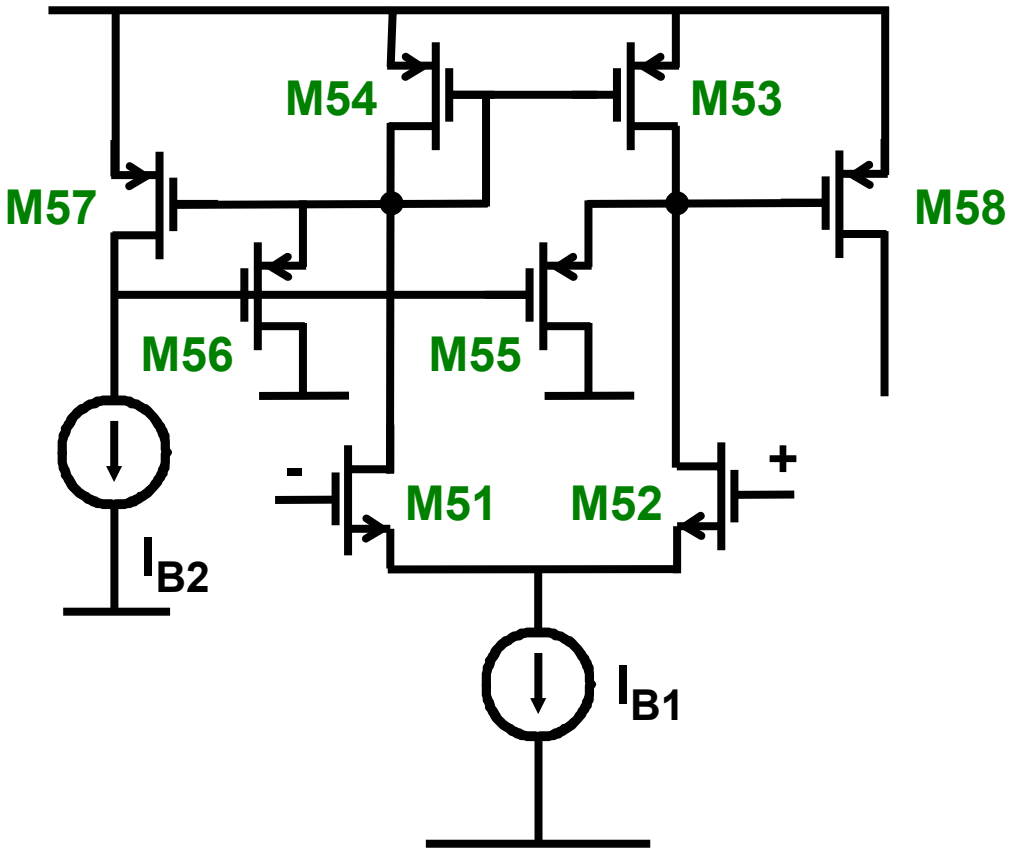
Differentially driven stage



Rail-to-rail input **CMFB + I_Q**

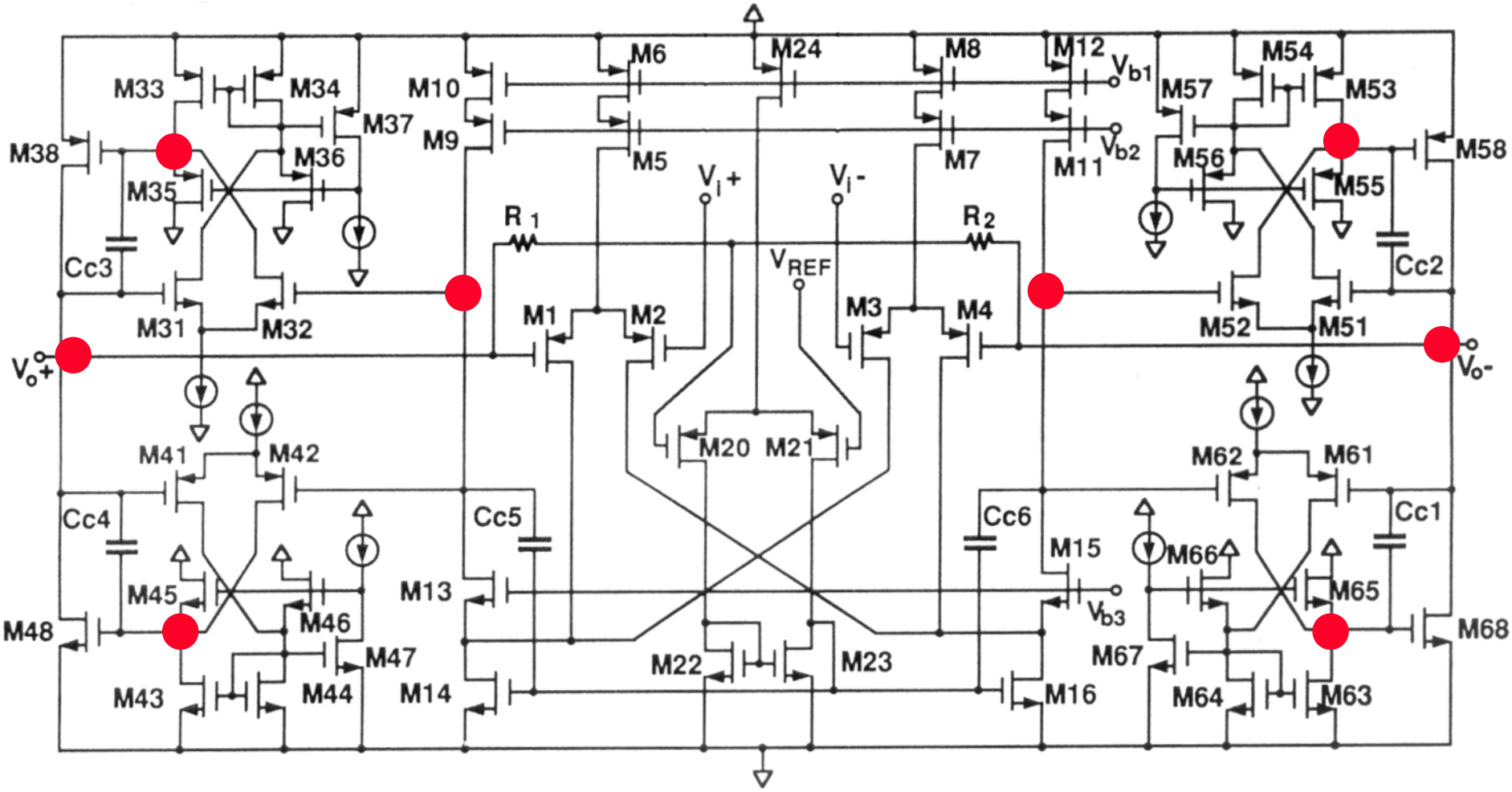
Class-AB amplifier with high linearity





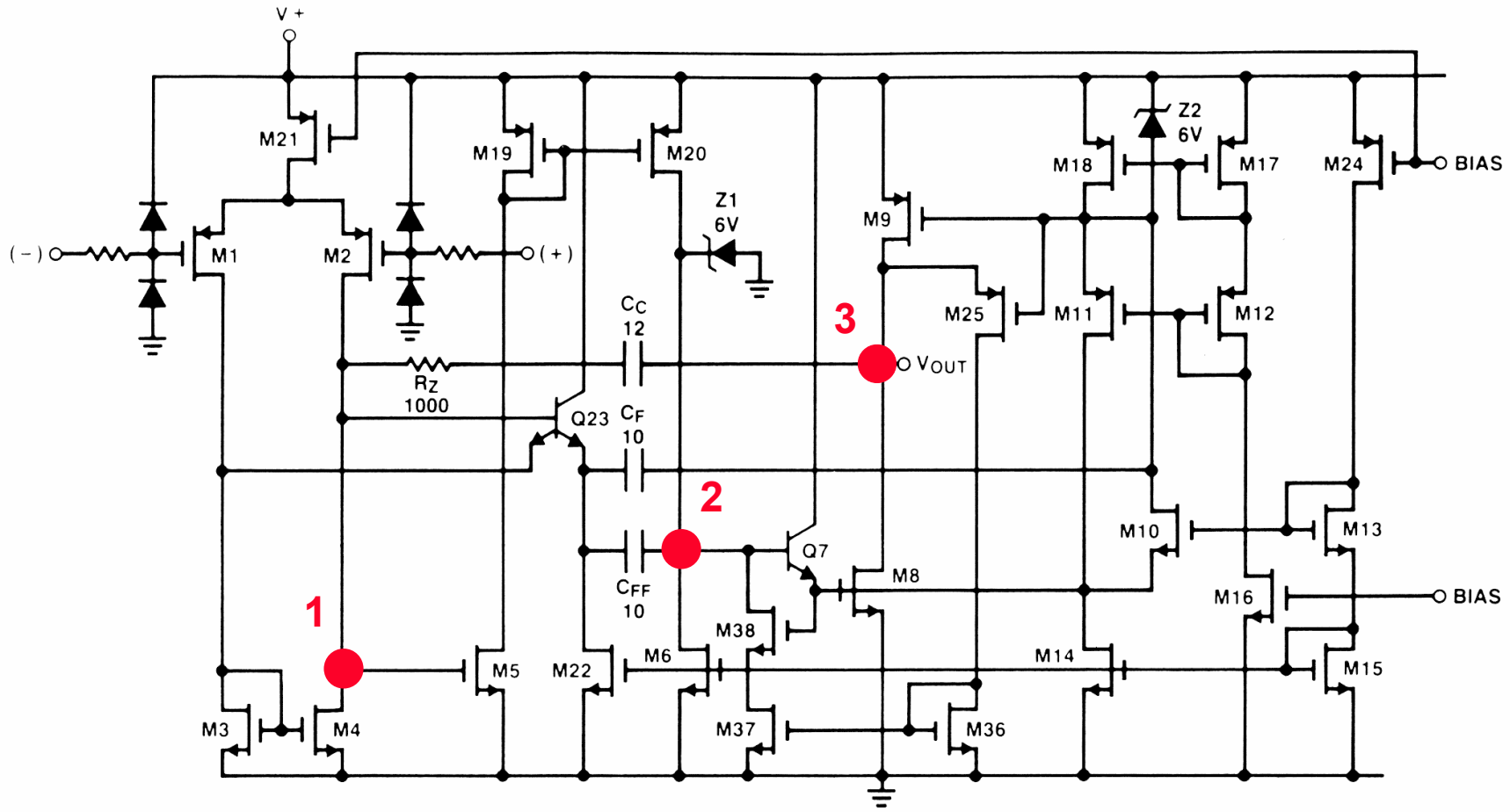
Ref. Khorramabadi, JSSC April 92, 539-544

Class-AB amplifier with high linearity



Ref. Khorramabadi, JSSC April 92, 539-544

Three-stage class AB amplifier with FF



M1, M2	700/13
M3, M4	120/40
M5	40/16
M6	80/9
M8	1500/9
M9	2200/7
M10, M11	100/11
M12, M13	75/11
M14	600/9
M15	75/9
M16	60/30
M17	100/7
M18	400/7
M19, M20	60/14
M21	320/20
M22	155/9
M24	150/20
M25	9/9
M36	9/4
M37	200/4
M38	200/9

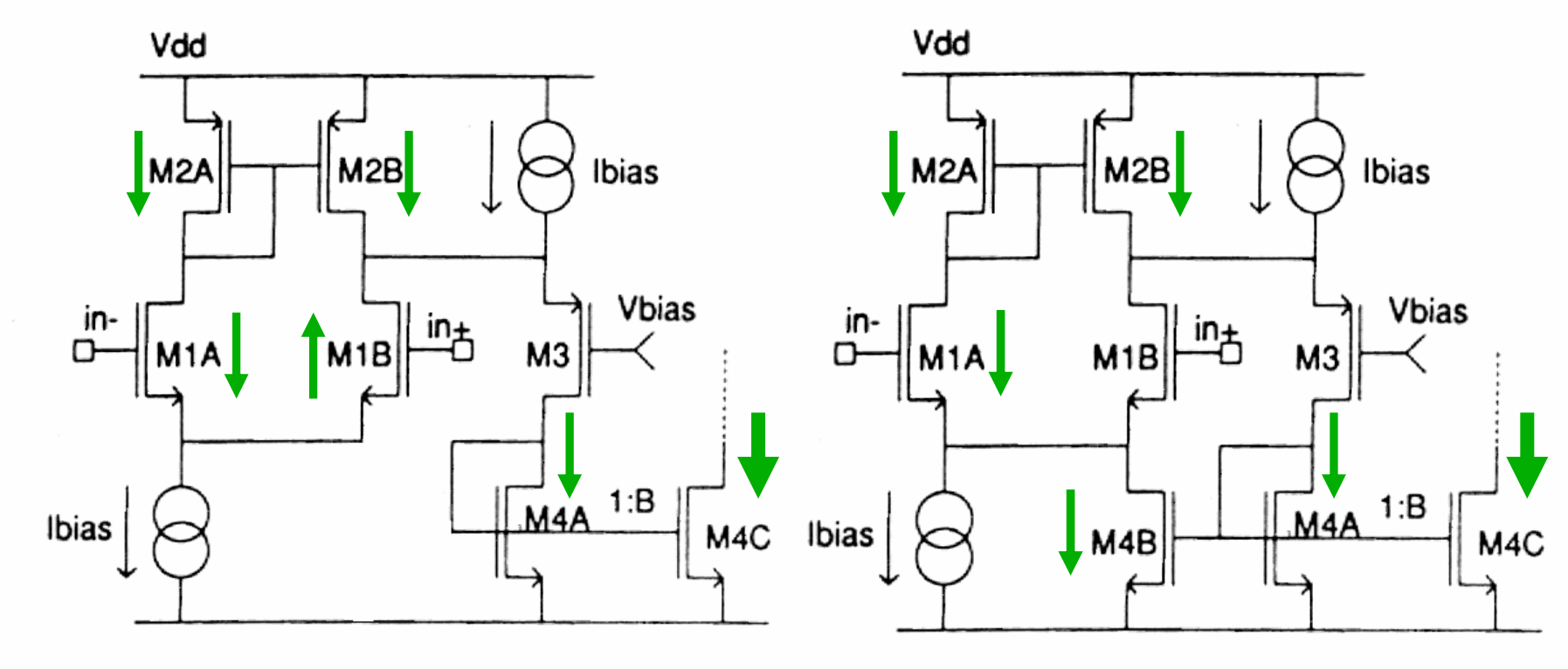
Protection : Z1, Z2, Q23, M25, M36, M37, M38

Ref. Monticelli JSSC Dec.86, 1026-1034

Outline

- Problems of class AB drivers
- Cross-coupled quads
- Adaptive biasing
- I_Q control with translinear circuits, etc.
- Current feedback and other principles
- Low-Voltage realizations

Current feedback



Folded Cascode OTA

Current Feedback

Ref. Callewaert, JSSC June 90, 684-691

Two-stage Miller Amplifier with current FB

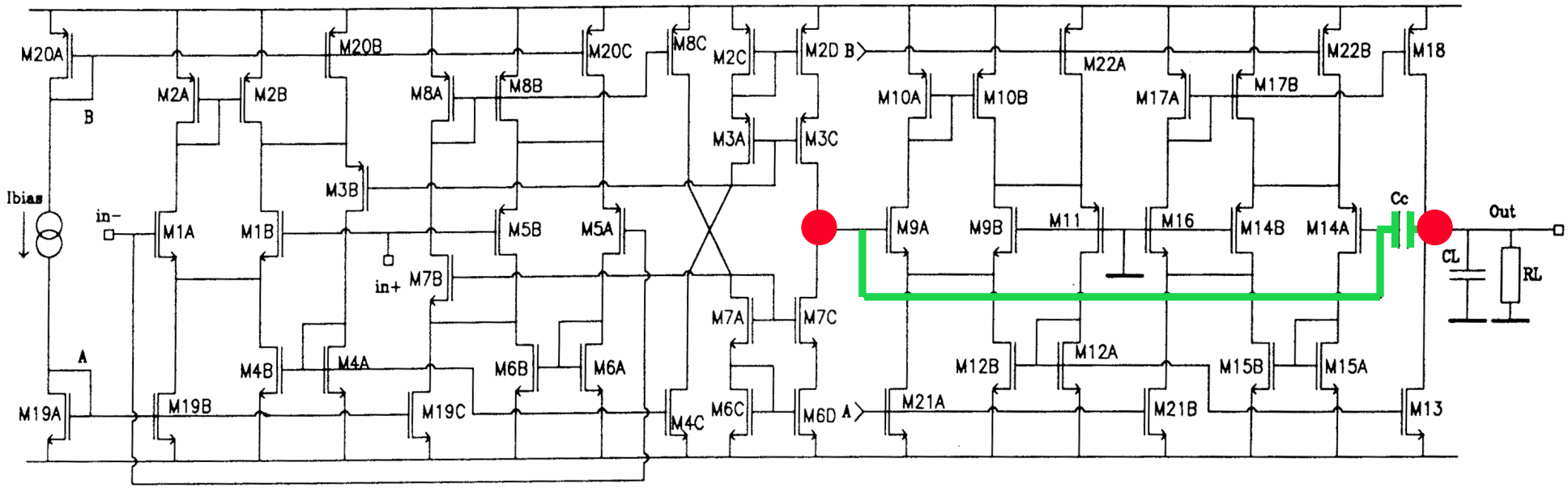
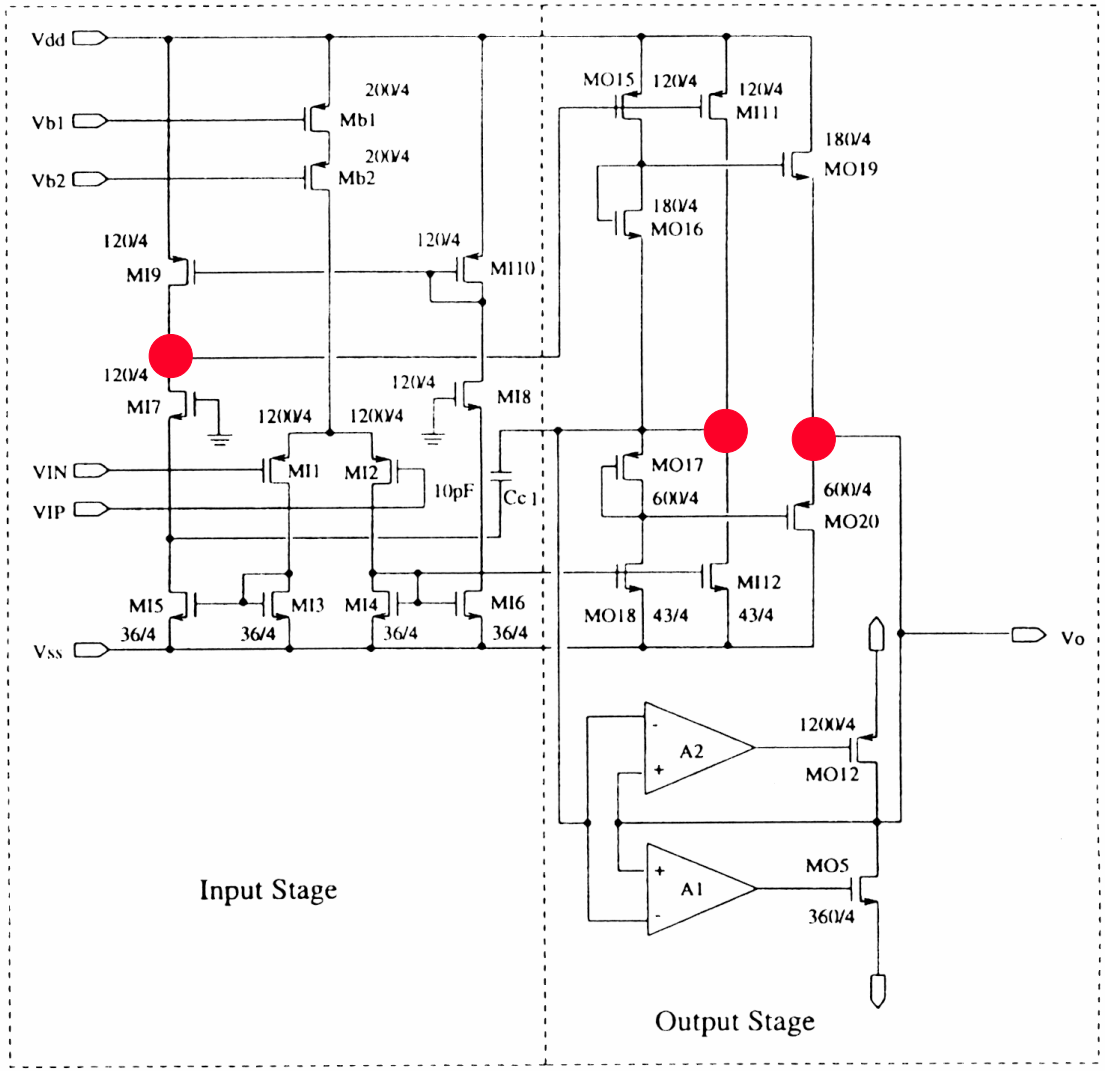


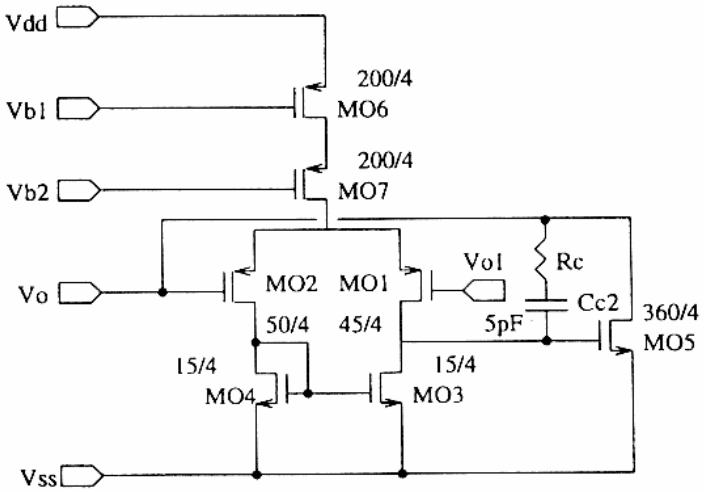
Fig. 11. Circuit diagram of the amplifier with both input and output stages based on the new class AB principle.

4 current feedback stages
2 stage Miller amplifier

Ref. Callewaert, JSSC June 90, 684-691

Low-distortion symmetrical class-AB amplifier





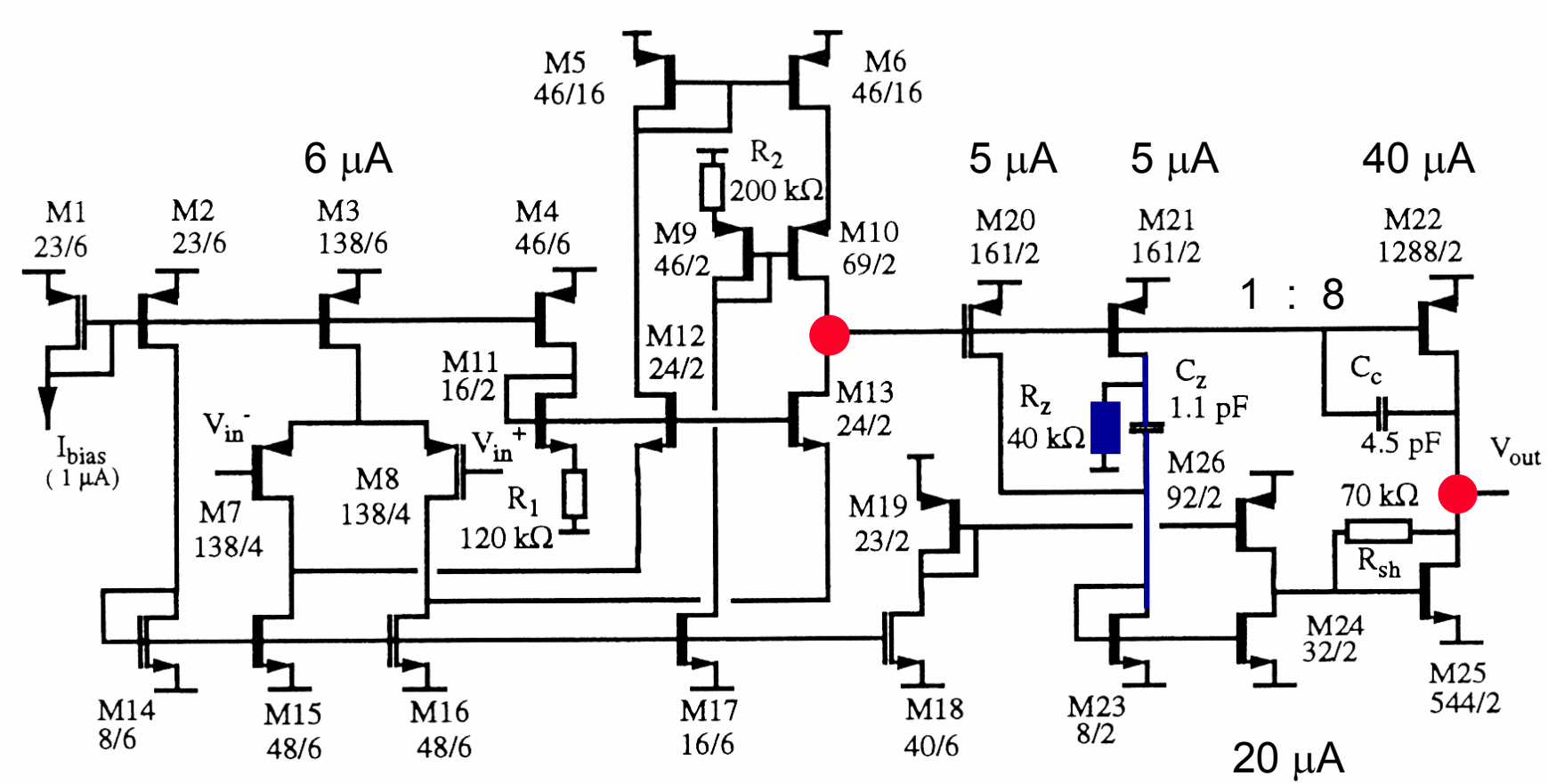
Class-AB source foll.
In parallel with
Class-AB power amp.

Ref. Saether, JSSC
Febr.96, 255-258

Outline

- Problems of class AB drivers
- Cross-coupled quads
- Adaptive biasing
- I_Q control with translinear circuits, etc.
- Current feedback and other principles
- Low-Voltage realizations

1.5 Vsupply voltage class-AB amp.

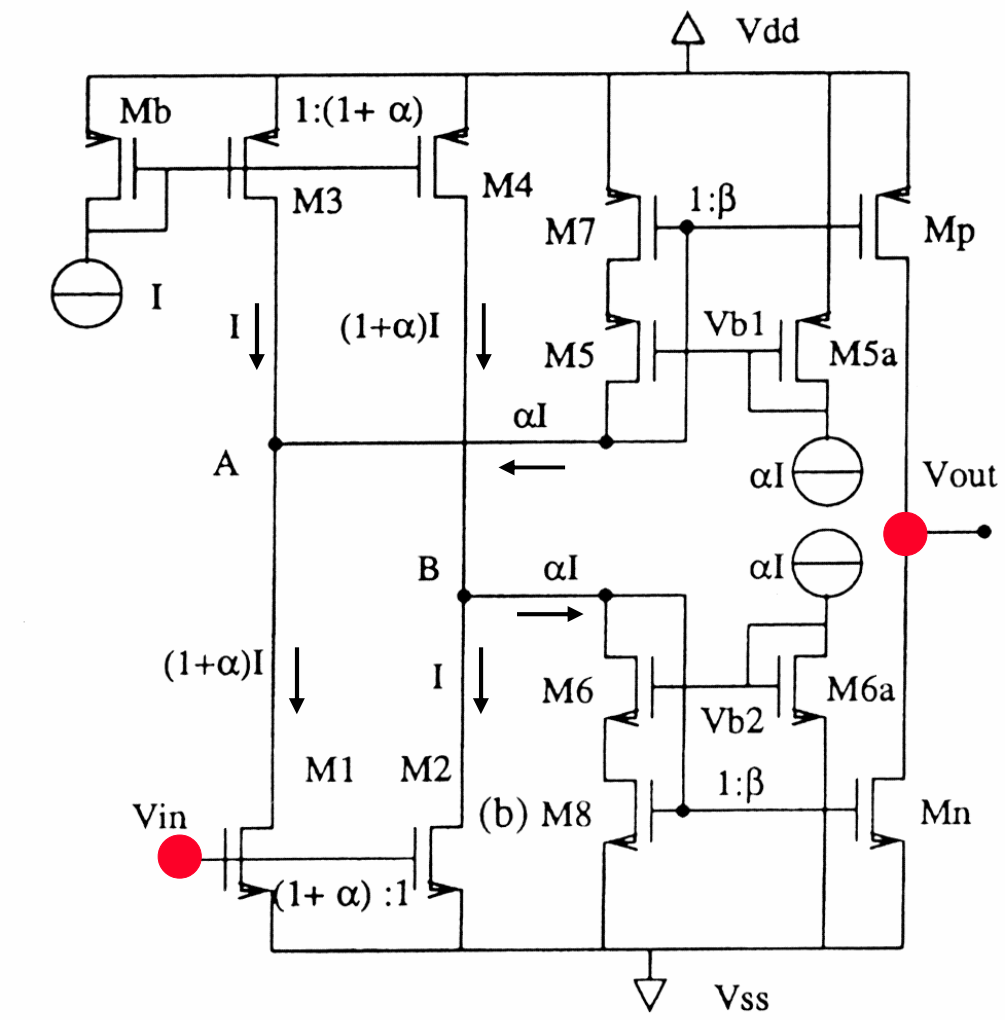


Zero

1.5 V 90 µA 1 MHz/150 pF

Ref. Van Dongen, JSSC Dec.95, 1333-1337

1.5 V class AB driver principle



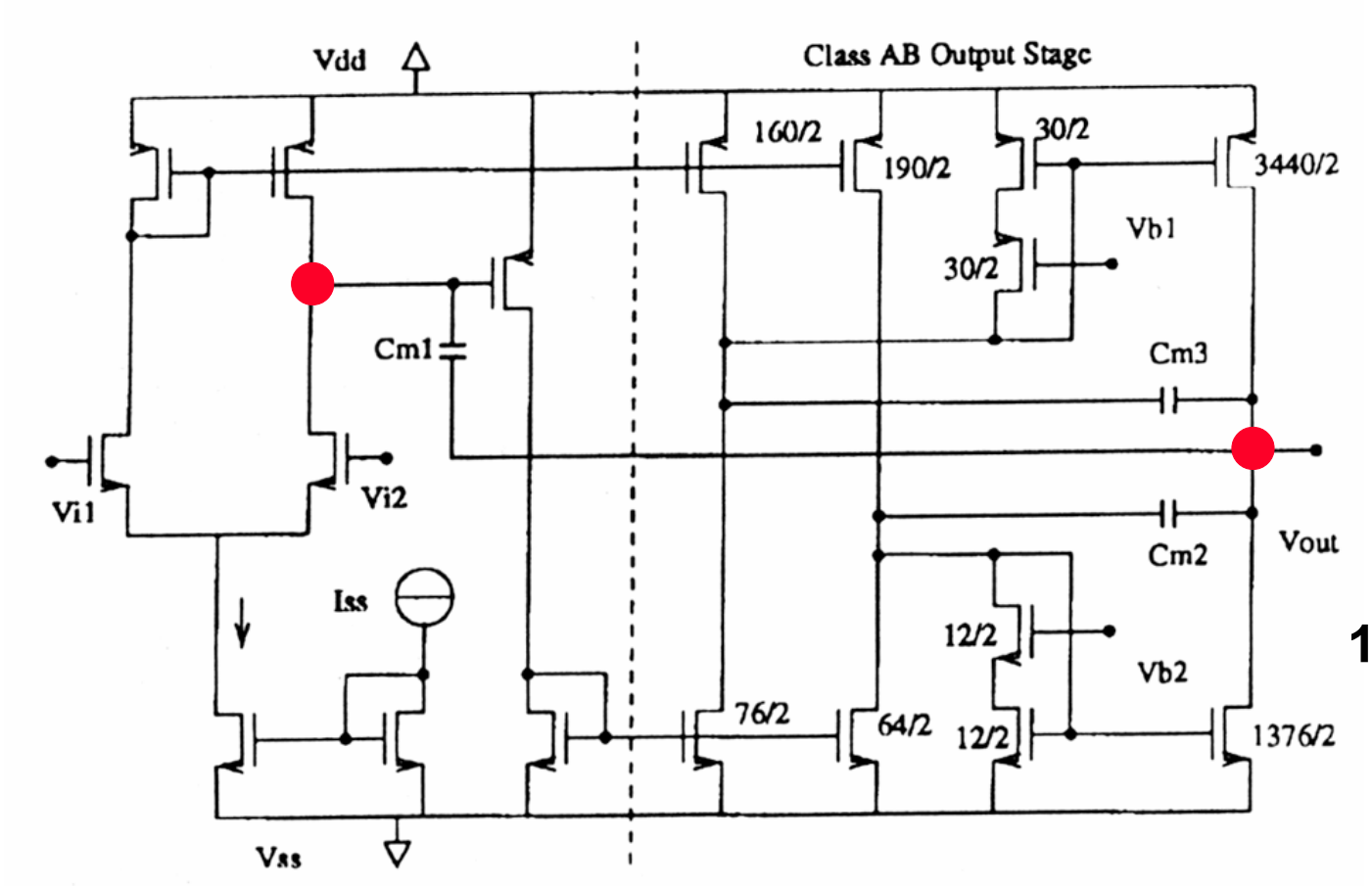
Maximum voltage swing on A & B:

$\alpha \approx 0.2$
For larger α :
- less gain (more current)
- more mismatch and distortion

$\beta \approx 120$

You, etal, JSSC June 98, pp. 915-920

1.5 V class AB driver opamp



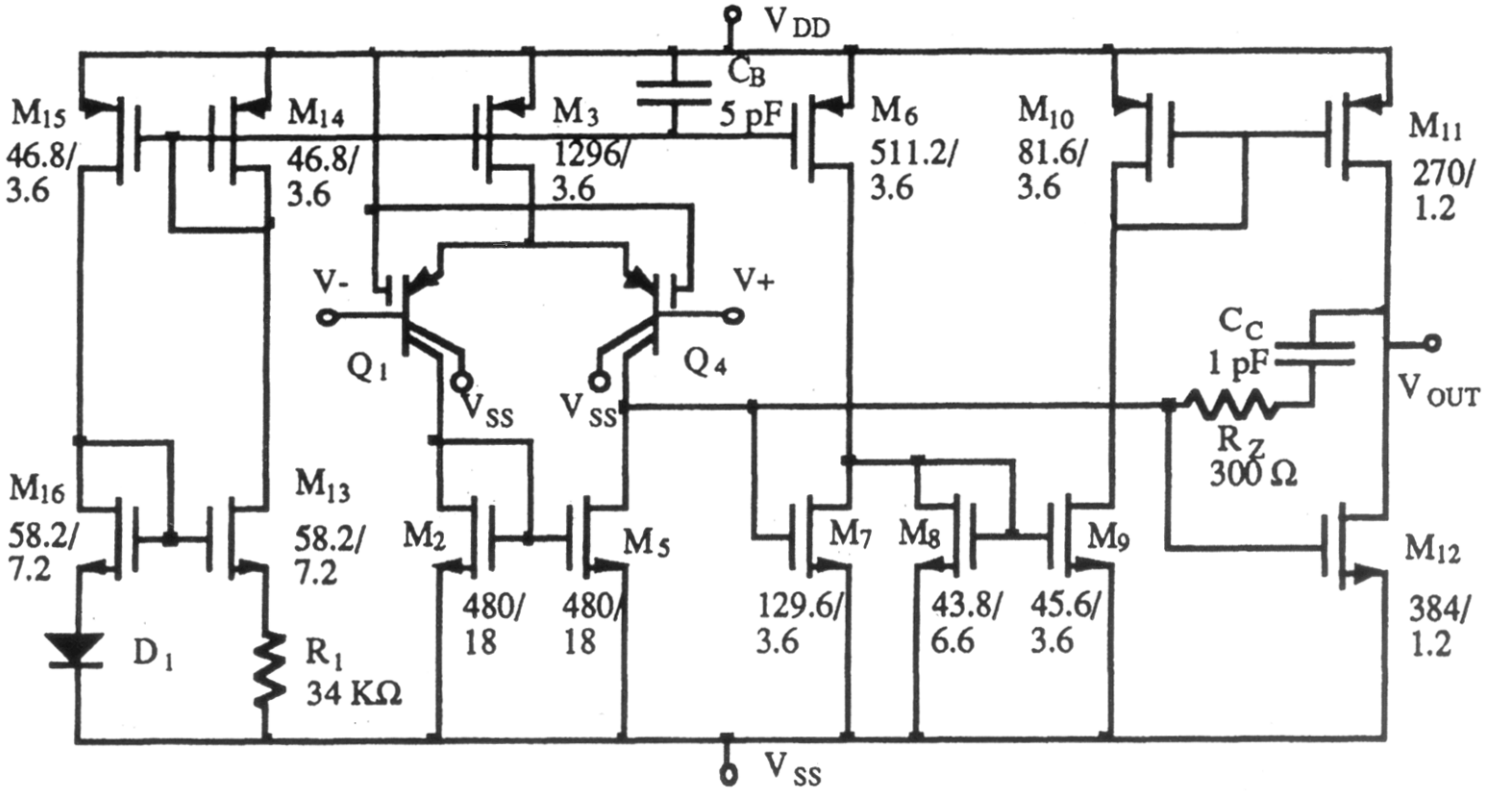
I_Q = 300 μA

100 pF // 200 Ω

Two stage Miller compensation

You, etal, JSSC June 98, pp. 915-920

BiCMOS low-voltage opamp

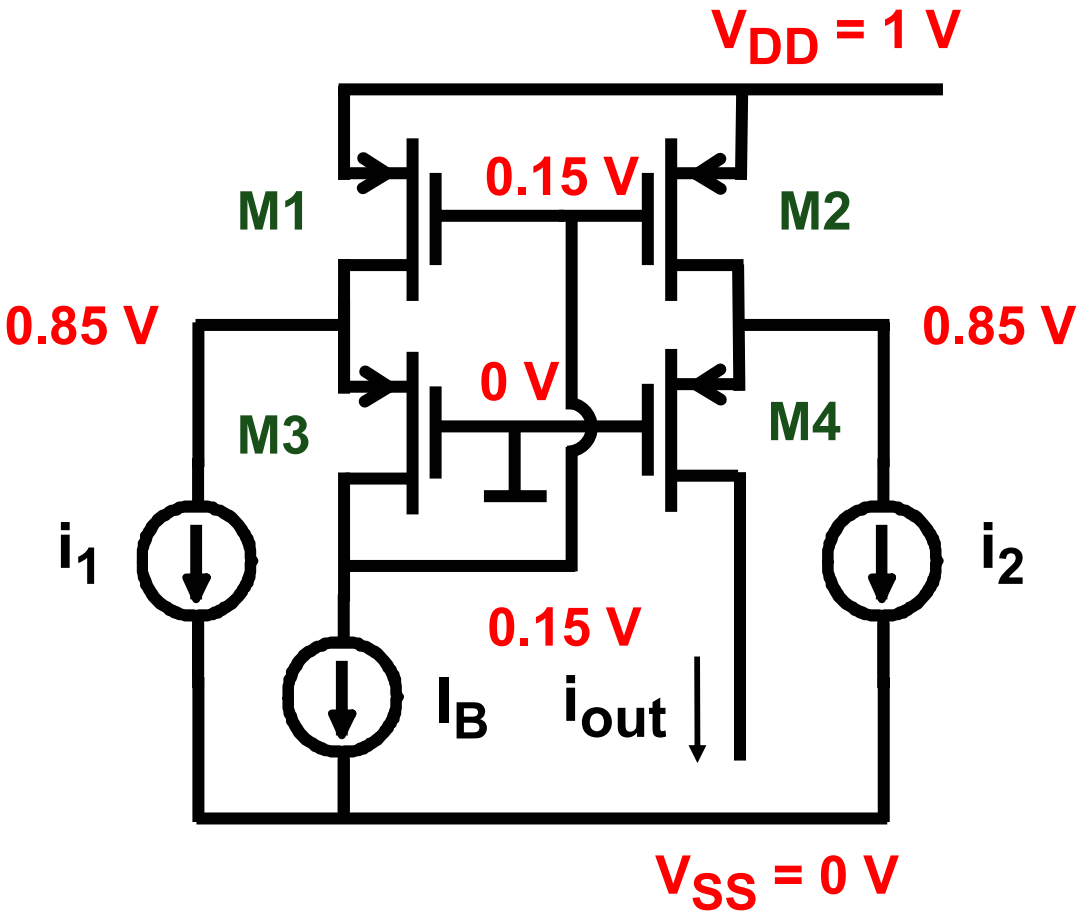


12 MHz 2.1 mA 3.2 $nV_{RMS}/\sqrt{Hz}$

Vittoz, JSSC June 83, pp. 273-279

Holman, JSSC June 95, pp. 710-714

Current differential amplifier for < 1V



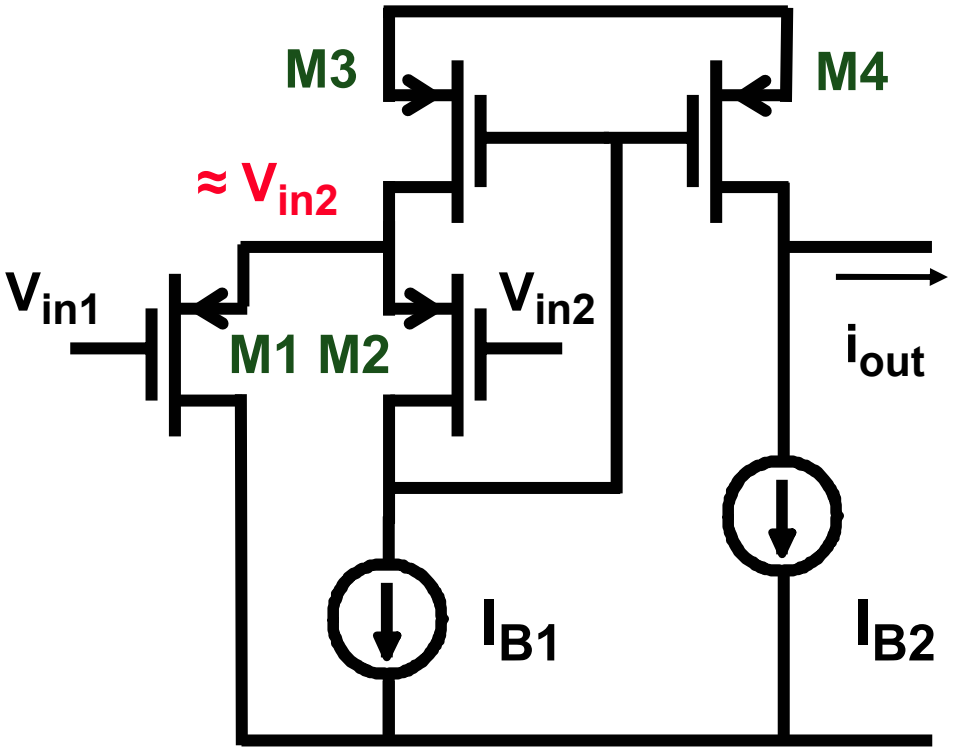
$$i_{out} = I_B + i_1 - i_2$$

V_{GS} = 0.85 V

V_{DSsat} = 0.15 V

V_{outmax} = 0.7 V

Class AB differential Voltage amplifier



M2 is source follower

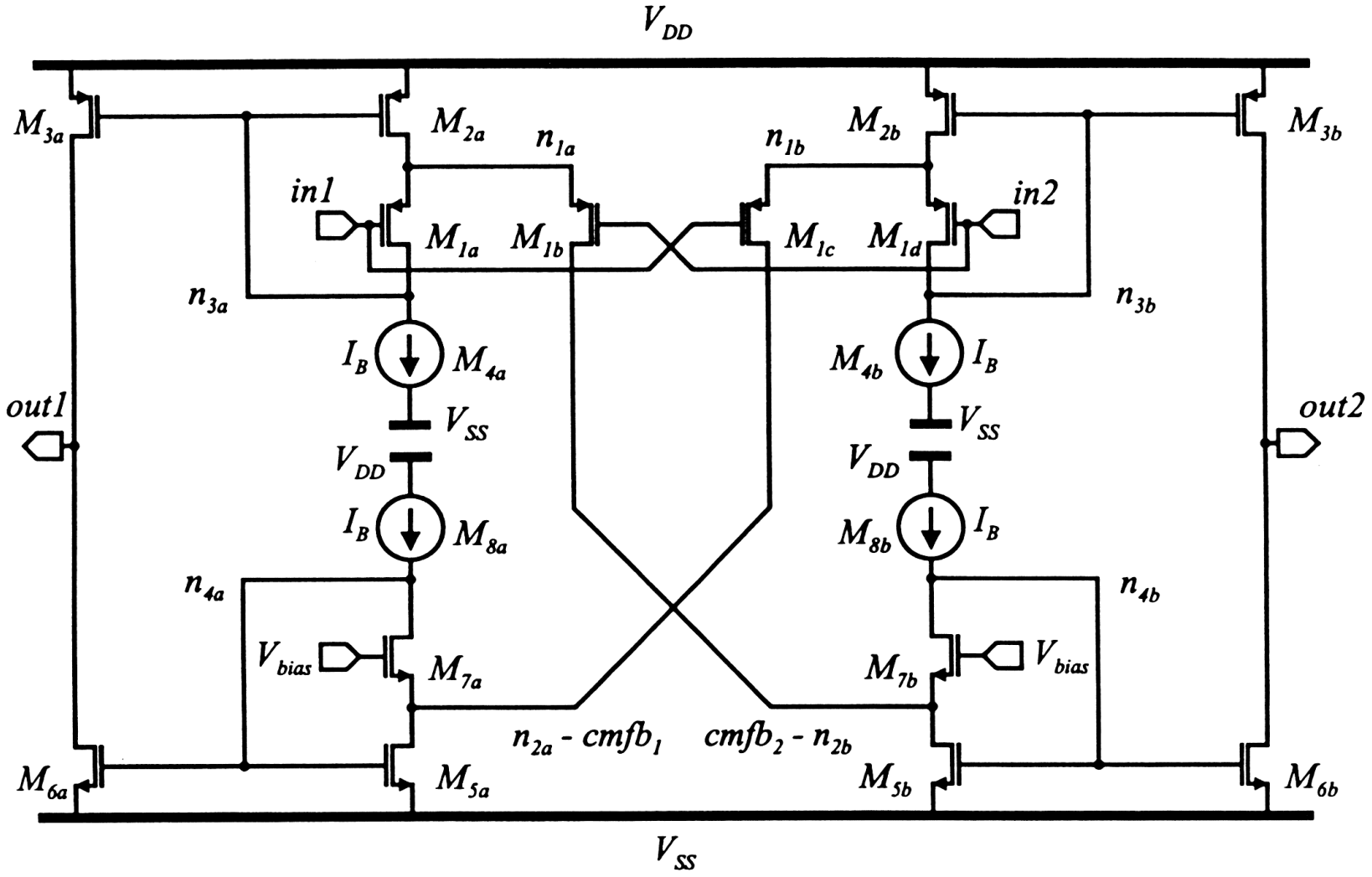
$V_{GS1} = V_{in1} - V_{in2}$

$i_{out} \sim (V_{in1} - V_{in2})^2$

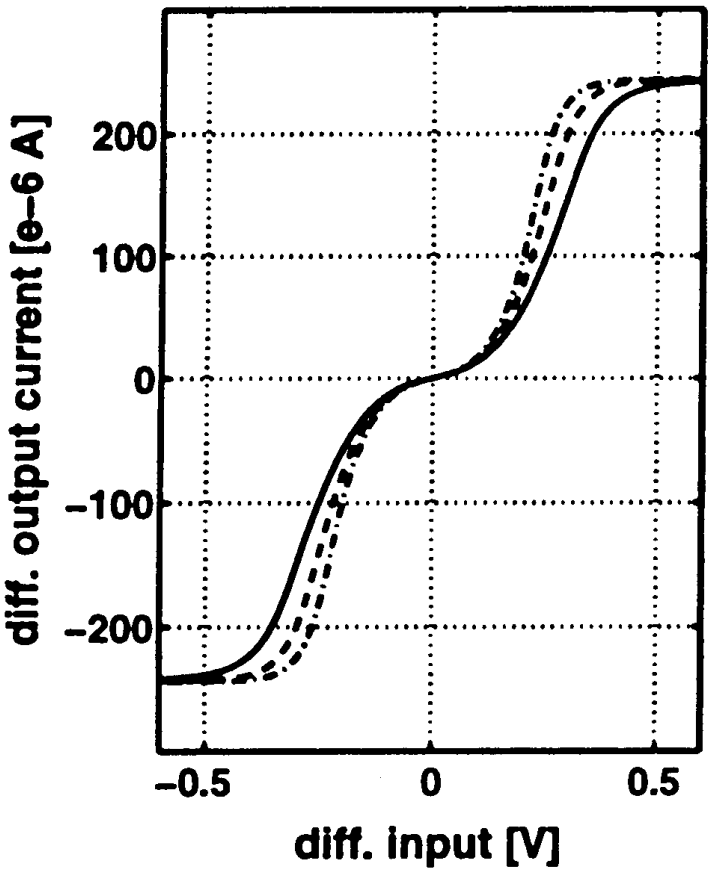
>>> Class AB

Ref. Peluso, JSSC Dec.98, 1887-1897

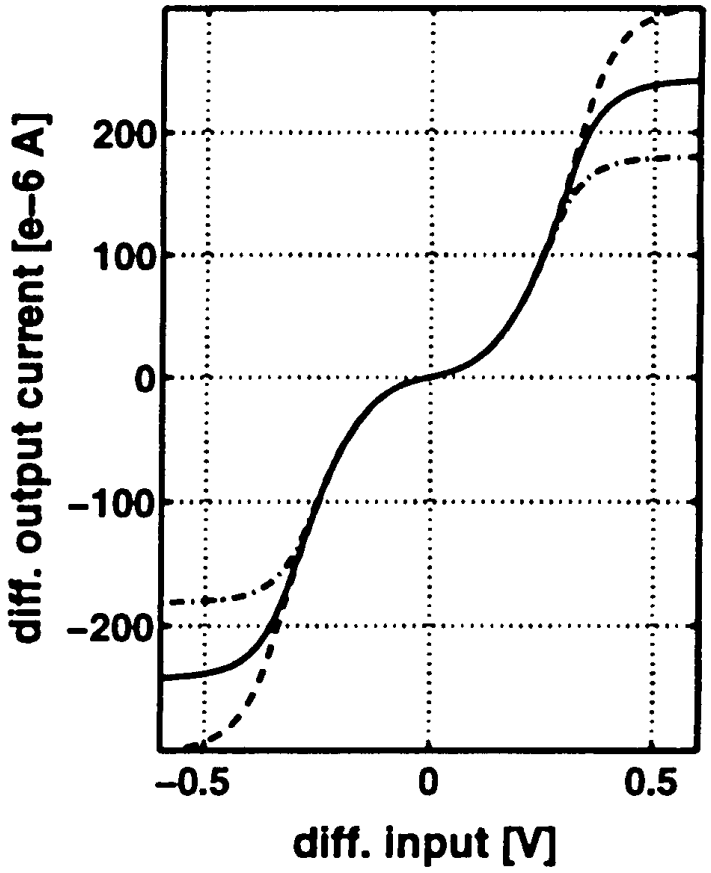
Differential class-AB OTA on 1 V supply voltage



Class-AB characteristic

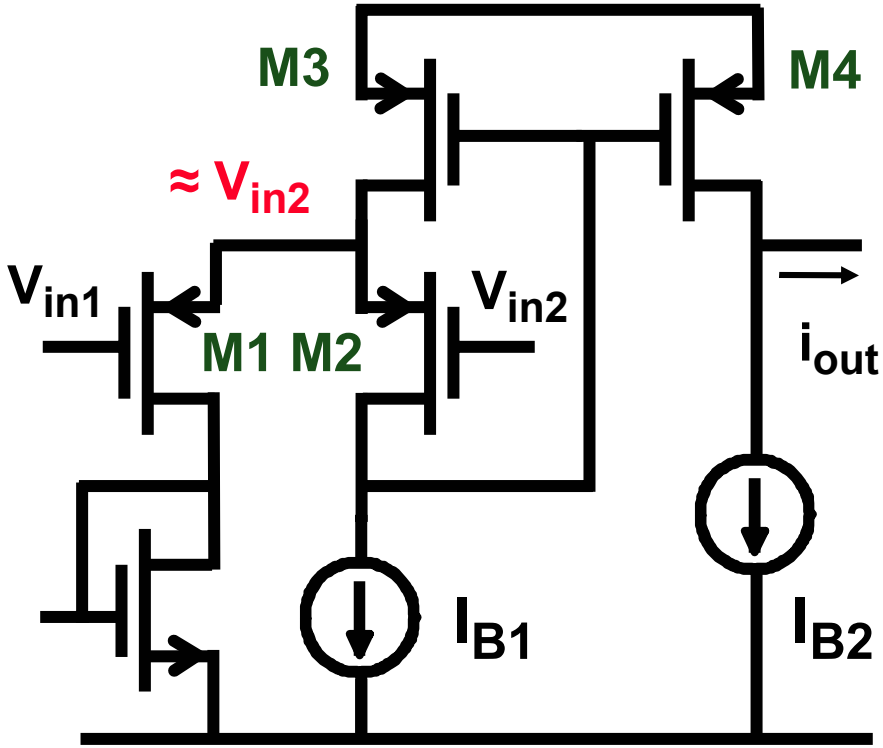


Larger input W/L



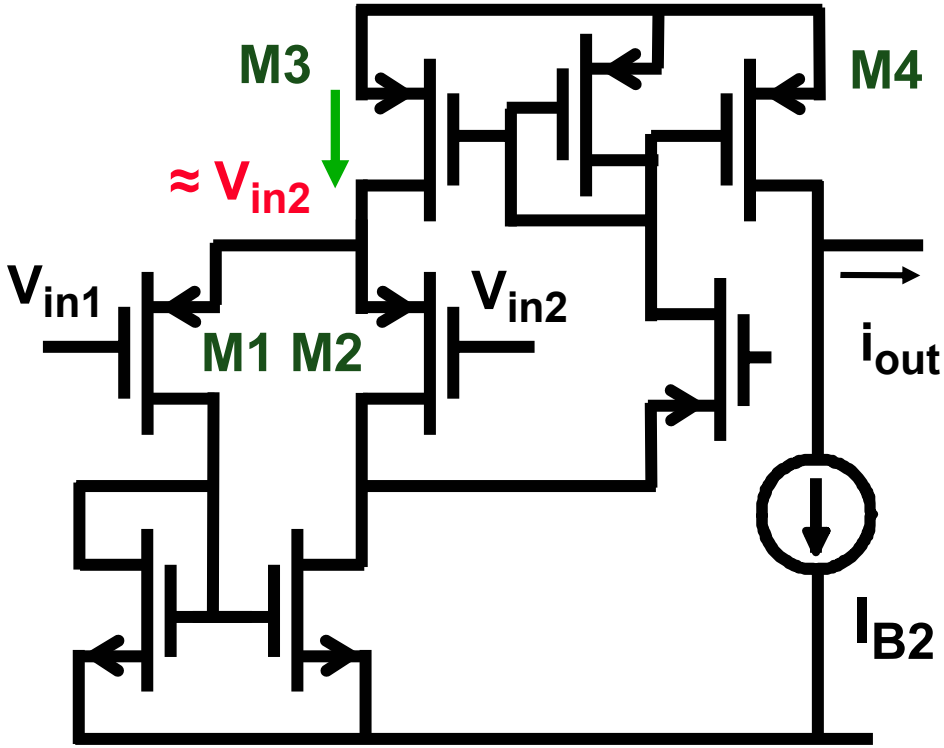
Larger current source W/L

Low-voltage Class AB amplifiers



M2 is source follower
3 trans. carry current
$V_{GS} + V_{DSsat}$

Ref. Peluso, JSSC Dec.98, 1887-1897



M2 is source follower
7 trans. carry current
$V_{GS} + 2V_{DSsat}$

Ref. Callewaert, JSSC June 90, 684-691

Conclusions

- Problems of class AB drivers
- Cross-coupled quads
- Adaptive biasing
- I_Q control with translinear circuits, etc.
- Current feedback and other principles
- Low-Voltage realizations

Reference list - 1

J.Babanezhad, "A rail-to-rail CMOS opamp", IEEE Journal Solid-State Circuits, Vol. SC-23, pp. 1414-1417, Dec.1988.

K. Brehmer, B. Wieser, "Large swing CMOS power amplifier", IEEE Journal Solid-State Circuits, Vol. SC-18, pp.624-629, Dec.1983.

L. Callewaert and W. Sansen, "Class AB CMOS amplifiers with high efficiency", IEEE Journal Solid-State Circuits, Vol. SC-25, pp. 684-691, June 1990.

H.Casier, etal, "A 3.3 V low-distortion ISDN line driver with a novel quiescent current control circuit", IEEE Journal Solid-State Circuits, Vol. SC-33, pp. 1130-1133, July 1998.

R. Castello, P. Gray, "A high-performance micropower switched-capacitor filter", IEEE Journal Solid-State Circuits, Vol. SC-20, pp. 1122-1132, Dec.1985.

M.Degrauwe, J.Rijmenants, E.Vittoz, H.De Man, "Adaptive biasing CMOS amplifiers" IEEE Journal Solid-State Circuits, Vol. SC-17, pp. 522-528, June 1982.

de Langen K., G. Eschauzier, G. van Dijk, J. Huijsing, "A 1-GHz bipolar class-AB operational amplifier with multipath nested Miller compensation for 76-dB gain", IEEE Journal Solid-State Circuits, Vol. SC-32, pp. 488-498, April 1997.

J. Fischer, R. Koch, "A highly linear CMOS buffer amplifier", IEEE Journal Solid-State Circuits, Vol. SC-22, pp. 330-334, June 1987.

Reference list - 2

K.Halonen "Low-power high-performance switched-capacitor circuits for data-acquisition systems", PhD KULeuven, October 1987.

R. Hogervorst, etal, "A compact power-efficient 3V CMOS rail-to-rail input/output operational amplifier for VLSI cell libraries", IEEE Journal Solid-State Circuits, Vol. SC-29, pp. 1504-1512, Dec.1994.

W.Holman, A.Connelly, "A compact low noise operational amplifier for a 1.2 micron digital CMOS technology", IEEE Journal Solid-State Circuits, Vol. SC-30, pp. 710-714, June 1995.

J. Huijsing, D. Linebarger, "Low-voltage operational amplifier with rail-to-rail input and output ranges", IEEE Journal Solid-State Circuits, Vol. SC-20, pp. 1144-1150, Dec.1985.

B.Lee, B.Sheu, "A high slew-rate CMOS amplifier for analog signal processing", IEEE Journal Solid-State Circuits, Vol. SC-25, pp. 885-889, June 1990.

K.Lee, R. Meyer, "Low-distortion switched-capacitor filter design techniques", IEEE Journal Solid-State Circuits, Vol. SC-20, pp. 1103-1113, Dec.1985.

D. Monticelli, "A quad CMOS single-supply op amp with rail-to-rail output swing", IEEE Journal Solid-State Circuits, Vol. SC-21, pp. 1026-1034, Dec.1986.

F. Op't Eynde, P. Ampe, L. Verdeyen and W. Sansen, "A CMOS large-swing low-distortion three-stage class AB power amplifier", IEEE Journal Solid-State Circuits, Vol. SC-25, pp. 265-273, Febr.1990.

Reference list - 3

M. Pardoen, M.Degrauwe, "A rail-to-rail input/output CMOS power amplifier", IEEE Journal Solid-State Circuits, Vol. SC-25, pp. 501-504, April 1990.

V. Peluso, etal, "A 900 mV low-power Delta-Sigma AD Converter with 77-dB dynamic range" IEEE Journal Solid-State Circuits, Vol. SC-33, pp. 1887-1897, Dec.1998.

T.Saether etal, "High-speed, high-linearity CMOS buffer amplifier", IEEE Journal Solid-State Circuits, Vol. SC-31, pp. 255-258, Febr.1996.

E. Seevinck etal "Low-distortion output stage for power amplifiers", IEEE Journal Solid-State Circuits, Vol. SC-23 pp. 794-801, June 1988.

M.Steyaert, W.Sansen, "A high-dynamic range CMOS opamp with low-distortion output structure", IEEE Journal Solid-State Circuits, Vol. SC-22 pp. 1204-1207, Dec.1987.

R. Van Dongen, V. Rikkink, "A 1.5 V Class AB CMOS buffer amplifier for driving low-resistance loads", IEEE Journal Solid-State Circuits, Vol. SC-30, pp. 1333-1337, Dec.1995.

W.Wu, etal, "Digital-compatible high-performance operational amplifier with rail-to-rail input and output ranges", IEEE Journal Solid-State Circuits, Vol. SC-29, pp. 63-66, Jan.1994

F. You, S.H.K. Embabi and E. Sanchez-Sinencio. "Low-voltage class AB buffers with quiescent current control." IEEE Journal of Solid-State Circuits , Vol SC-33, pp. 915-920, June 1998.