Important opamp configurations

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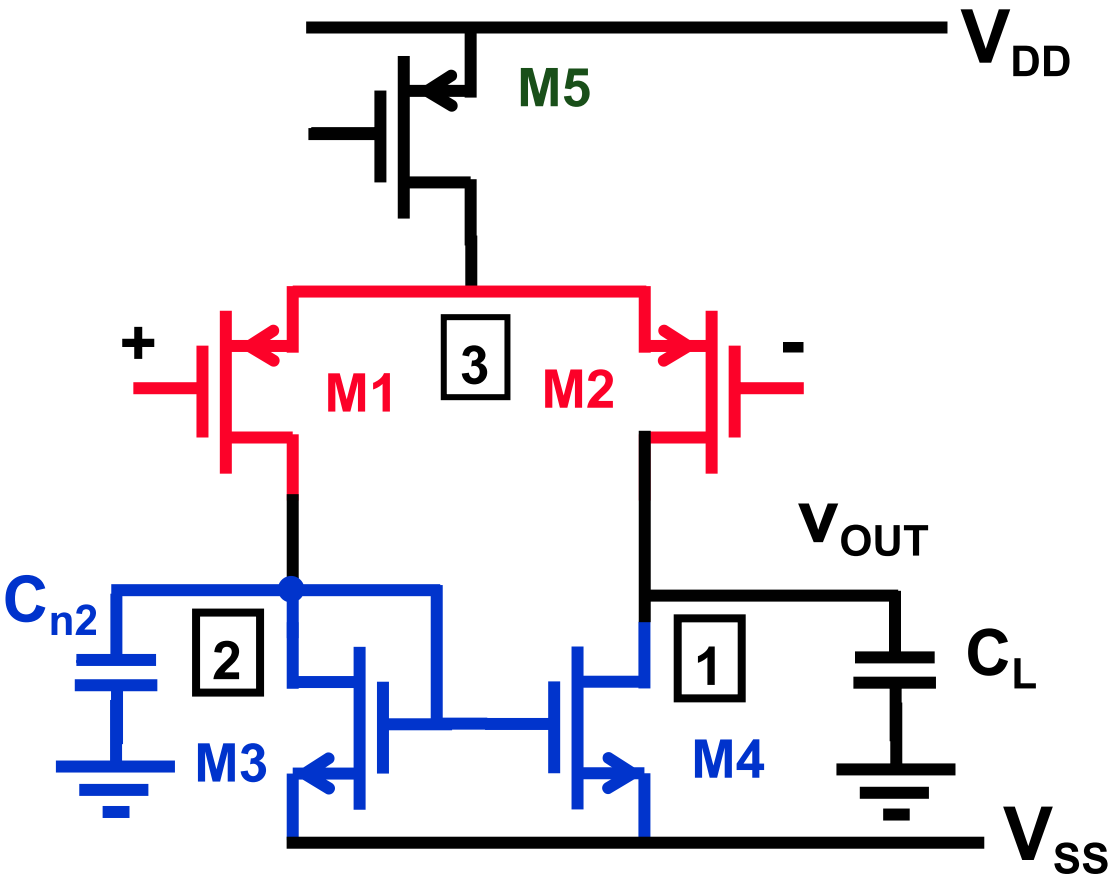
Table of contents

- Simple CMOS OTA
- CMOS Miller OTA
- Symmetrical CMOS OTA
- Folded cascode OTA
- Other opamps

Simple CMOS OTA



$$C_{n2} = 2C_{GS3} + C_{DB3} + C_{DB1} \approx 4C_{GS3}$$

Differential pair

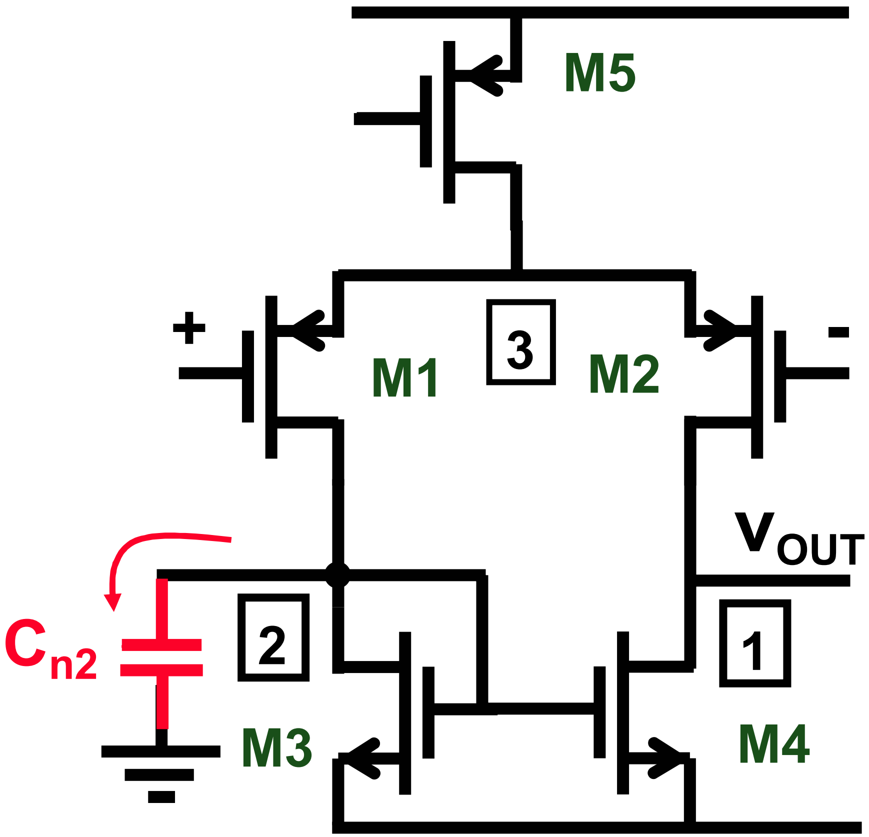
Current mirror

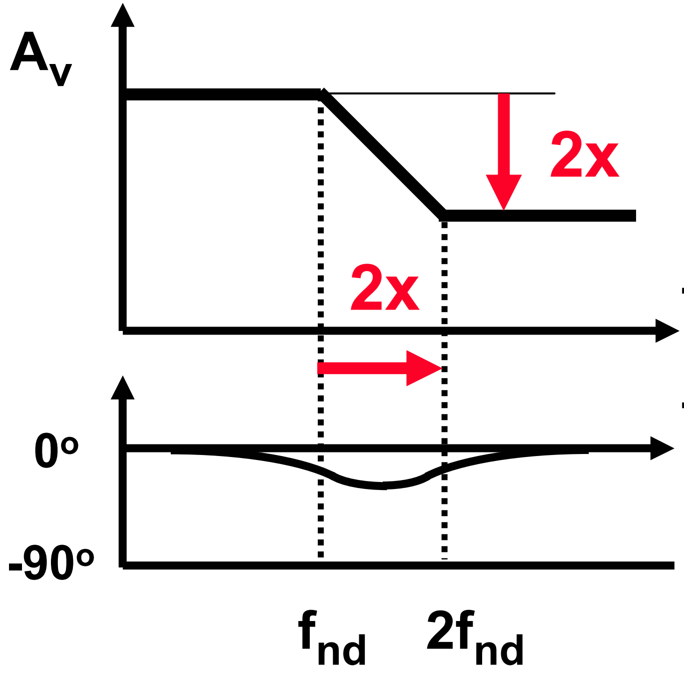
$$GBW = \frac{g_{m1}}{2\pi\, C_L}$$

$$f_{nd} = \frac{g_{m3}}{2\pi\, C_{n2}}$$

$$f_{nd} \approx \frac{f_{T3}}{4} \quad ?$$

Simple CMOS OTA : f_{nd}

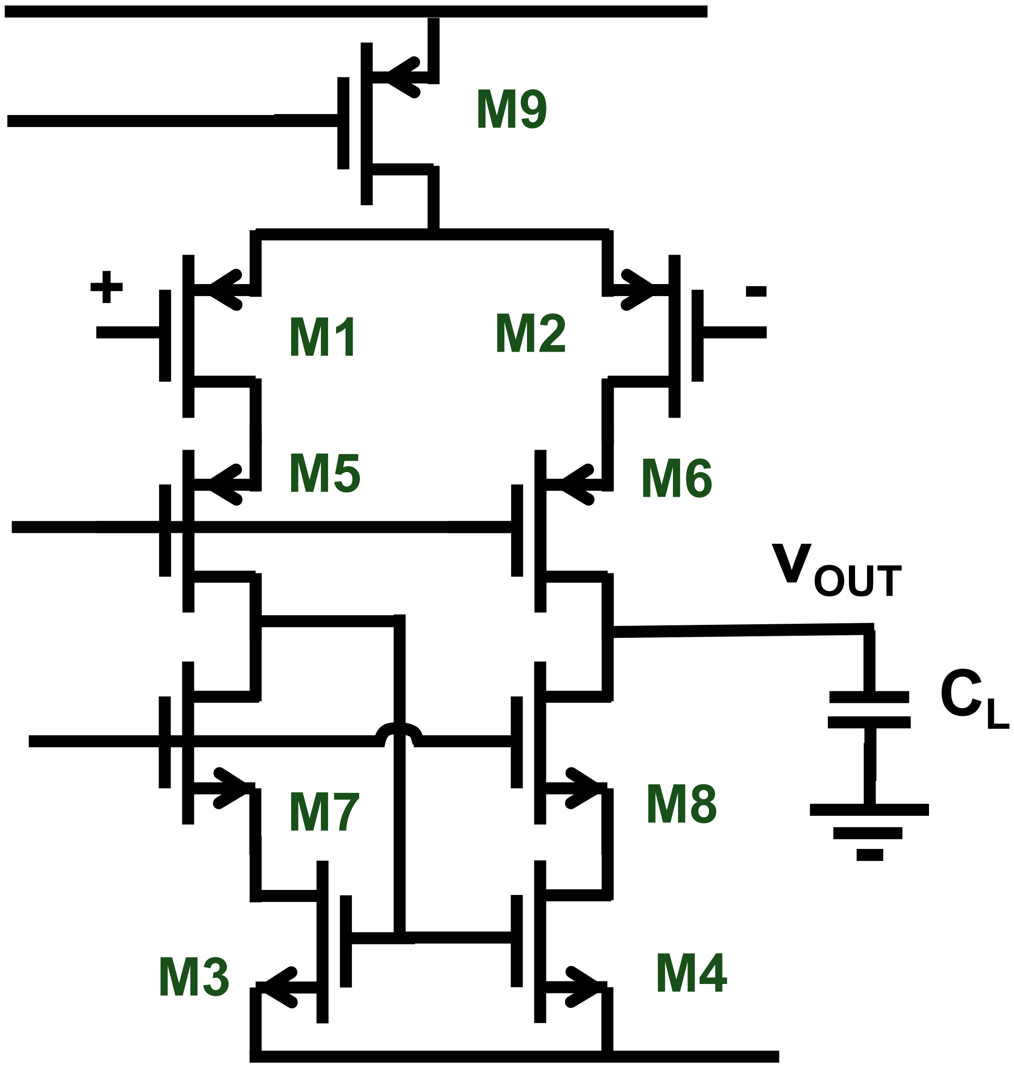




$$f_{nd} = \frac{g_{m3}}{2\pi\, C_{n2}}$$

$$PM = 90^\circ - \arctan \frac{GBW}{f_{nd}} + \arctan \frac{GBW}{2\, f_{nd}} \approx 85^\circ$$

Telescopic CMOS OTA

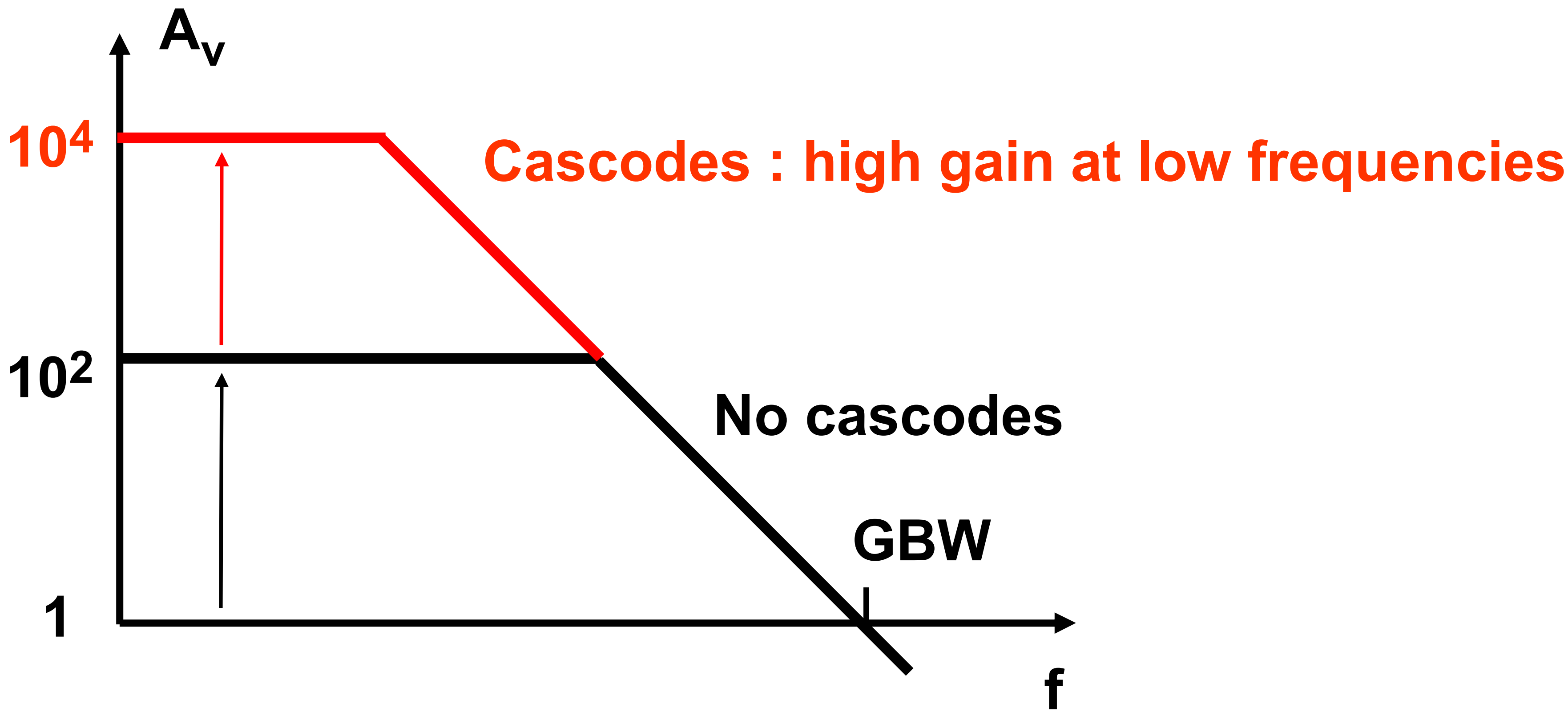


More gain
At low frequencies

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

Gulati, JSSC Dec.98, 2010-2019

Cascodes increase gain at low frequencies



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

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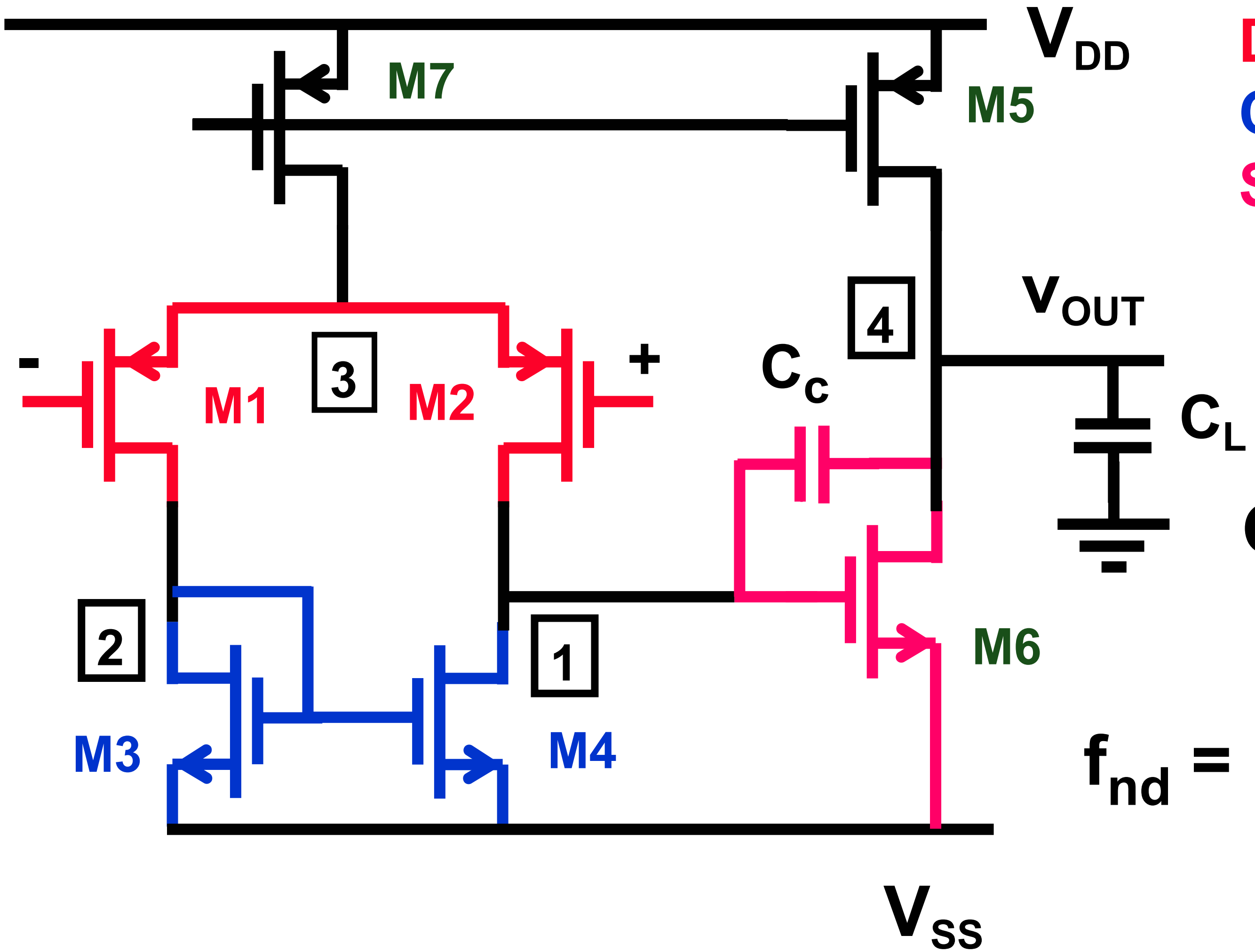
Miller CMOS OTA

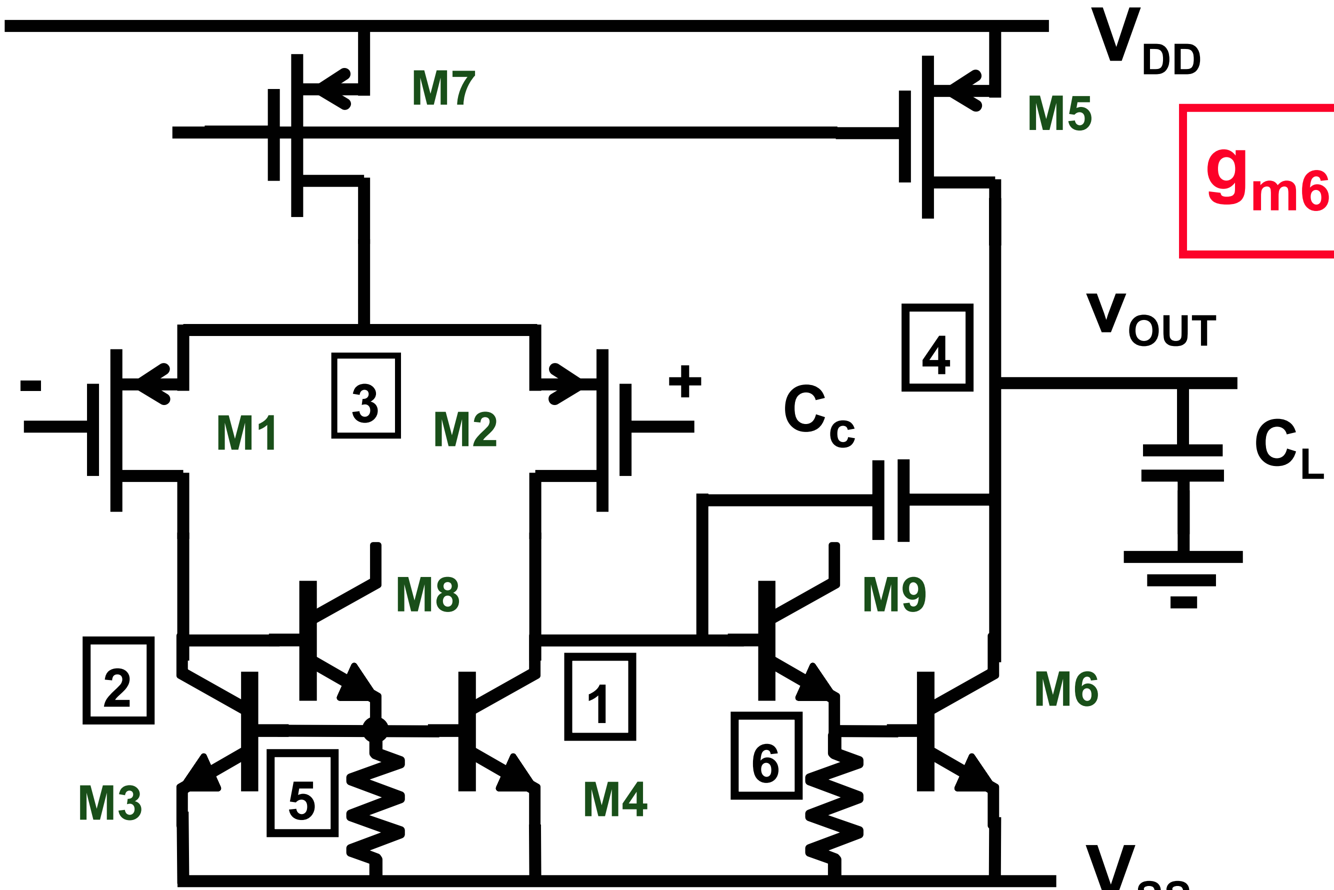


Differential pair
Current mirror
Second stage

$$GBW = \frac{g_{m1}}{2\pi\, C_c}$$

$$f_{nd} = \frac{g_{m6}}{2\pi\, C_L} \frac{1}{1 + \frac{C_{n1}}{C_c}}$$

Miller BiCMOS OTA



$g_{m6NPN} > g_{m6NMOS}$

Node 1:
High impedance

Extra nodes 5, 6

f_{nd} ?

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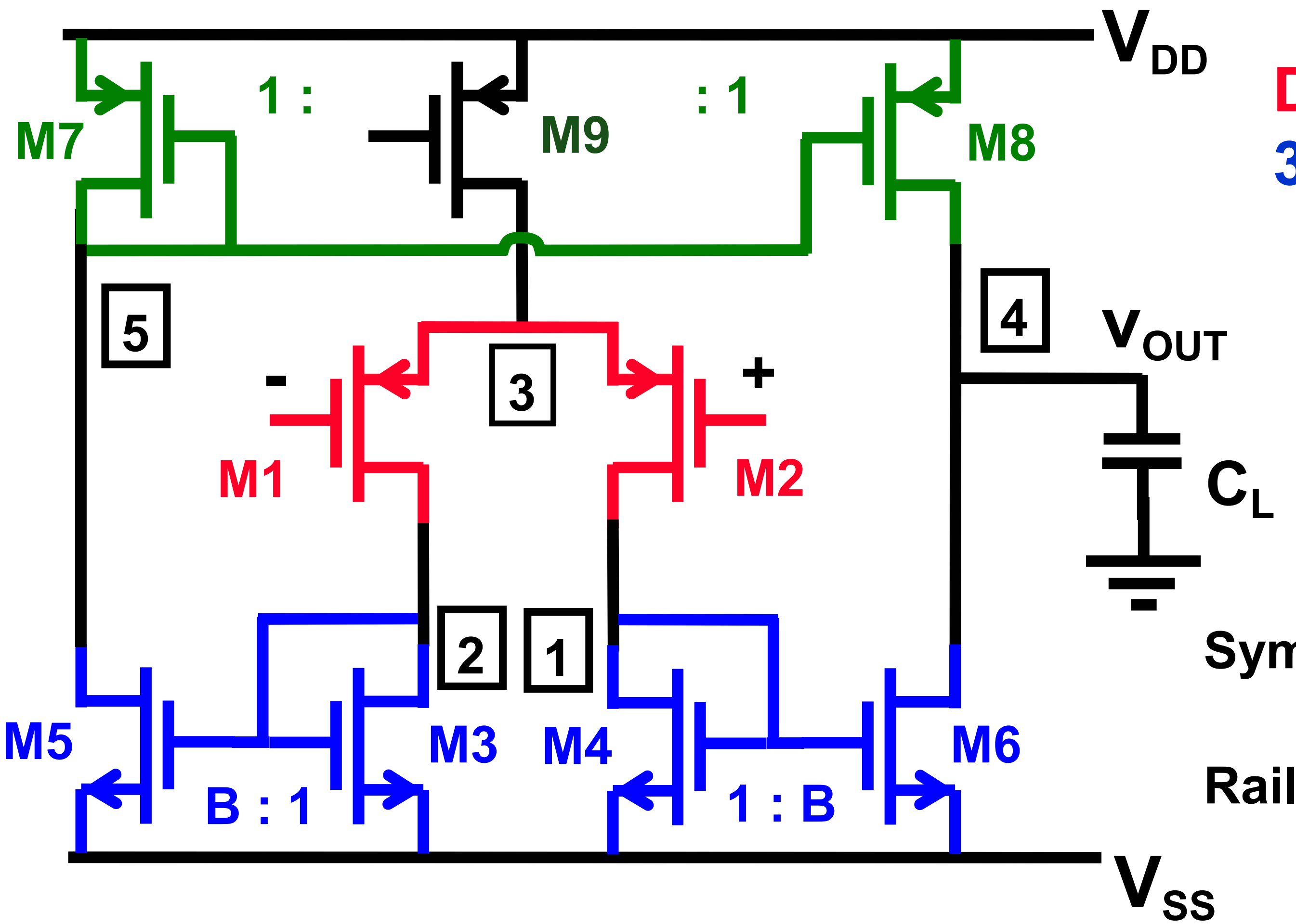
Symmetrical CMOS OTA

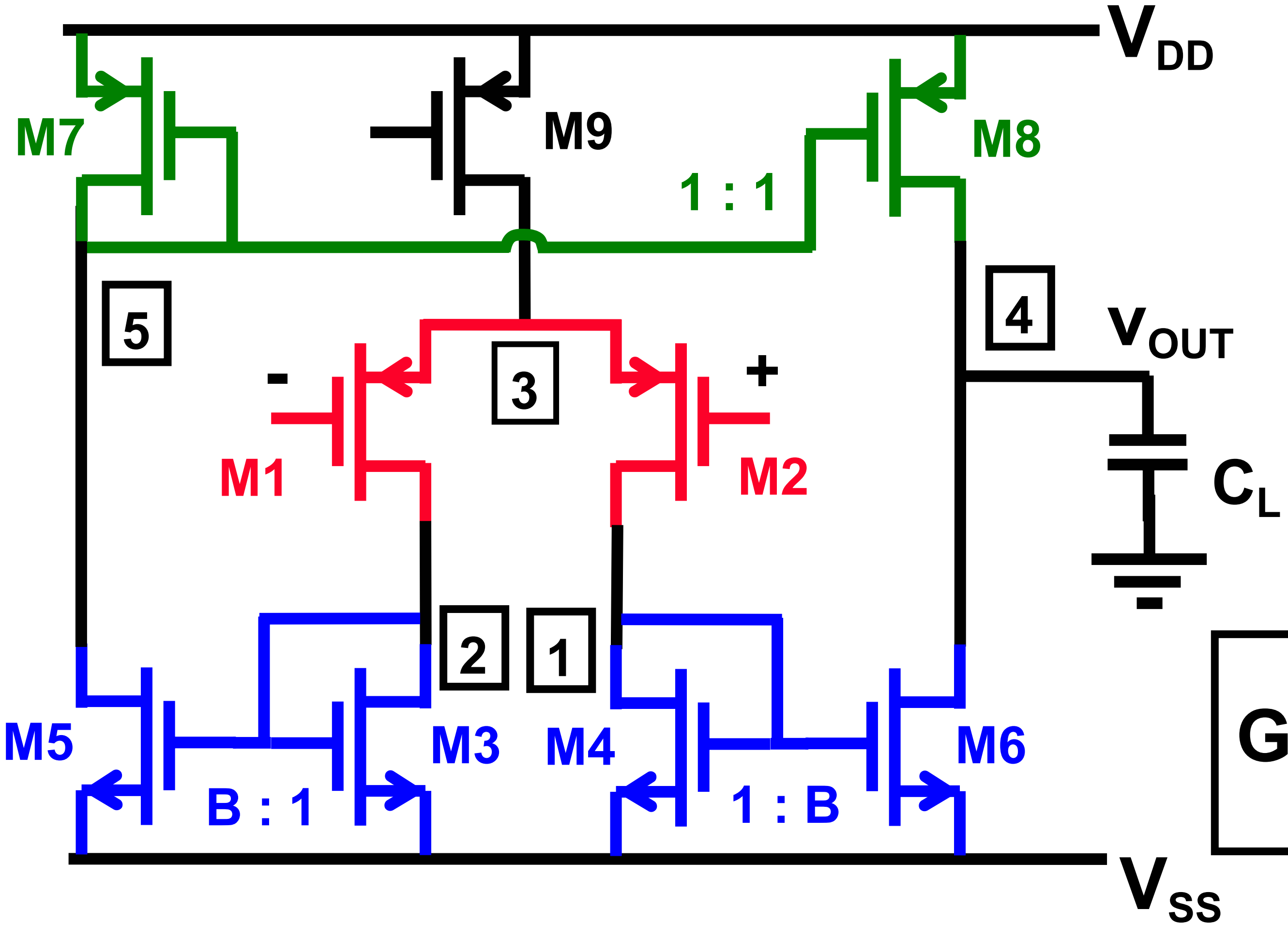


Differential pair
3 Current mirrors

Symmetrical :
Node 1 = Node 2
Rail-to-rail output swing

B ?

Symmetrical CMOS OTA : GBW



$$A_v = g_{m1} B R_{n4}$$

$$= \frac{2 V_{En} L_6}{V_{GS1} - V_T}$$

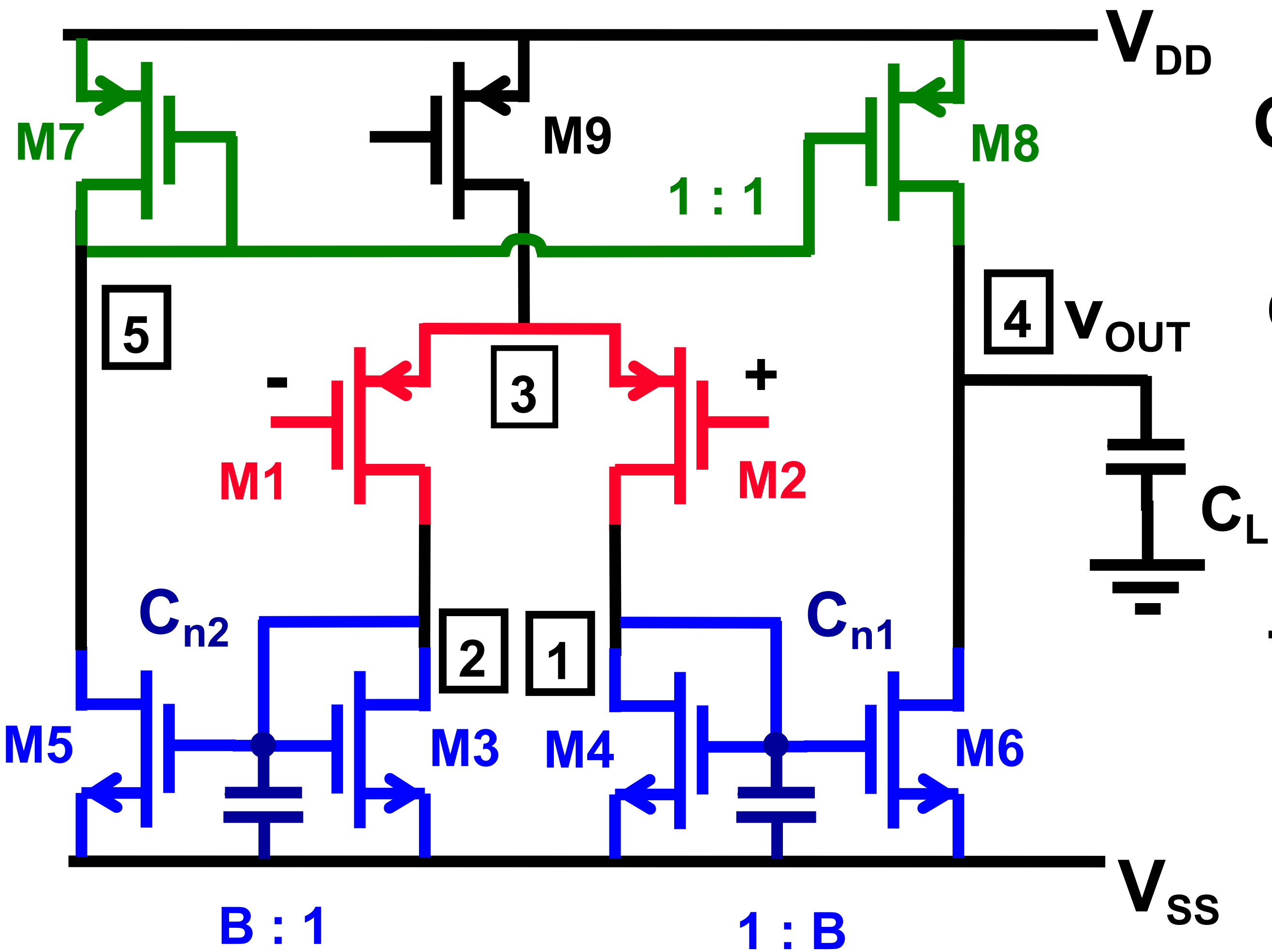
if $L_8 > L_6$

$$BW = \frac{1}{2\pi\, R_{n4} C_L}$$

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

B ?

Symmetrical CMOS OTA : $f_{nd1,2}$

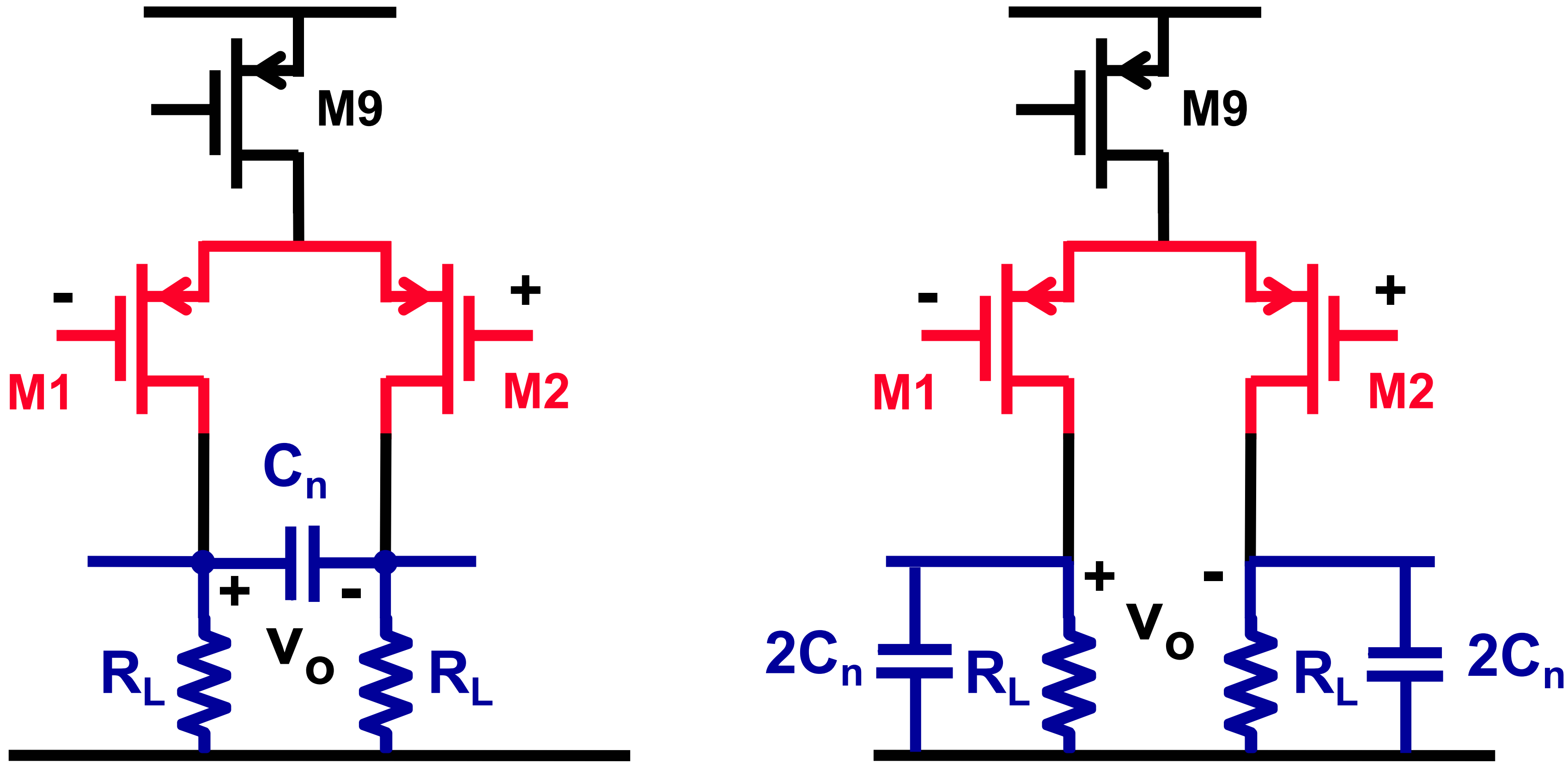


$$GBW = B\,\frac{g_{m1}}{2\pi\,C_L}$$

$$C_{n1} = (1+B)C_{GS4} + C_{DB4} + C_{DB2} \approx (3+B)C_{GS4}$$

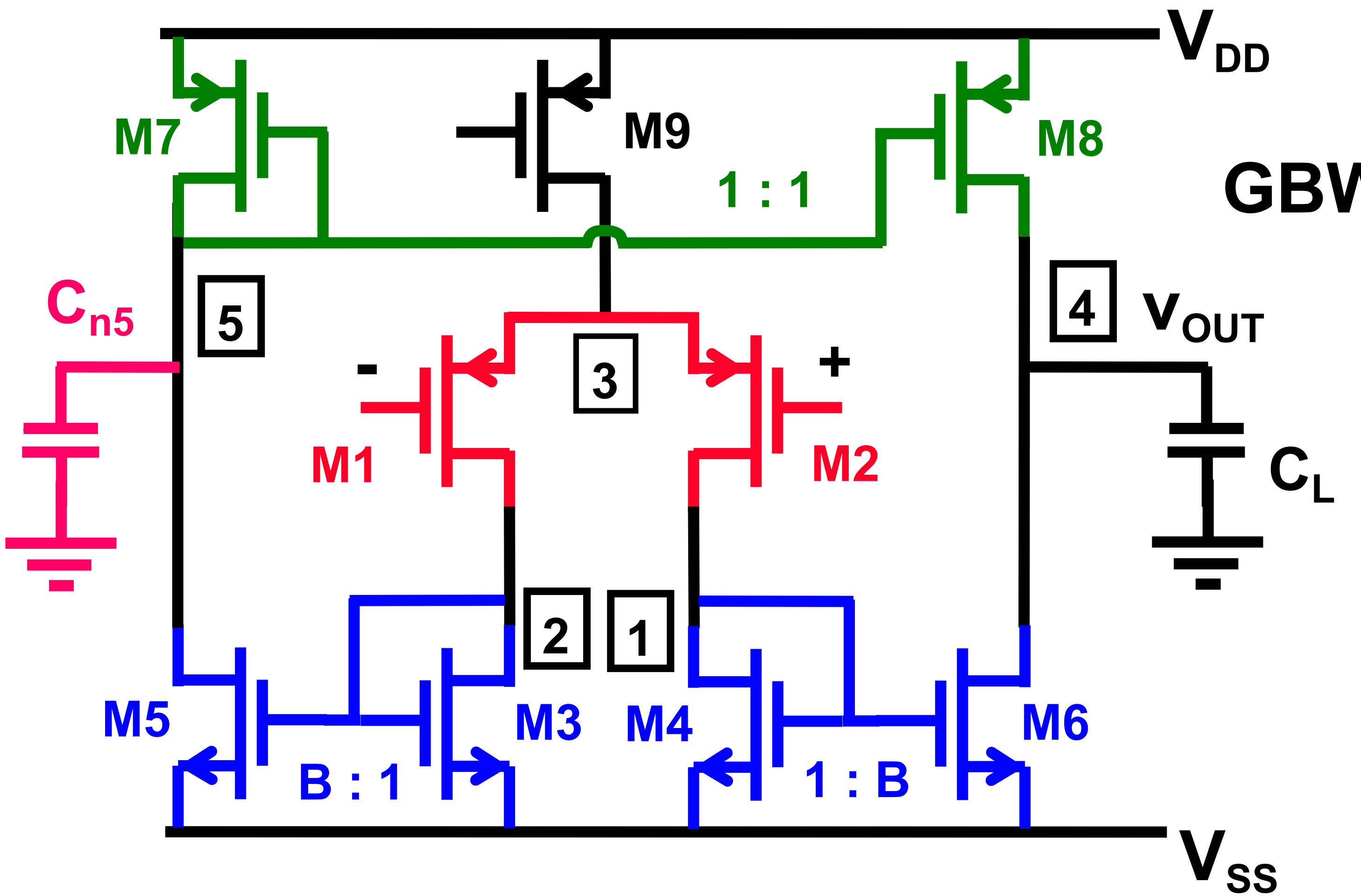
$$f_{nd} = \frac{g_{m4}}{2\pi\,C_{n1}} \approx \frac{f_{T4}}{3+B}$$

Pole at output of a differential pair



$$\text{One single pole : } f_p = \frac{1}{2\pi \, 2R_L C_n}$$

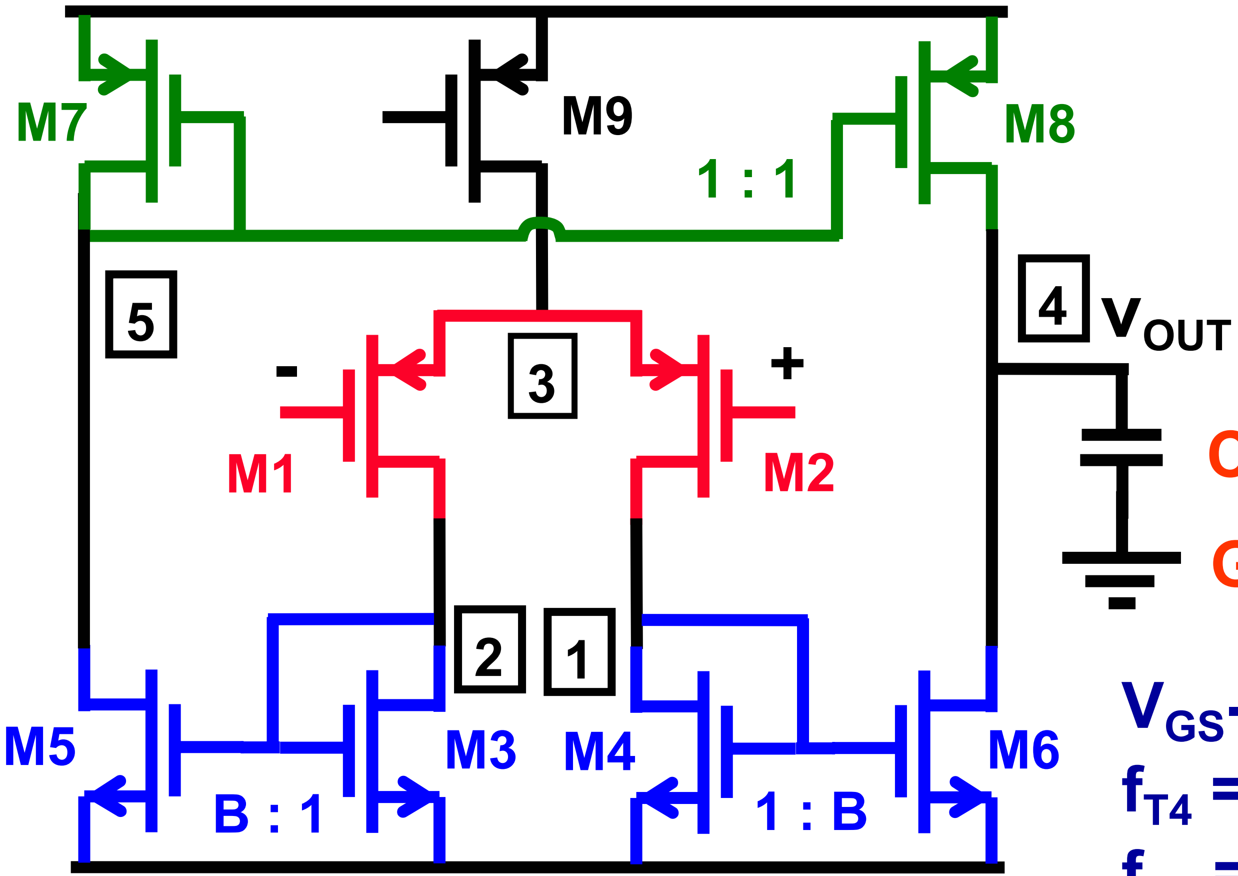
Symmetrical CMOS OTA : f_{nd5}



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

C_{n5} causes pole and zero at 2 x freq.: $\approx$ 3 …6 °

Symmetrical CMOS OTA : Design Example



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

$$f_{nd} \approx \frac{f_{T4}}{3+B}$$

C_L = 2 pF

GBW = 200 MHz

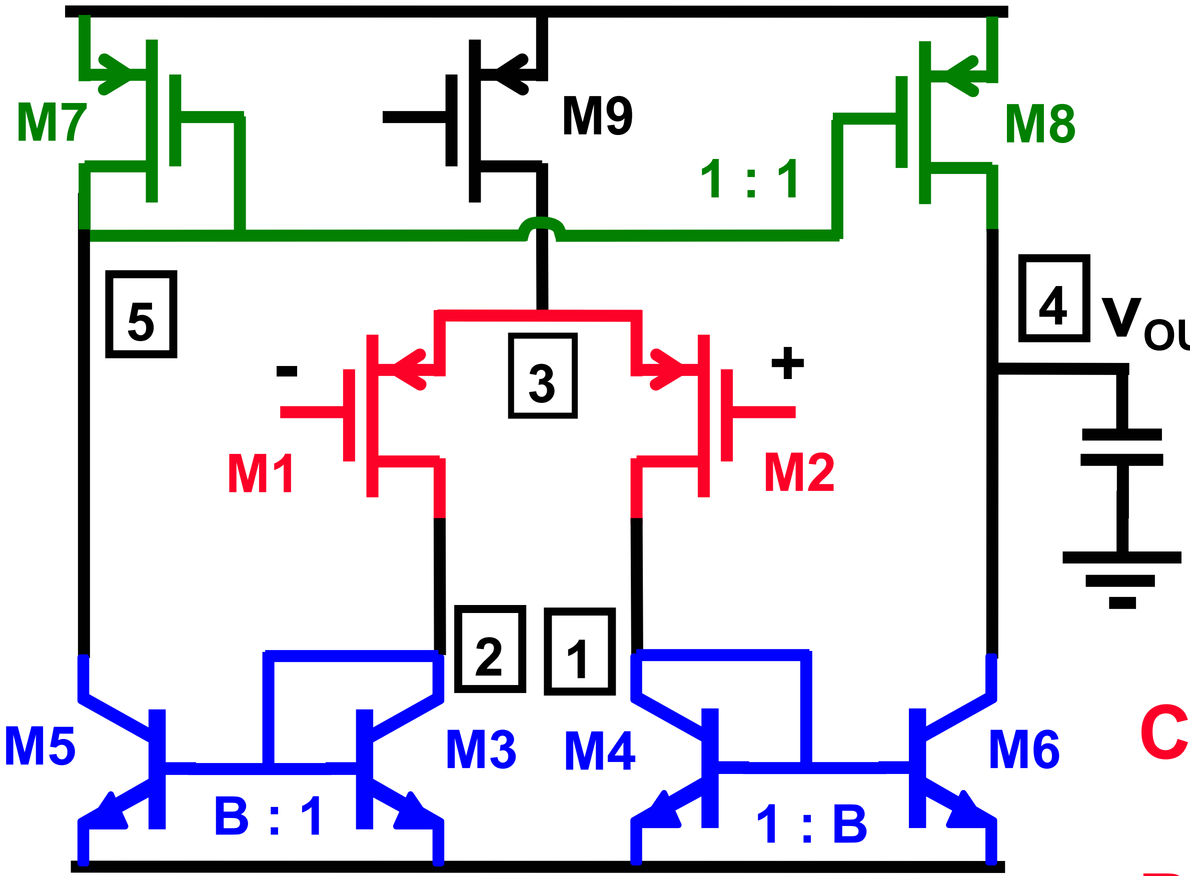
V_{GS}-V_T = 0.5 V; L = 1 μm

f_{T4} = 5 GHz

f_{nd} = 0.6 GHz

B ≈ 5

Symmetrical BiCMOS OTA



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

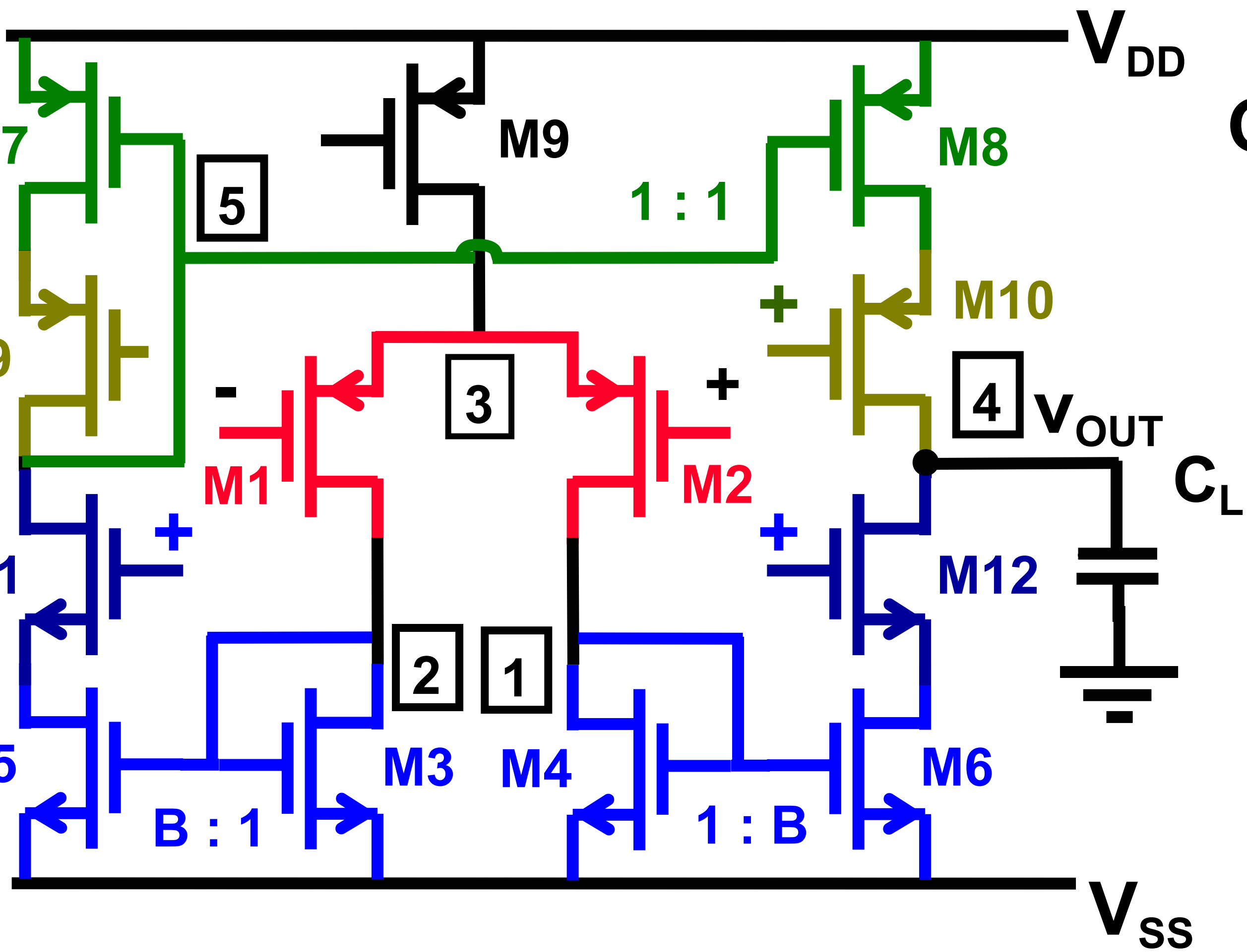
$$f_{nd} \approx \frac{f_{T4}}{3+B}$$

$g_{m4NPN} > g_{m4NMOS}$

$C_{CS4NPN} > C_{DB4NMOS}$

BiCMOS > CMOS ?

Symmetrical CMOS OTA with cascodes

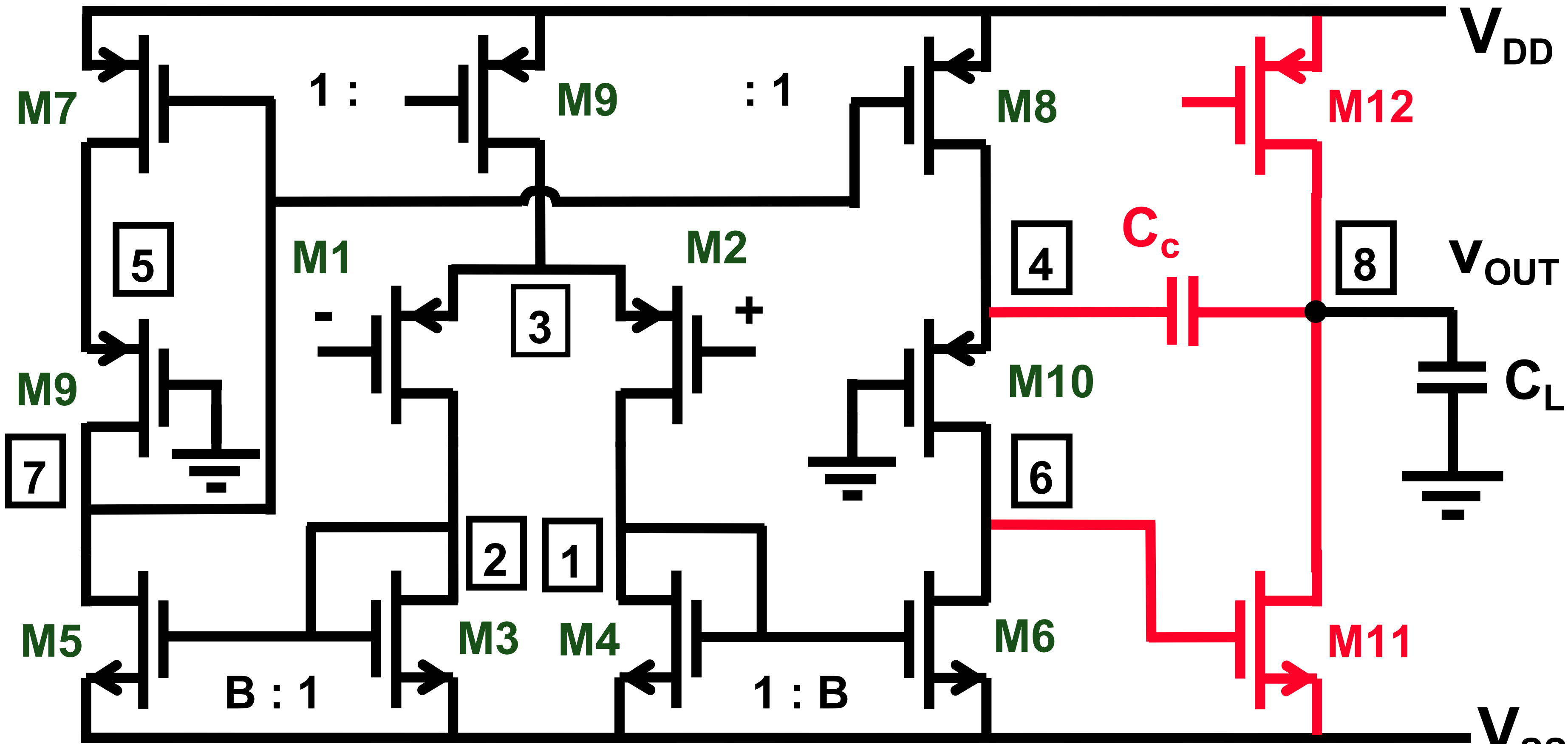


$$GBW = B \frac{g_{m1}}{2\pi C_L}$$

GBW same but A_v is 100* x higher !!!

* $g_m r_o \approx 100$

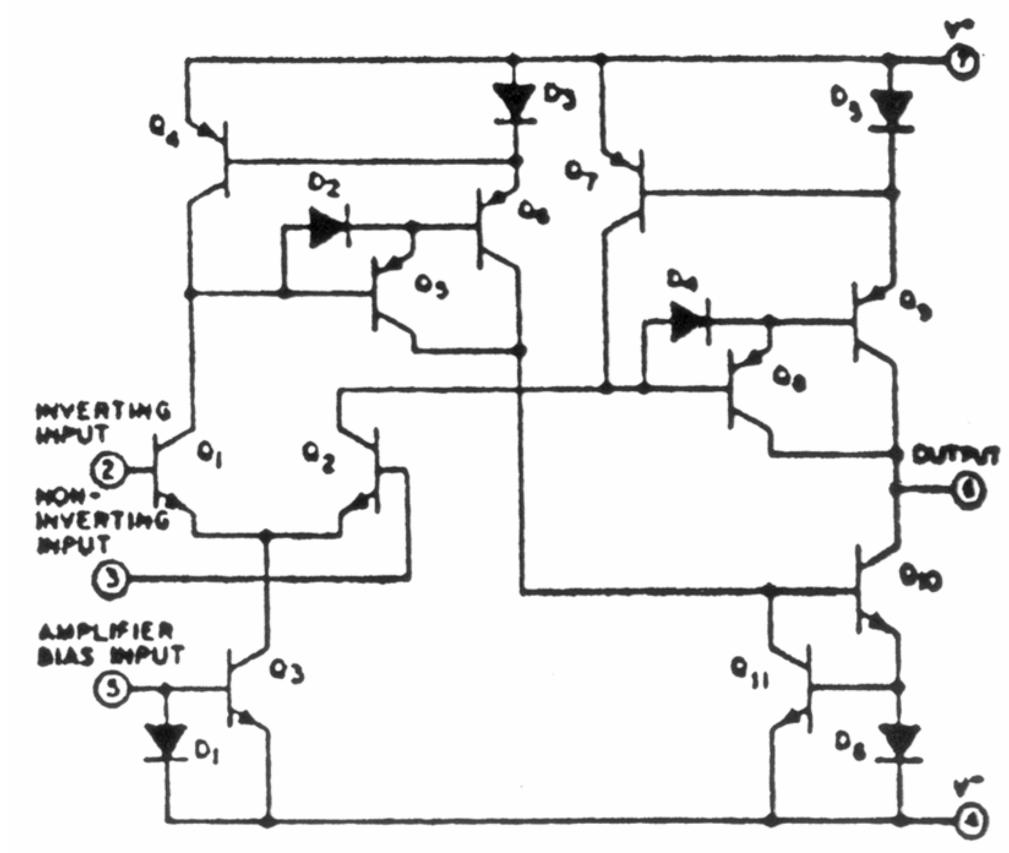
Symmetrical Miller CMOS OTA



$$GBW = B \frac{g_{m1}}{2\pi C_c}$$

No zero !

Bipolar transistor symmetrical amplifier



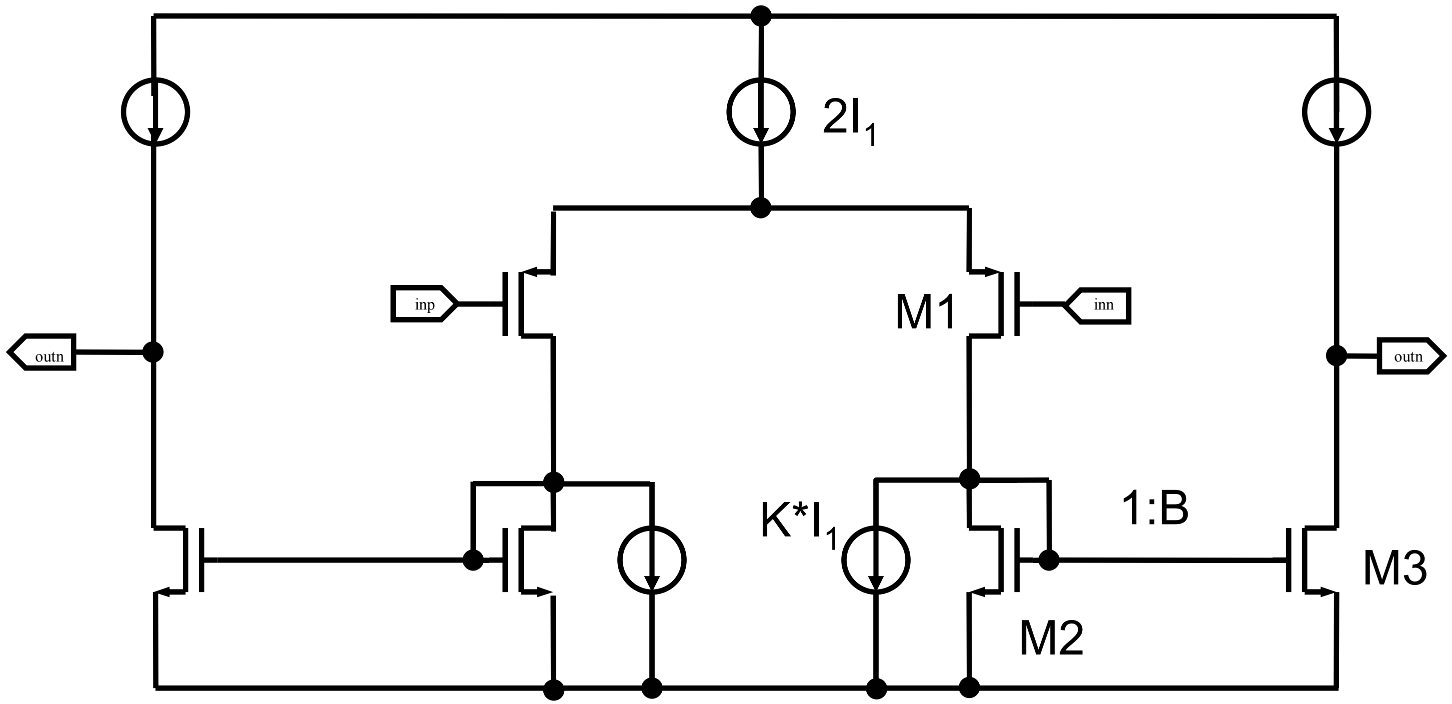
CA3080

0.12 MHz

1.2 V/μs

I_3 = 10 μA

Gain enhancement by current starving



$$A = \frac{2}{(1-k)(V_{GS}-V_T)_1 \cdot \lambda_3} = \frac{A_0}{1-k}$$

Yao, ..., JSSC Nov.04, 1809-1818

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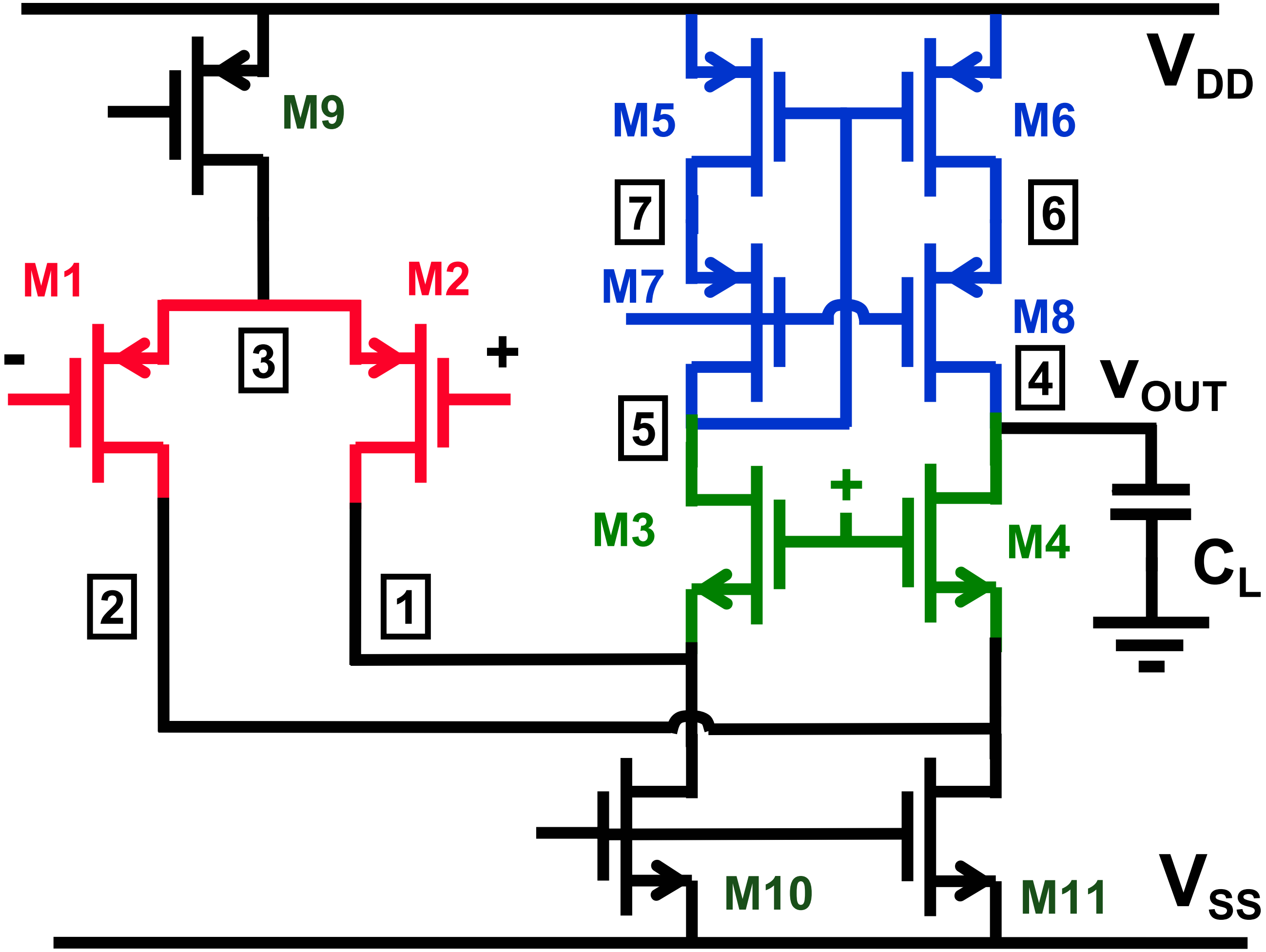
Folded cascode CMOS OTA



Differential pair

Cascode pair

2 Current mirrors

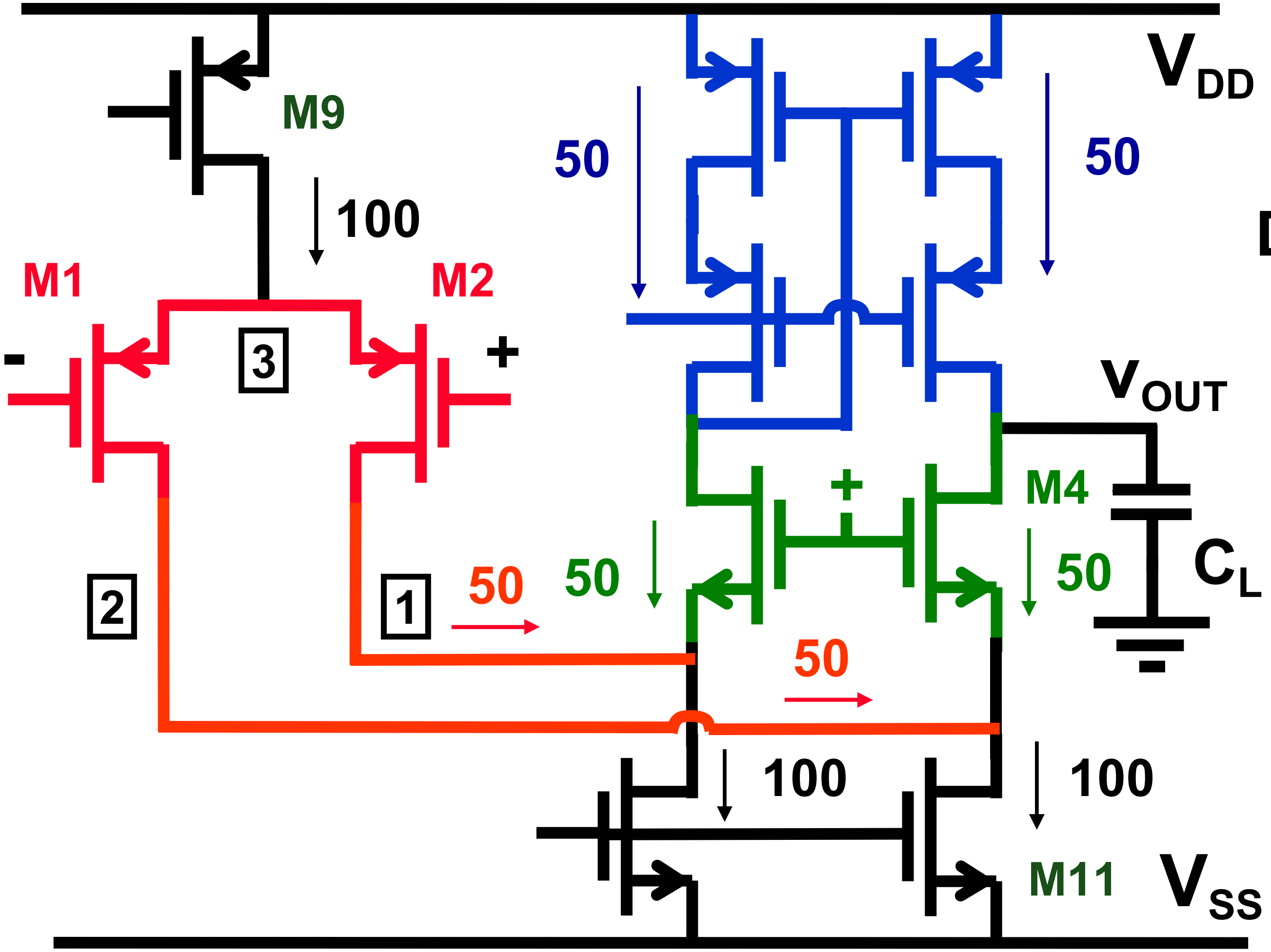
Symmetrical

Node 1 = Node 2

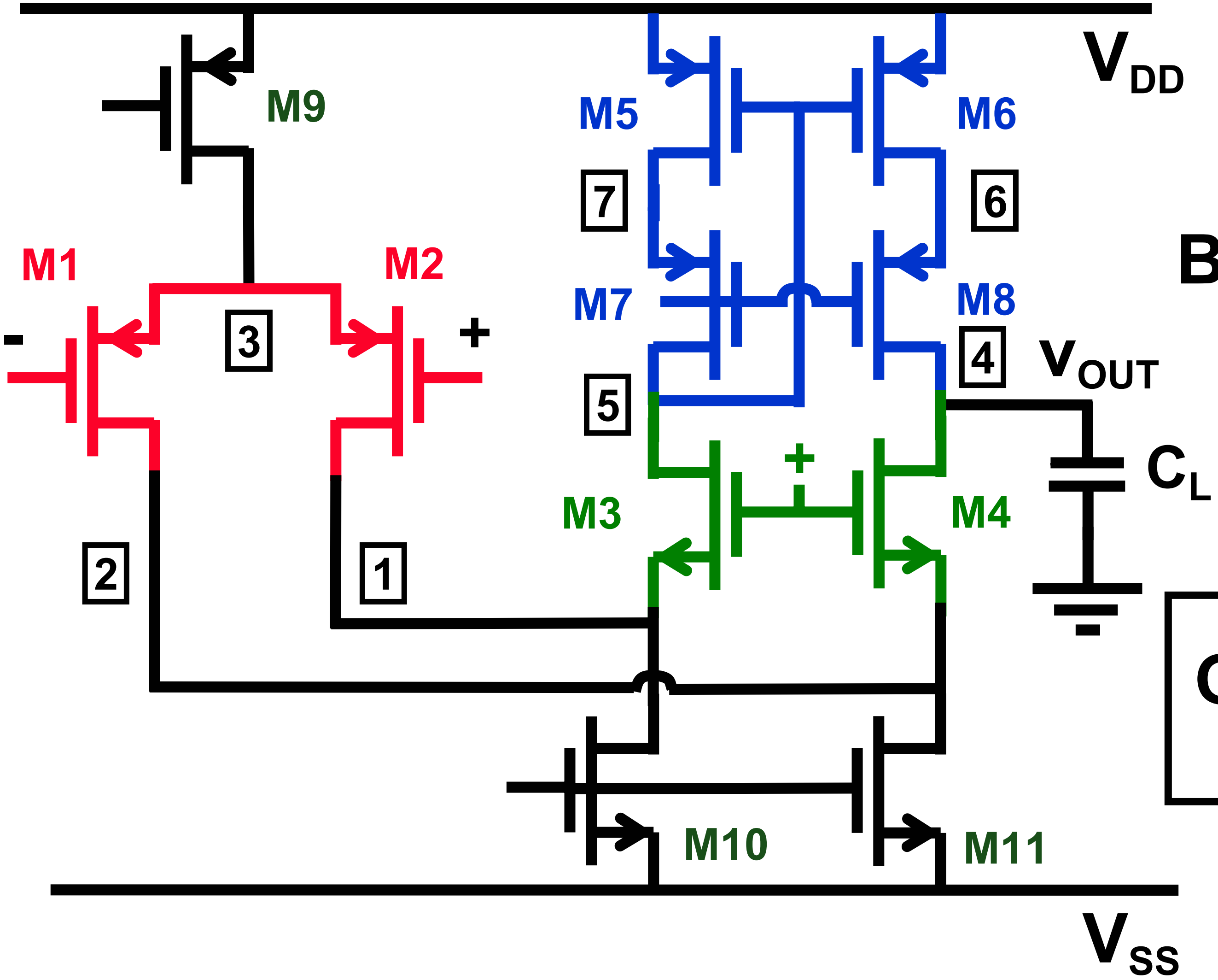
High speed

Input to rail

Folded cascode CMOS OTA : DC



Folded cascode CMOS OTA :



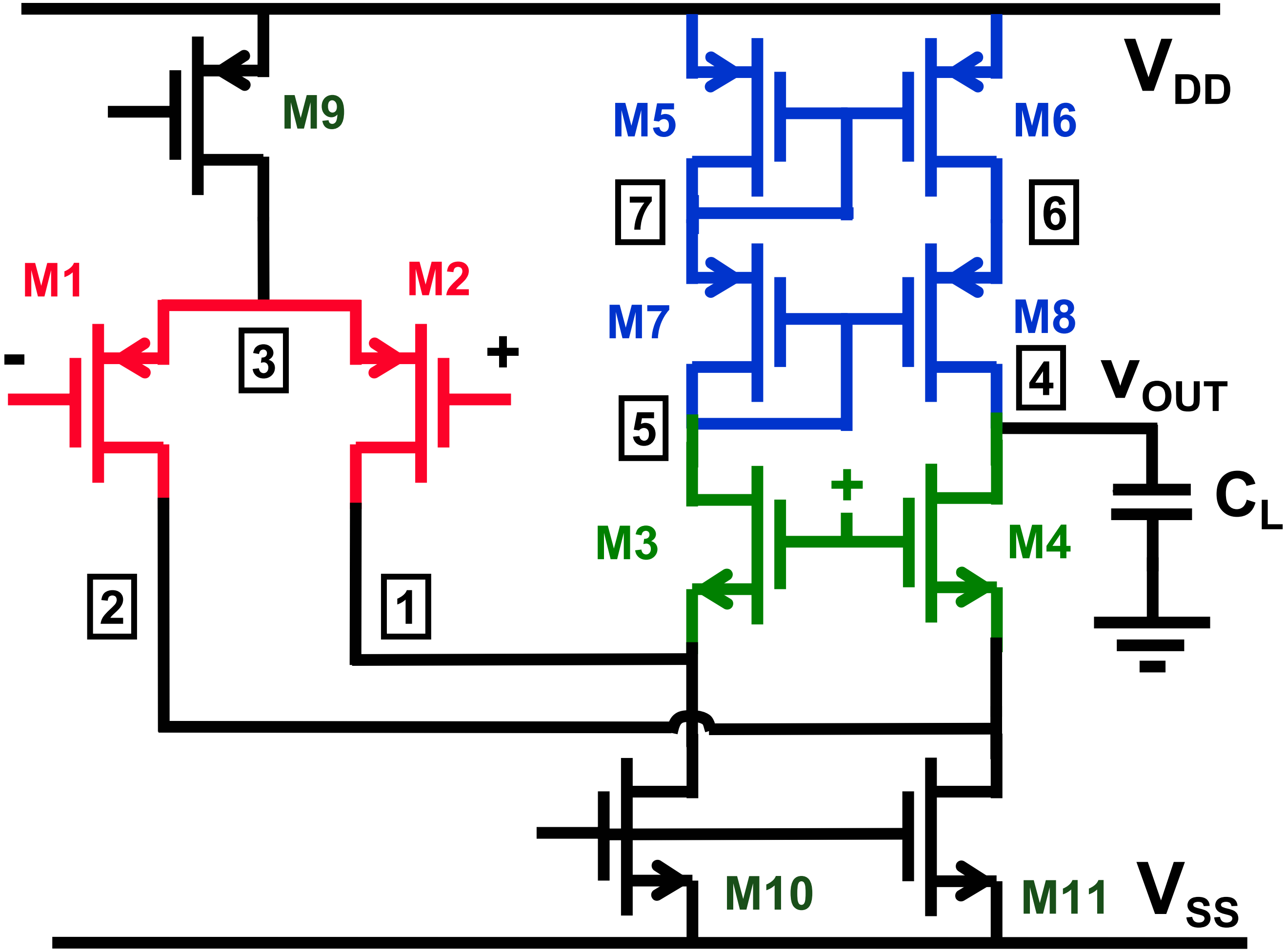
$$A_v = g_{m1}R_{n4}$$

$$BW = \frac{1}{2\pi\, R_{n4}C_L}$$

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

Single stage ?

Folded cascode CMOS OTA :

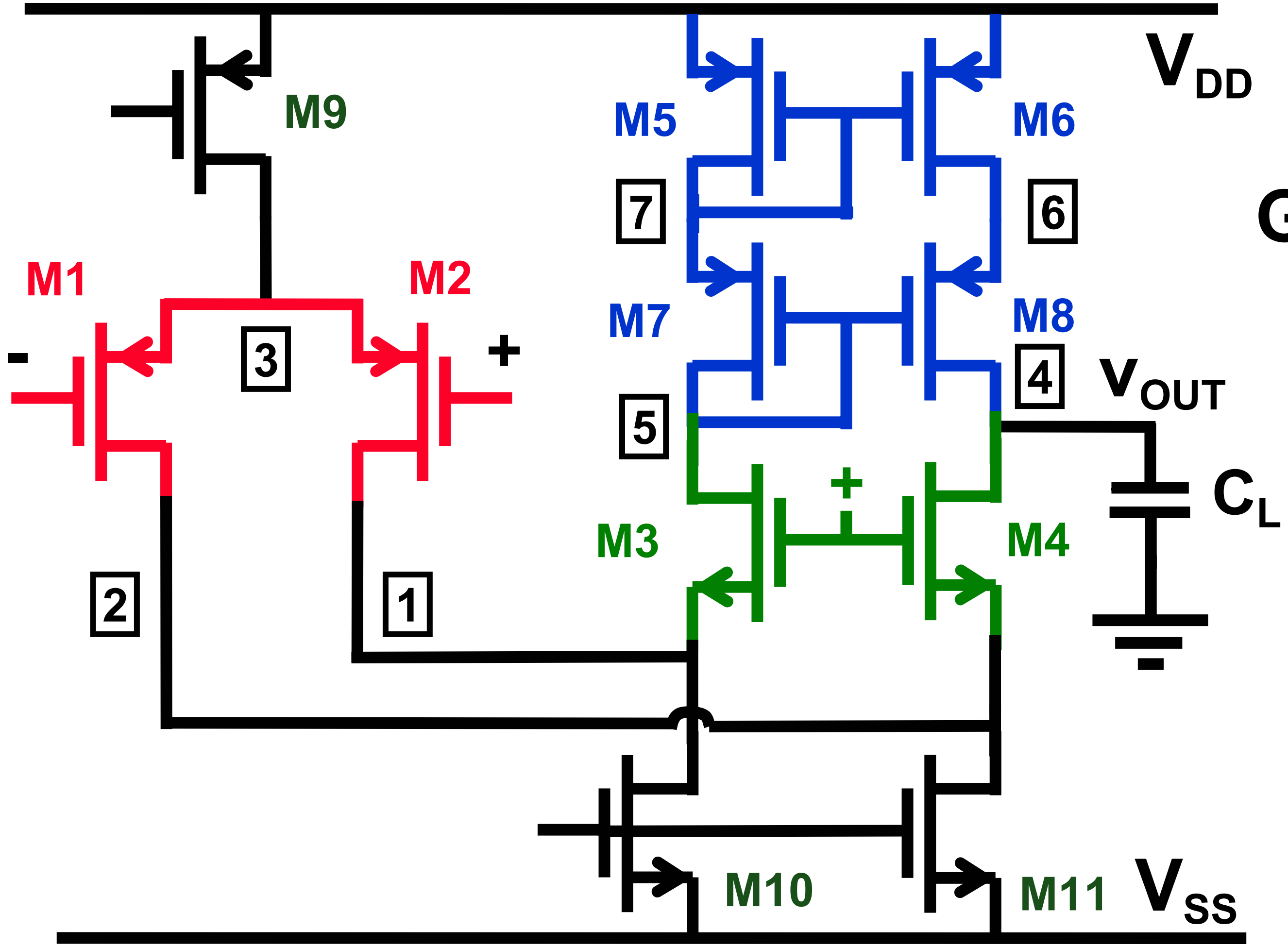


$$GBW = \frac{g_{m1}}{2\pi\, C_L}$$

$$C_{n1} = C_{GS3} + C_{DB1} + C_{DB10} \approx 3\, C_{GS3}$$

$$f_{nd} = \frac{g_{m3}}{2\pi\, C_{n1}} \approx \frac{f_{T3}}{3} \quad \text{Hi !}$$

Folded cascode CMOS OTA :

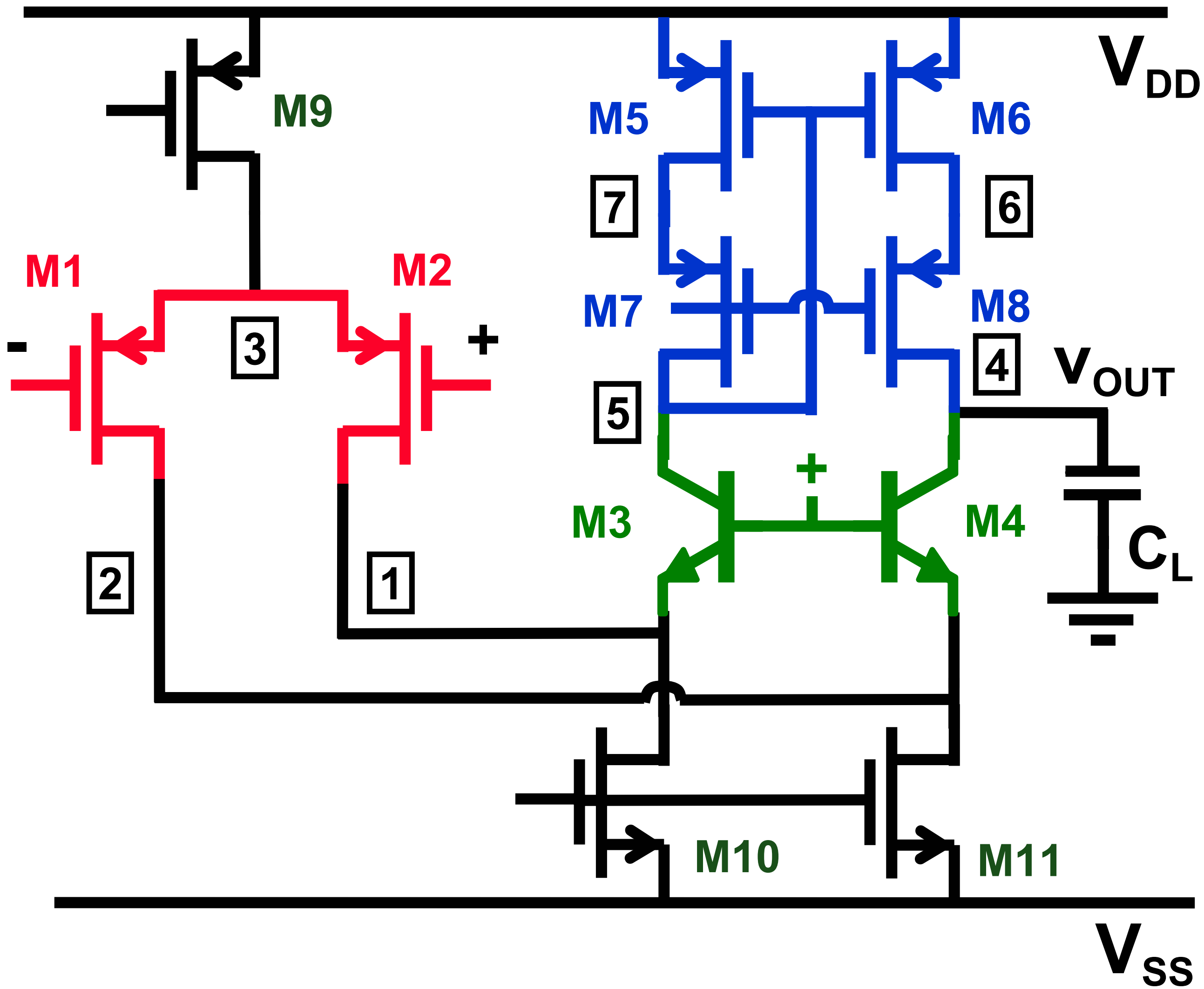


$$GBW = \frac{g_{m1}}{2\pi\, C_L}$$

C_{n5}, C_{n7} ,C_{n6}
Cause pole
and zero
at 2 x freq.:
≈ 5 …10 °

Ref Mallya, JSSC Dec 89, 1737-1740

Folded cascode BiCMOS OTA



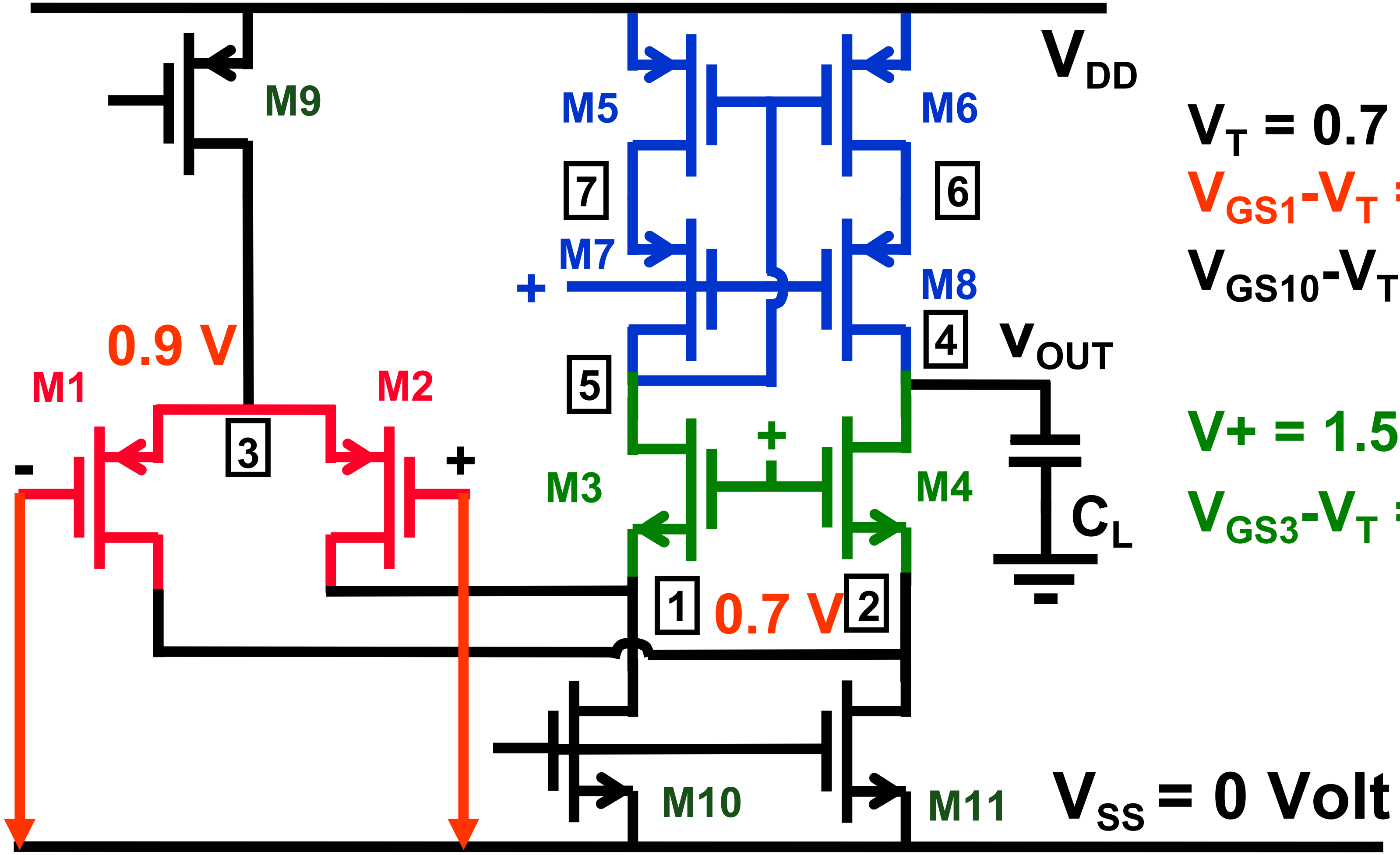
$$GBW = \frac{g_{m1}}{2\pi\, C_L}$$

$$f_{nd} = \frac{g_{m3}}{2\pi\, C_{n1}}$$

$$\approx \frac{f_{T3NPN}}{3}$$

Higher !

Folded cascode OTA: input to V_{ss} rail



$V_T = 0.7\ V$

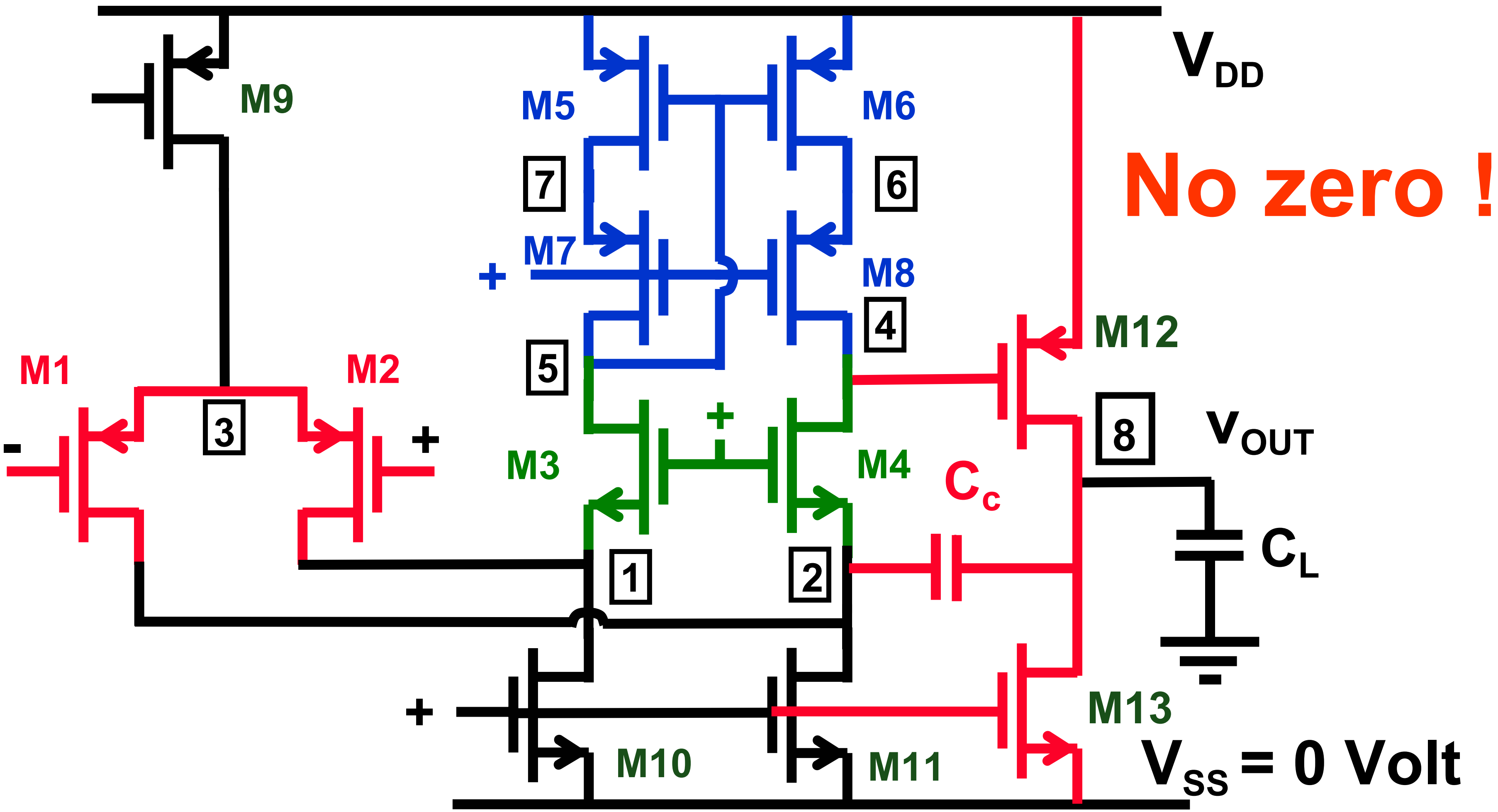
$V_{GS1} - V_T = 0.2\ V$

$V_{GS10} - V_T = 0.5\ V$

$V+ = 1.5\ V$

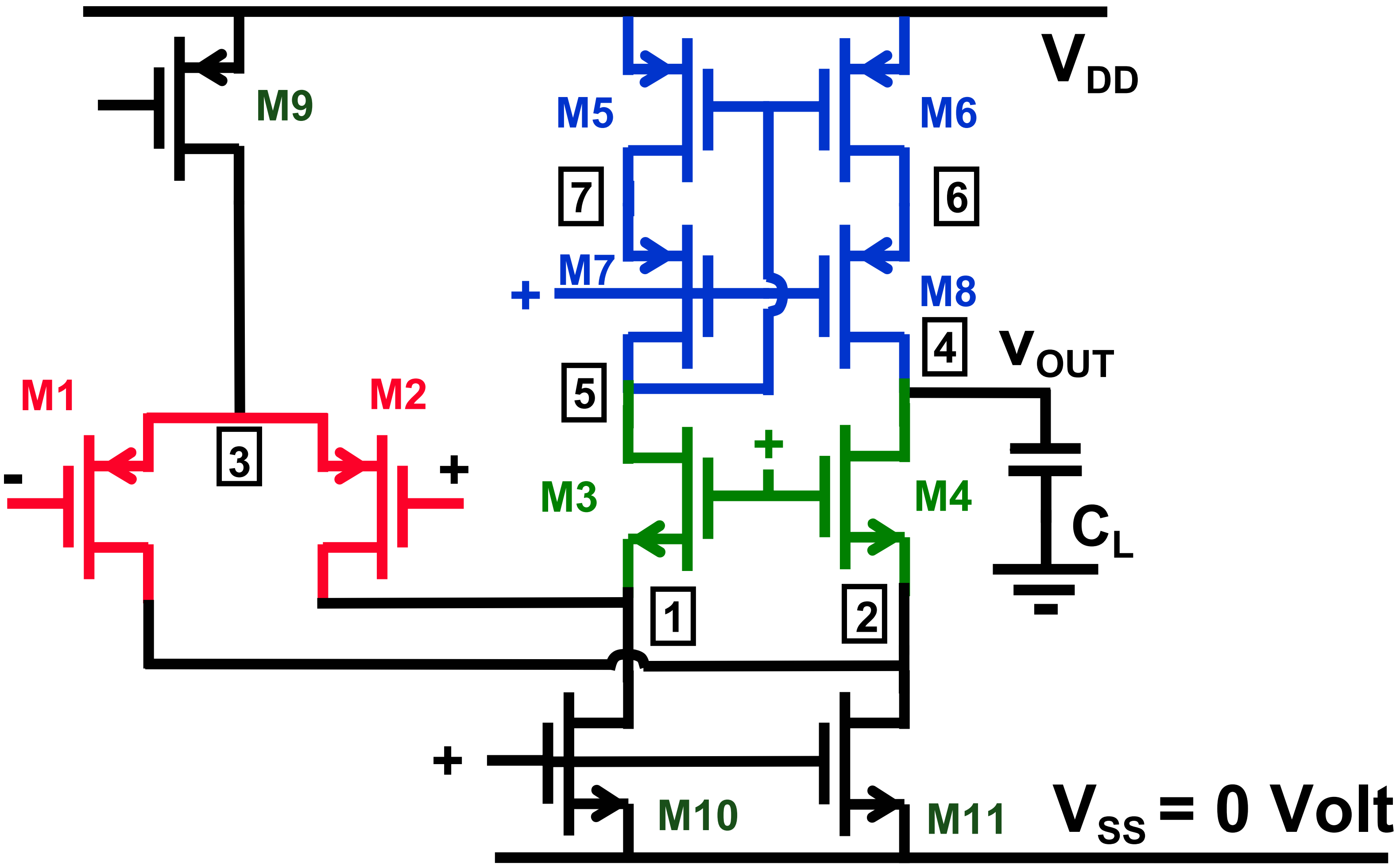
$V_{GS3} - V_T = 0.2\ V$

Folded cascode OTA with 2nd stage

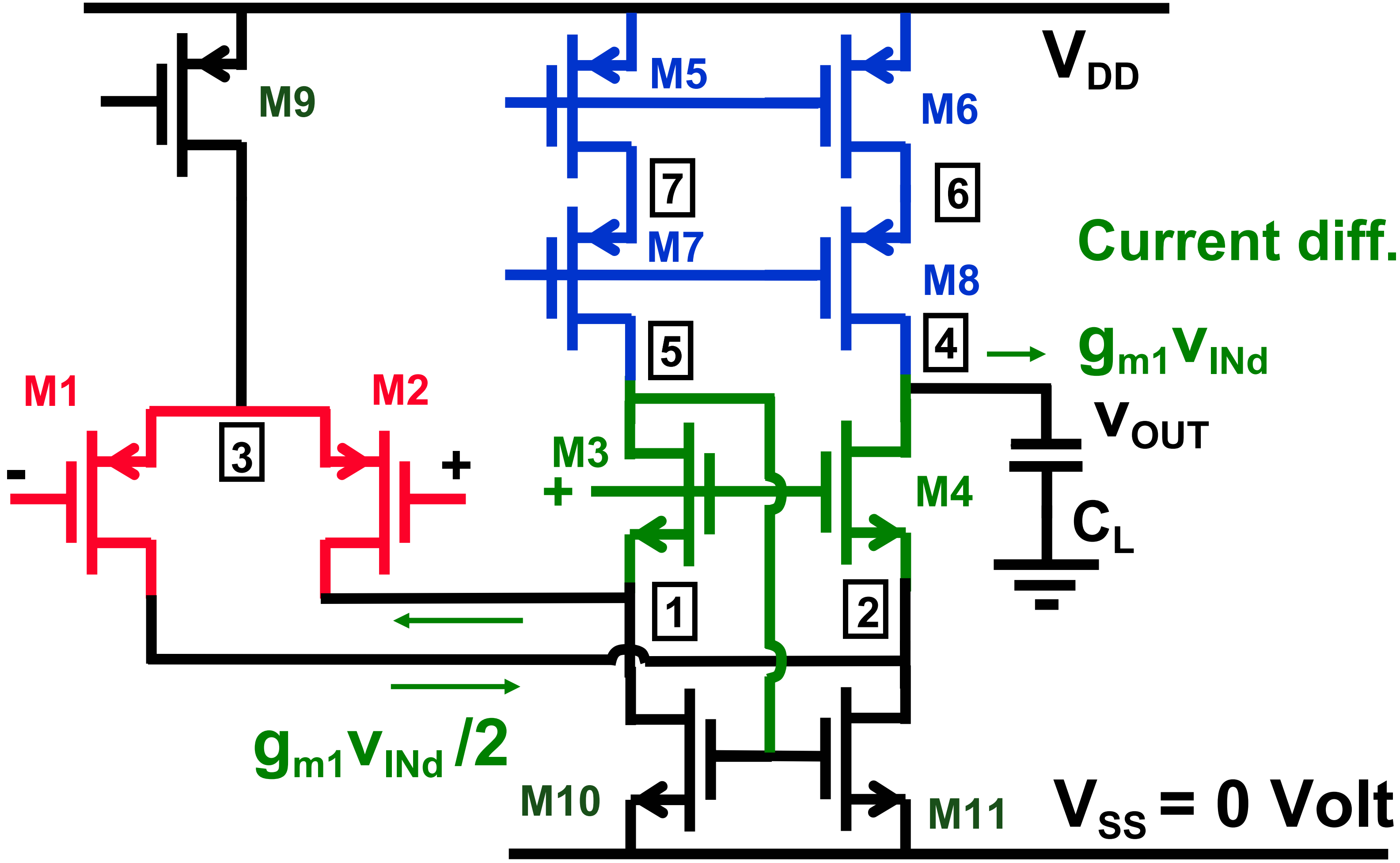


Ribner, JSSC Dec.84, 919-925

Conventional folded cascode OTA



Alternative folded cascode OTA



Comparison amplifiers

	I_{TOT} mA	$\overline{dv_{in,eq}^2}$ / $\frac{8/3\ kT\ df}{g_{m1}}$	Swing
Volt. OTA (4 Ts)	0.25	4	avg.
Symmetrical (B= 3)	0.33	16	max.
Telescopic	0.25	4	small
Folded casc.	0.5	4	avg.
Miller 2-stage (C_L/C_c= 2.5)	1.1	4	max.

GBW = 100 MHz C_L = 2 pF V_{GS}-V_T = 0.2 V Fully differential

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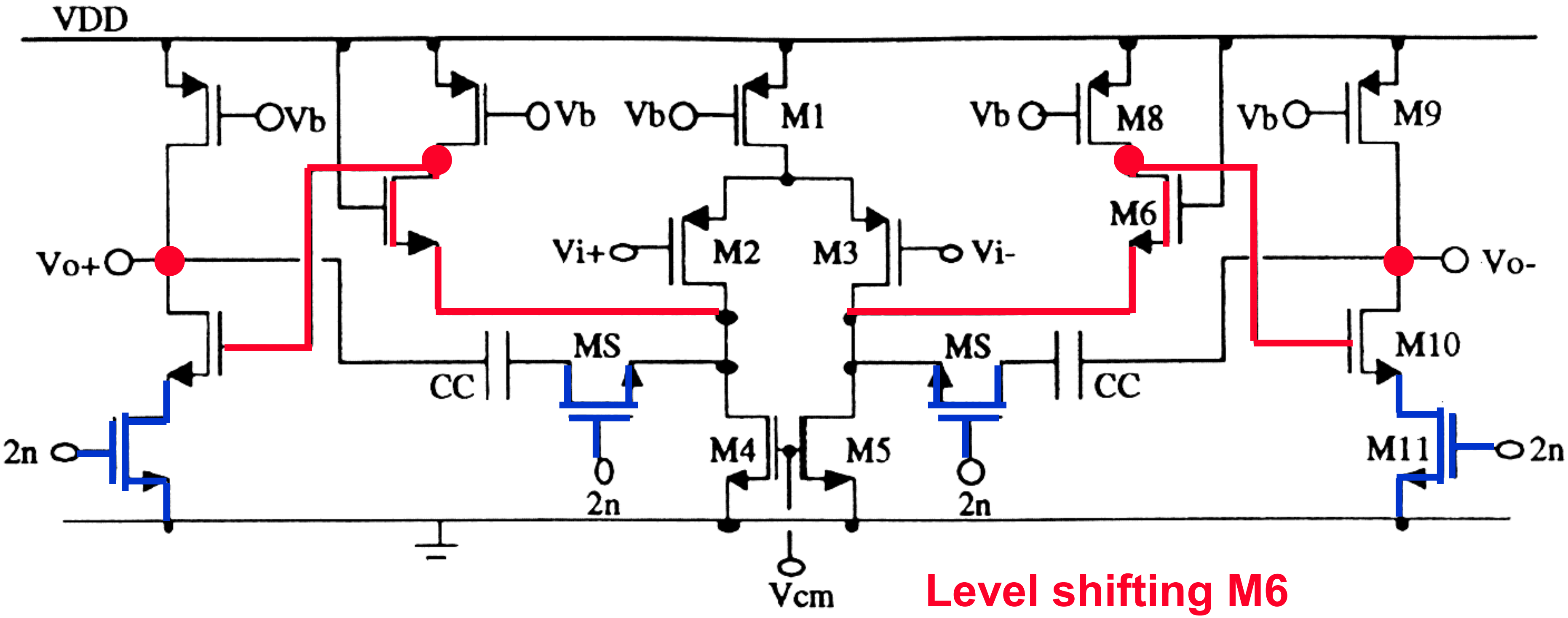
Sub-1 Volt OTA

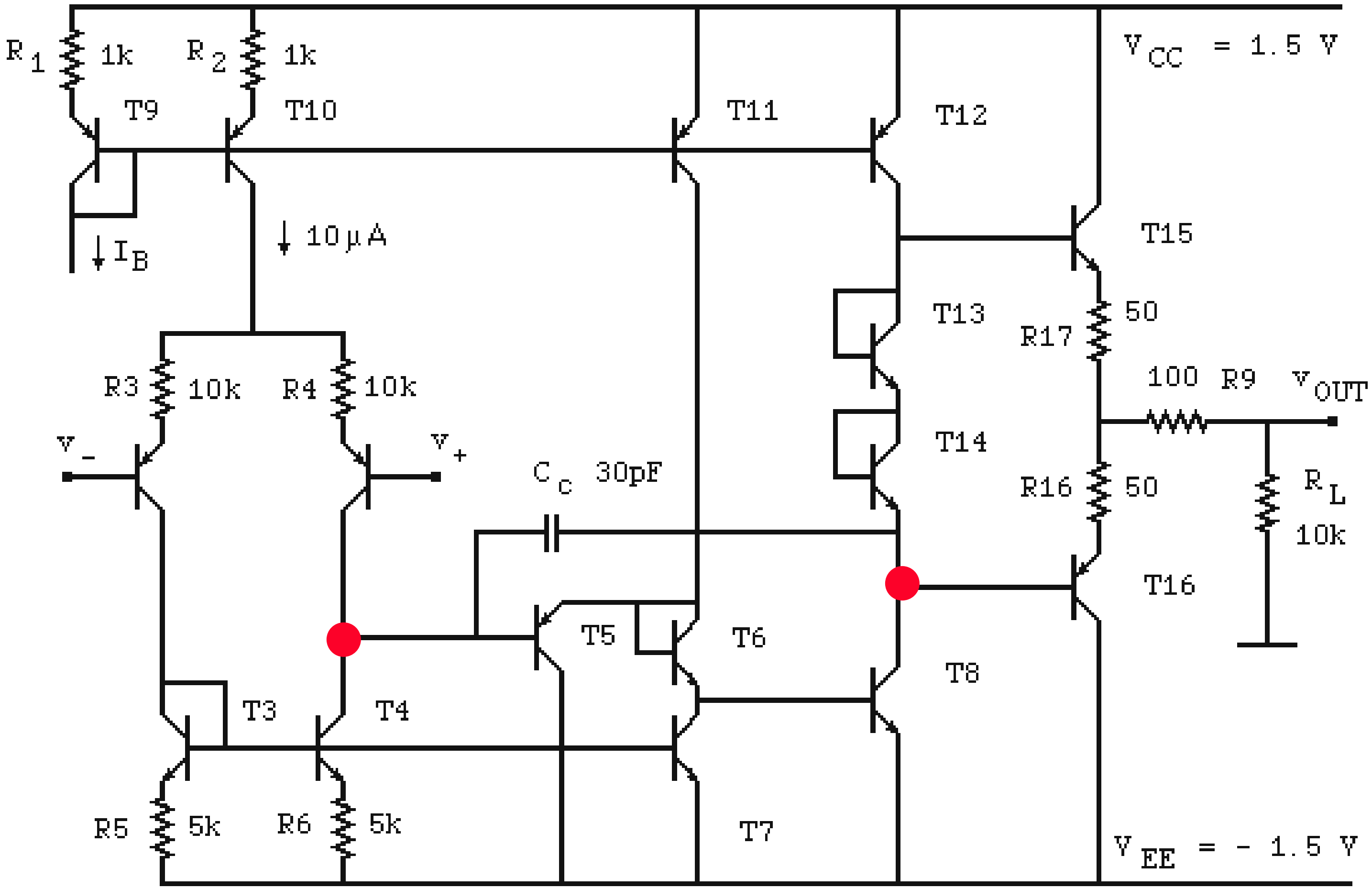


1 V 80 µW (min: V_T+2V_{DSsat})
Fully differential
75 dB 30 MHz (0.1 pF)
< 100 ns

Level shifting M6
4 Switches 2n :
Only 2nd stage switched off !

Baschirotto, .. JSSC Dec.97,pp.1979-1986

LM 4250



GBW = 0.25 MHz

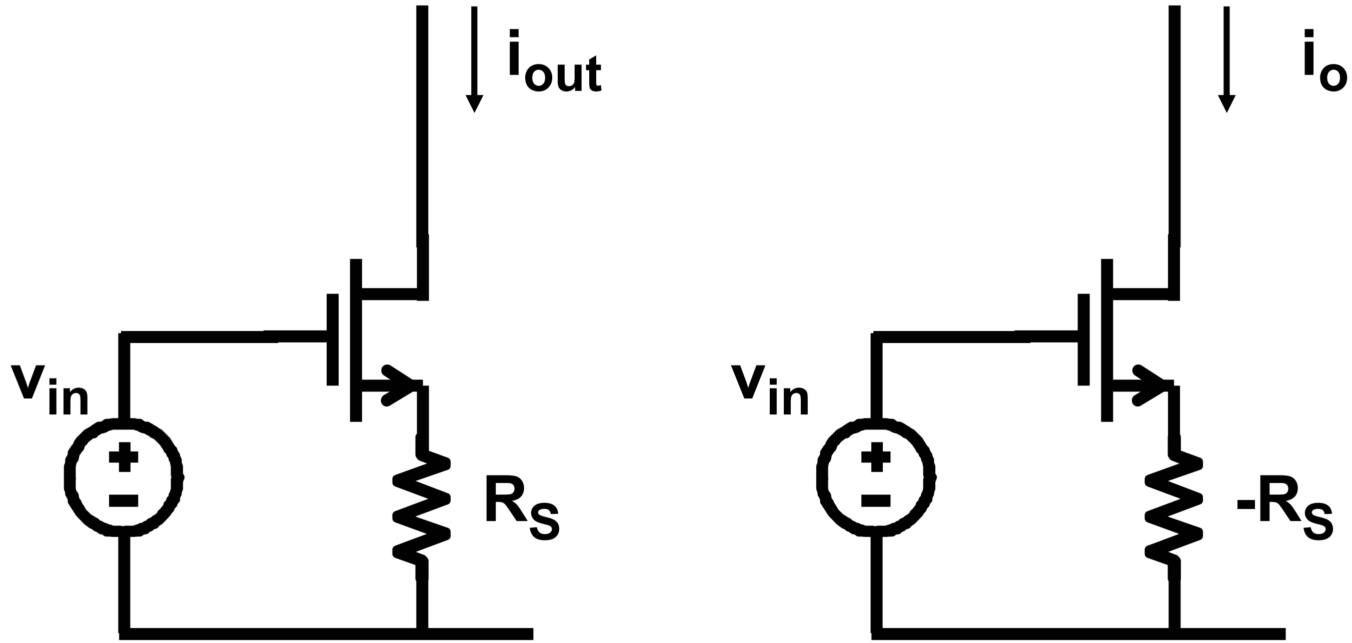
SR = 0.2 V/µs

I_1 = 10 µA

I_{TOT} = 90 µA

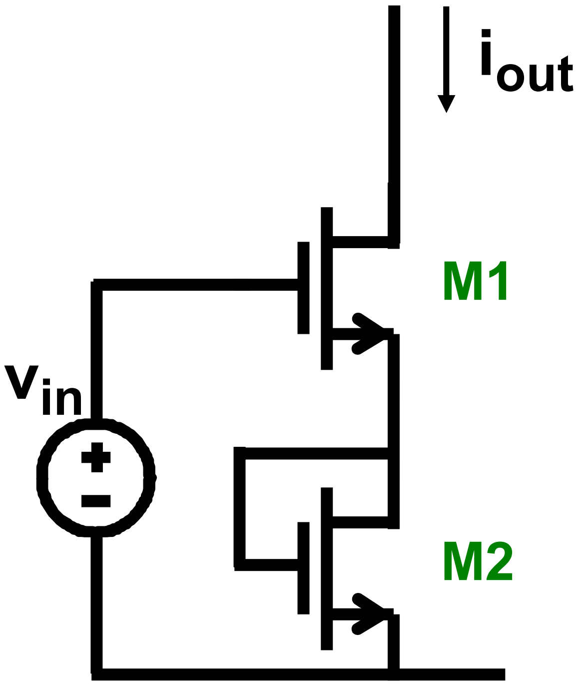
38 $nV_{RMS}/\sqrt{Hz}$

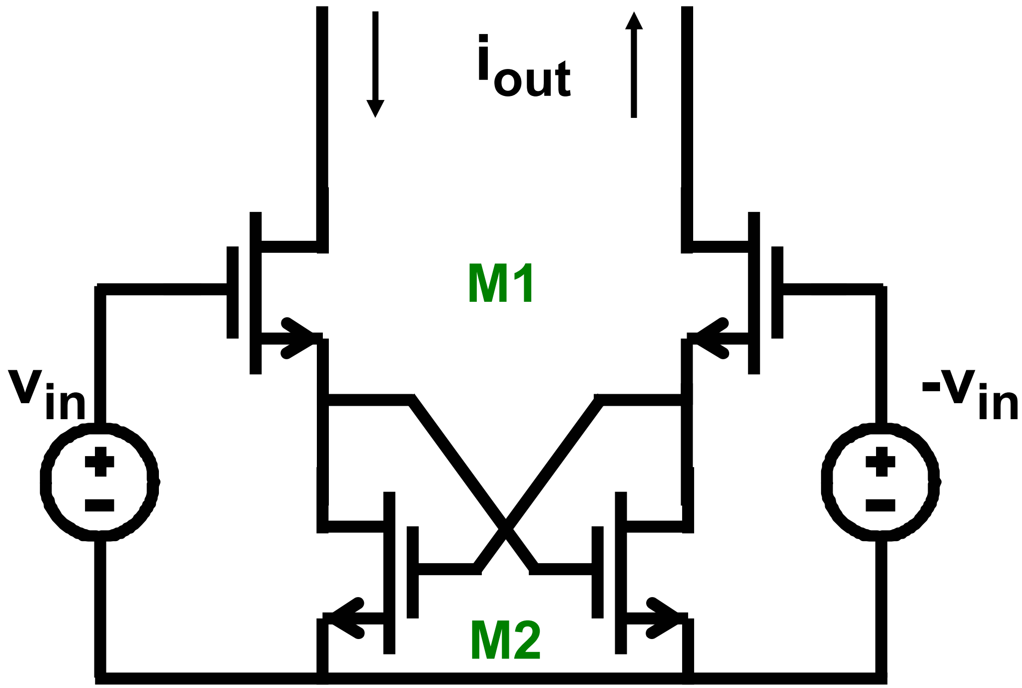
Increased input transconductance - 1



$$g_{mR} = \frac{g_m}{1 + g_m R_S} \qquad g_{mR} = \frac{g_m}{1 - g_m R_S}$$

Increased input transconductance - 2

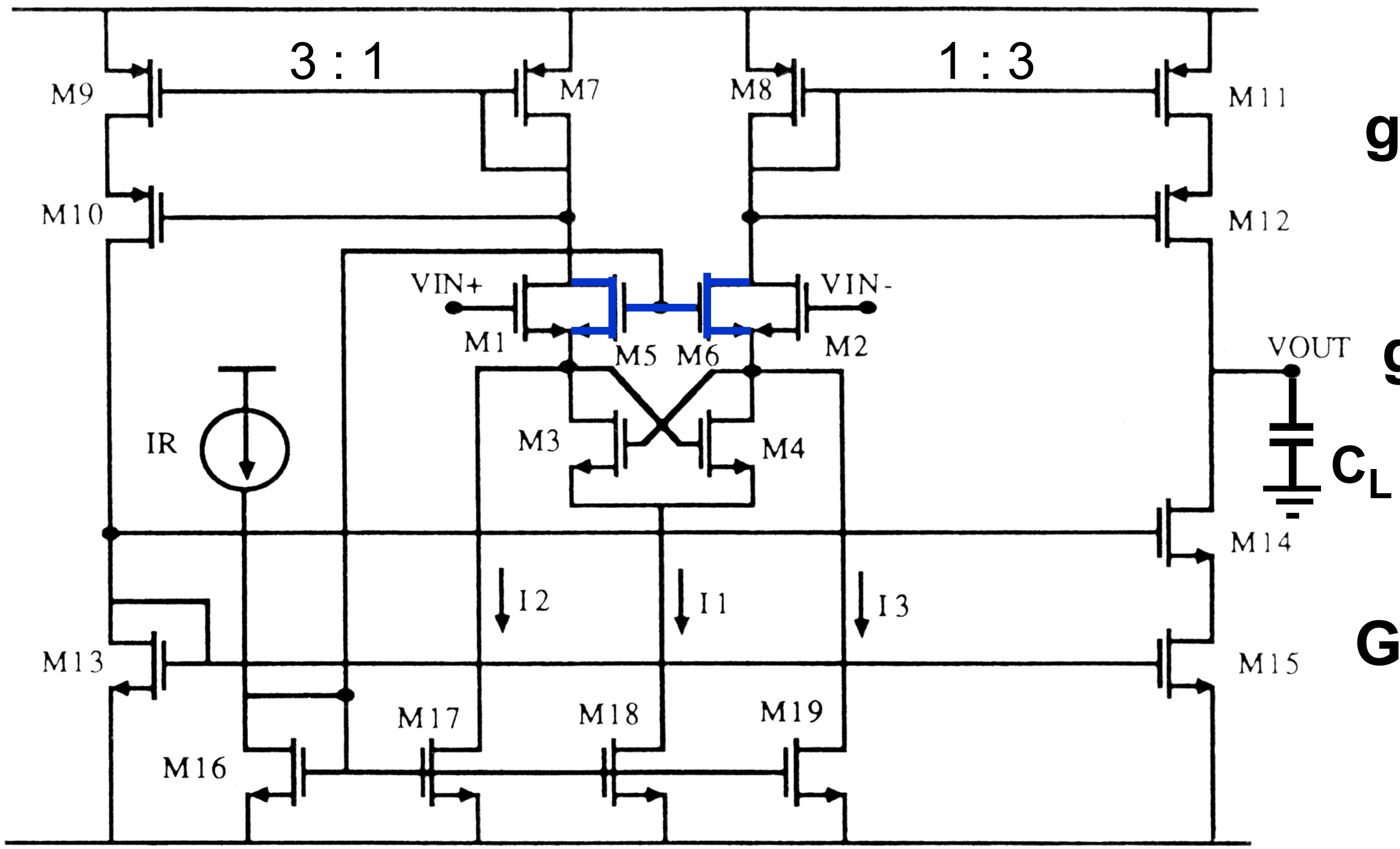




$$g_m = \frac{g_{m1}}{1 + \frac{g_{m1}}{g_{m2}}}$$

$$g_m = \frac{g_{m1}}{1 - \frac{g_{m1}}{g_{m2}}}$$

Increased input transconductance - 3



$$g_m = \frac{g_{m1}}{1 - \frac{g_{m1}}{g_{m3}}}$$

$$g_m \approx 3\, g_{m1}$$

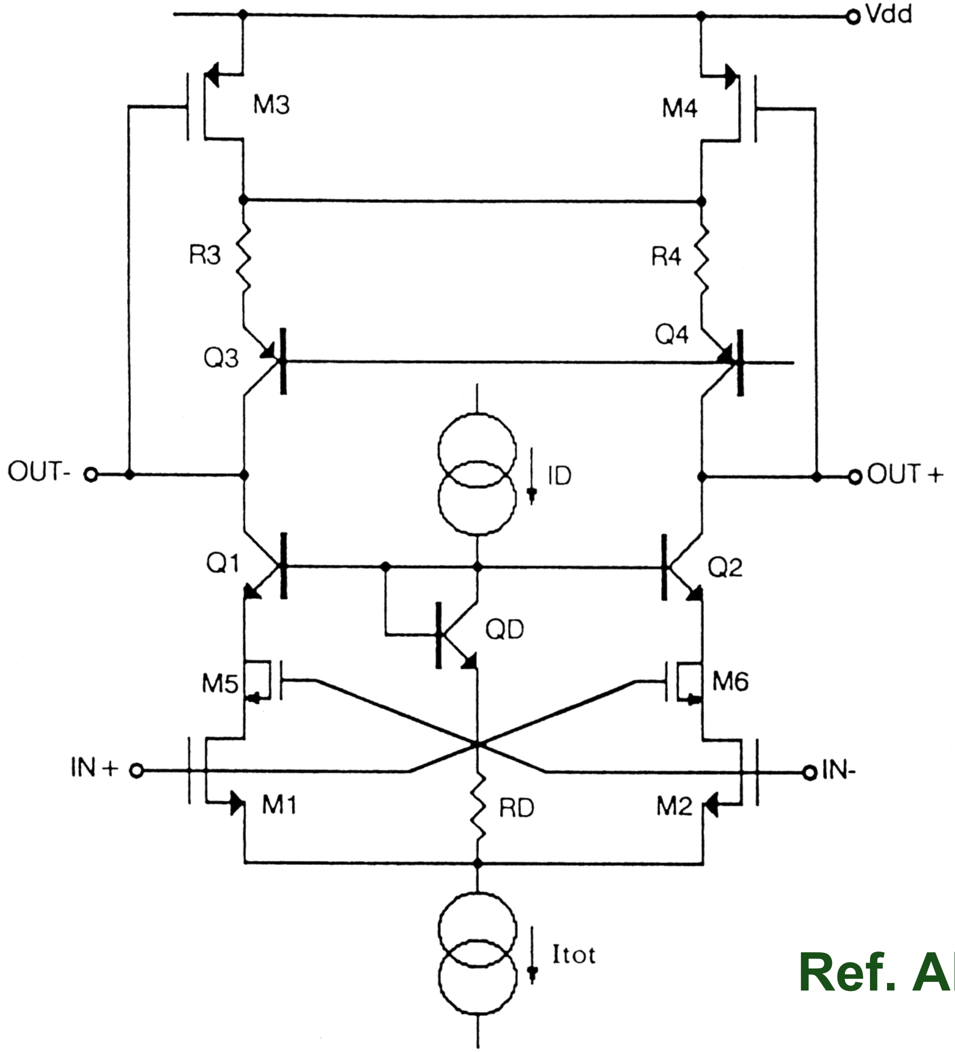
$$GBW = \frac{3\, g_m}{2\pi C_L}$$

$$\approx \frac{9\, g_{m1}}{2\pi C_L}$$

Ref.: Castello, JSSC June 1990, pp. 669-676

M5,M6 for overdrive !

Transconductor with C$\square_{DG}$ compen.



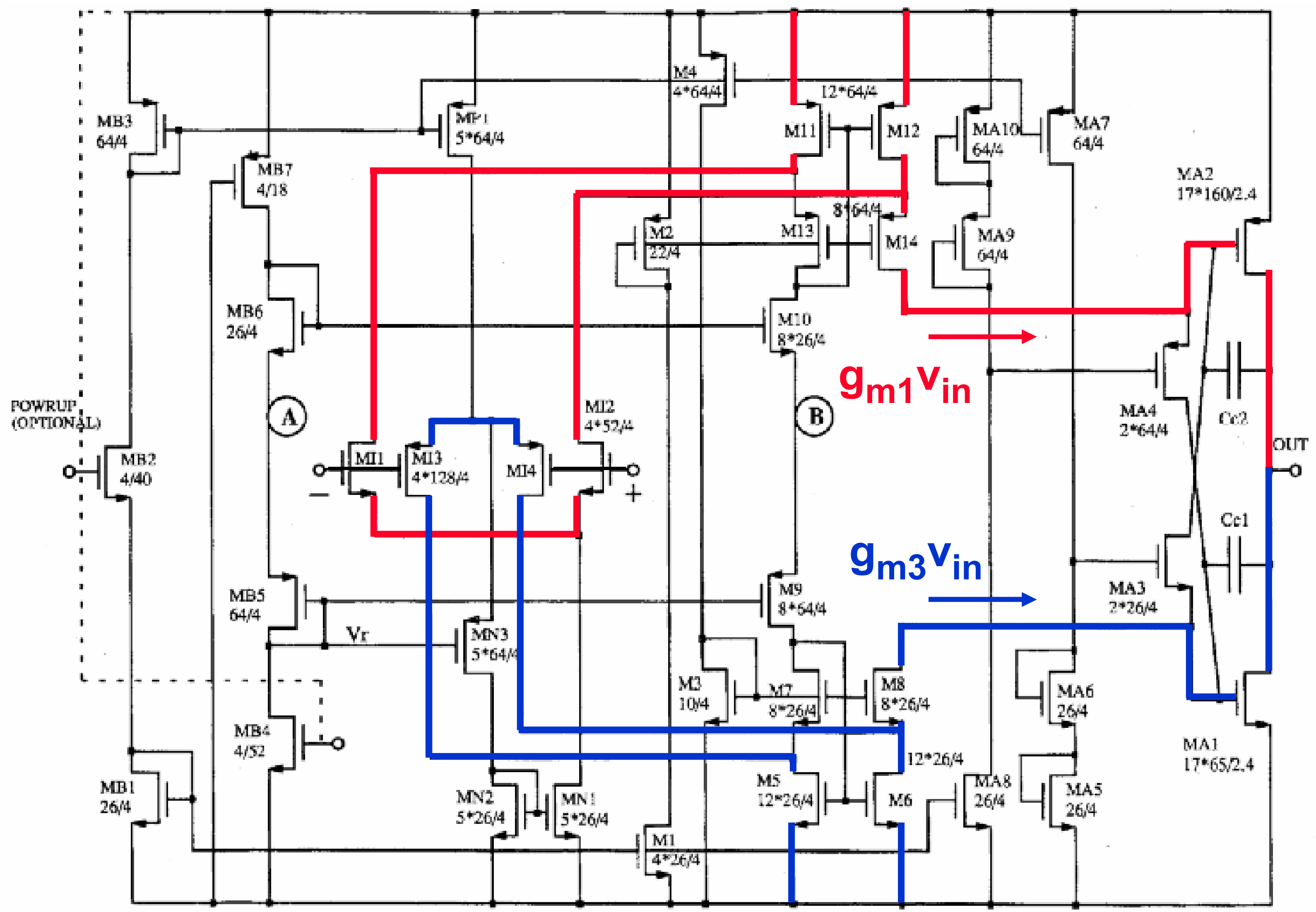
$V_{DS1} = R_D I_D \approx 0.2\ V$

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

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

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

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



14 MHz
/ 11pF

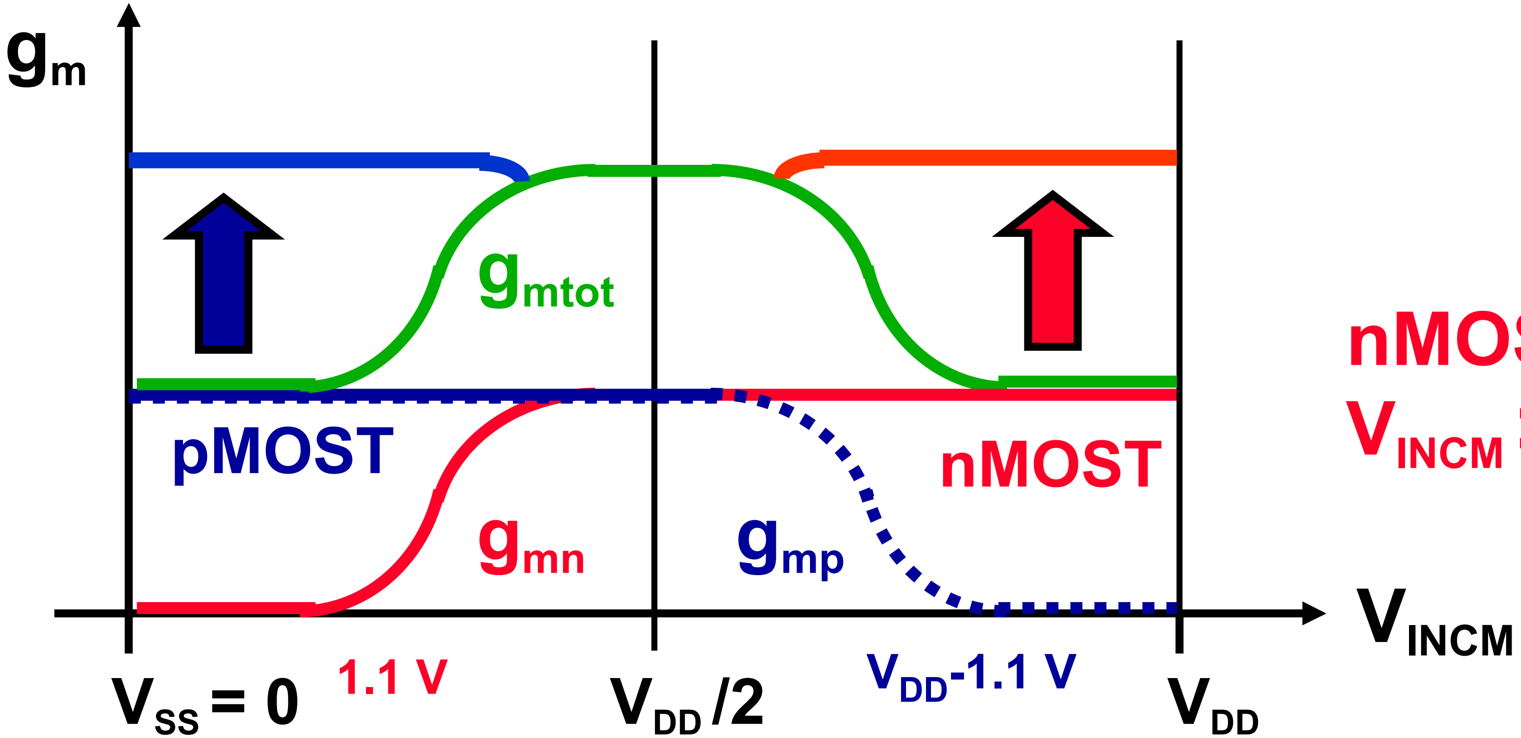
5.6 MHz
/ 100pF

4 V/μs

36 nV/√ Hz

5 V
0.4 mA

Problem: unequal g_{mtot}

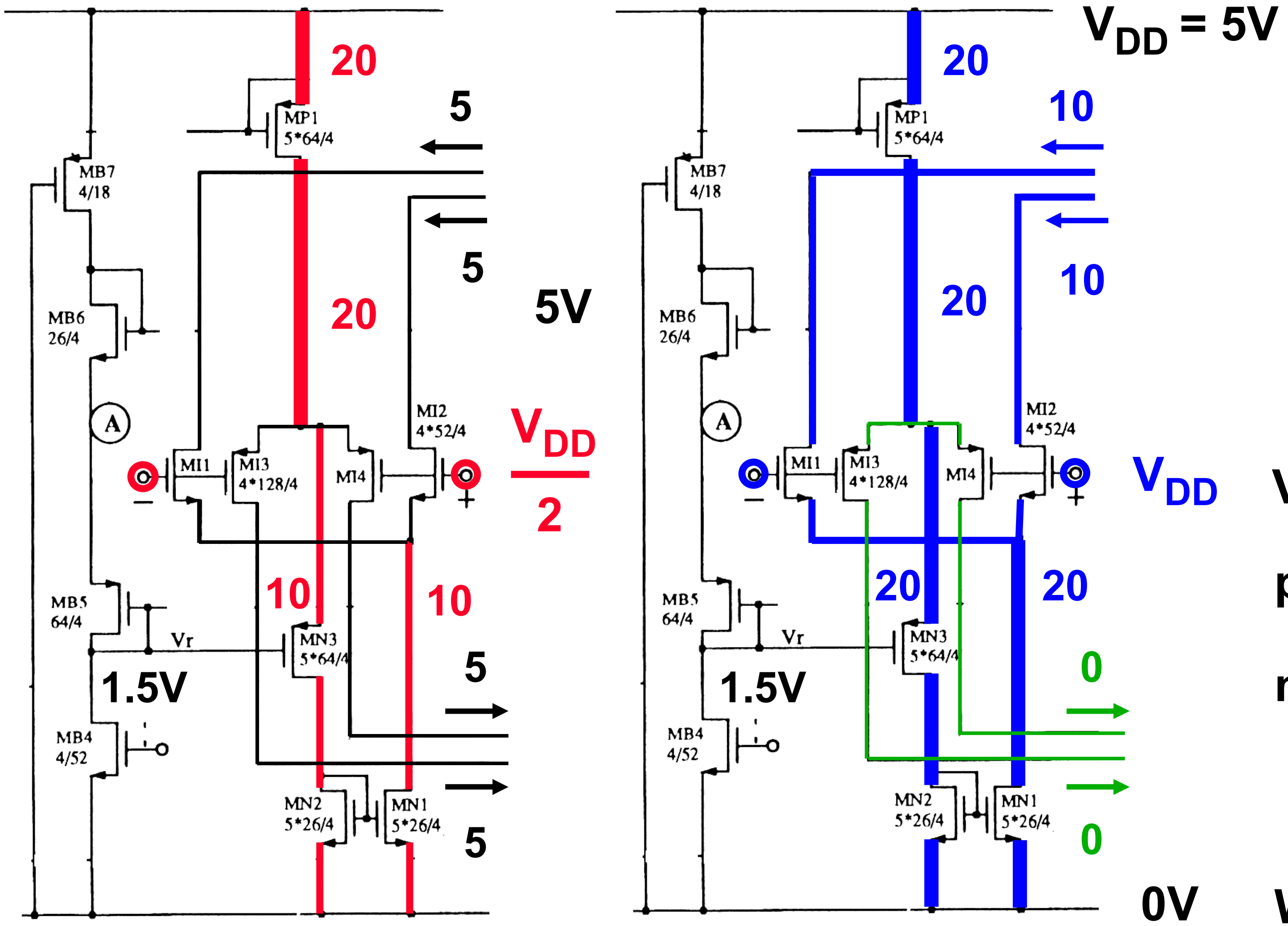


nMOST on : $V_{INCM} > 1.1$ V

pMOST on : $V_{INCM} < V_{DD} - 1.1$ V

Increase g_m: $g_{mn} + g_{mp} = ct$

Wu : input rail-to-rail stage



V_{+-} high :

pMOSTs off !

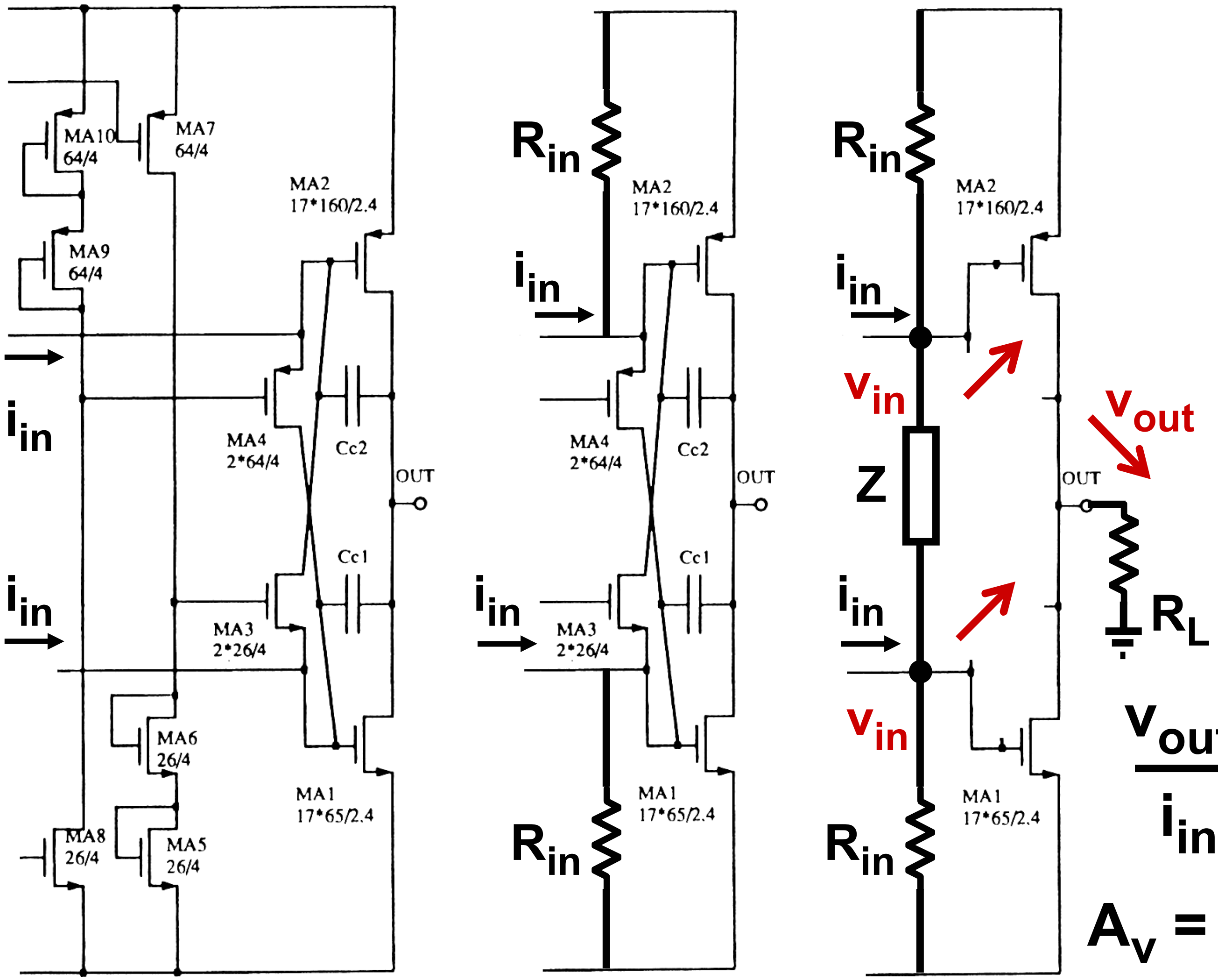
nMOSTs :

I_{DS1} x 2

g_{m1} x 2

Weak inv.

Wu : output stage : gain



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

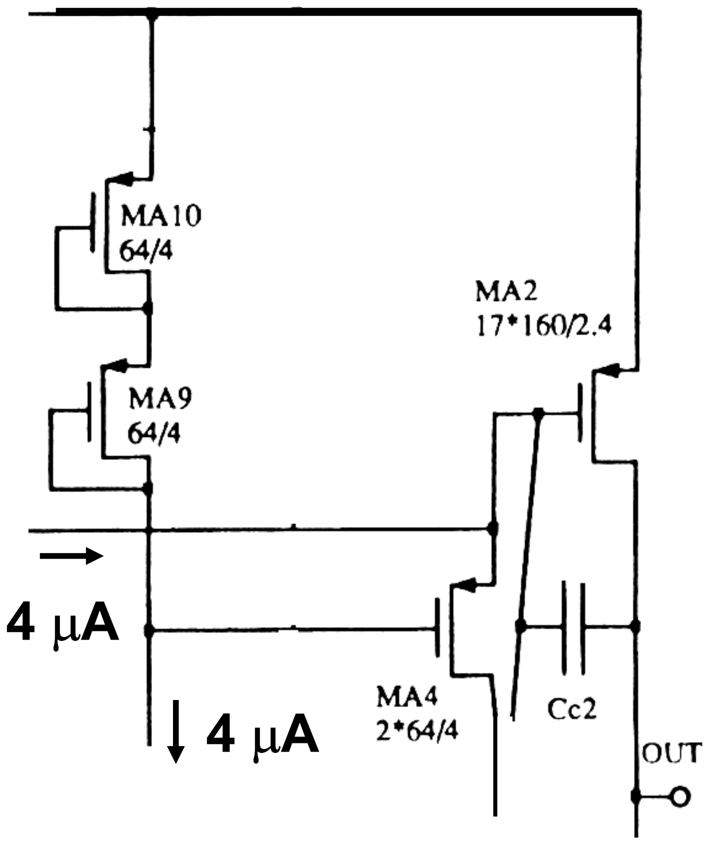
$$\frac{v_{in}}{i_{in}} = R_{in}$$

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

$$\frac{v_{out}}{i_{in}} = -\,2R_{in}g_{mA1}R_L$$

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

Wu : output quiescent current control



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

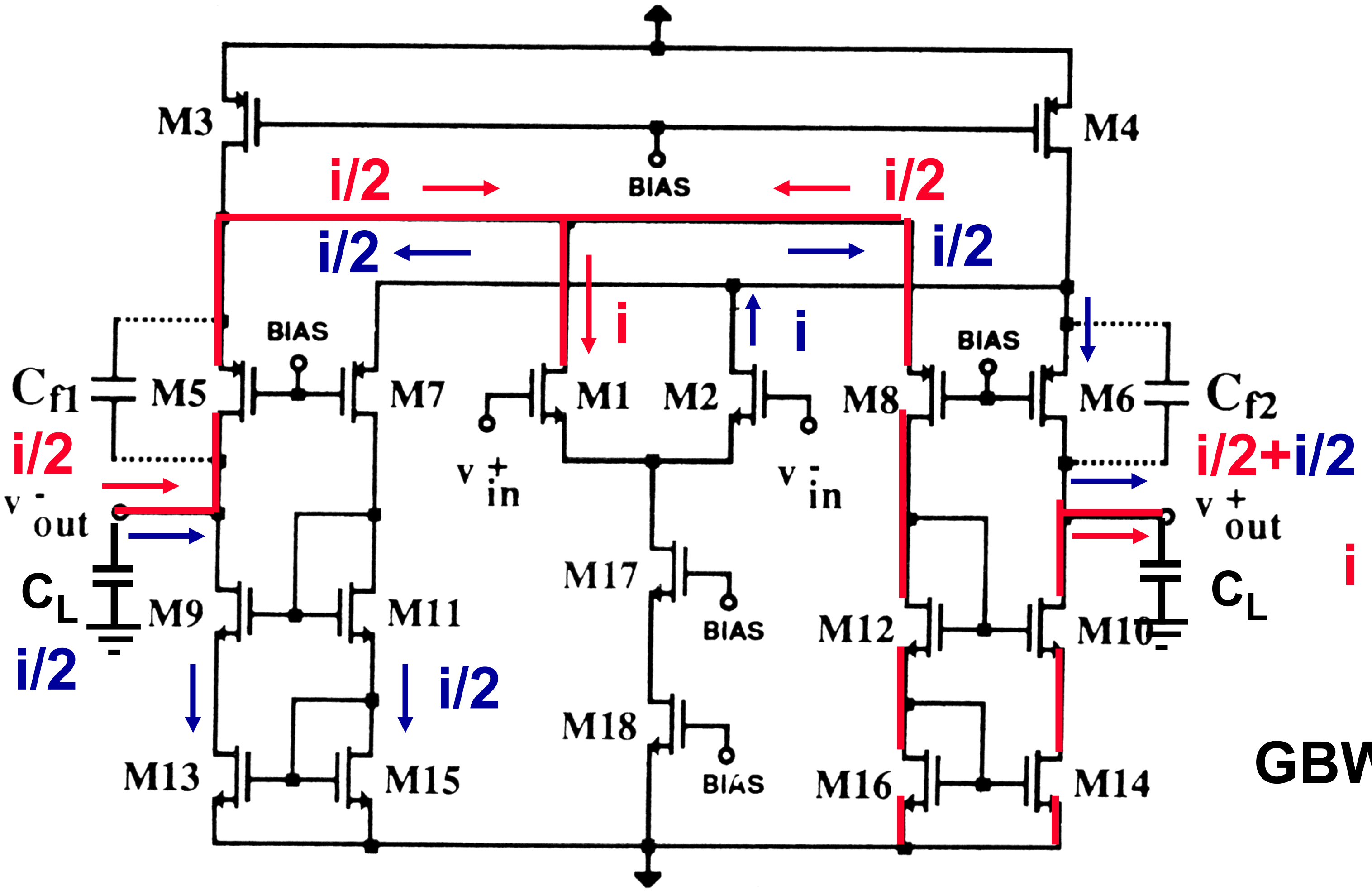
$$M_4 = 2\ M_{10} \quad \& \quad M_9 = M_{10}$$

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

$$\frac{I_{DS2}}{I_{DS9}} = \frac{W/L_2}{W/L_9}\left(2 - \frac{1}{\sqrt{2}}\right) \approx 91$$

$I_{DS2} \approx 364\ \mu A$ since $I_{DS9} \approx 4\ \mu A$

Enhanced full-differential folded-cascode

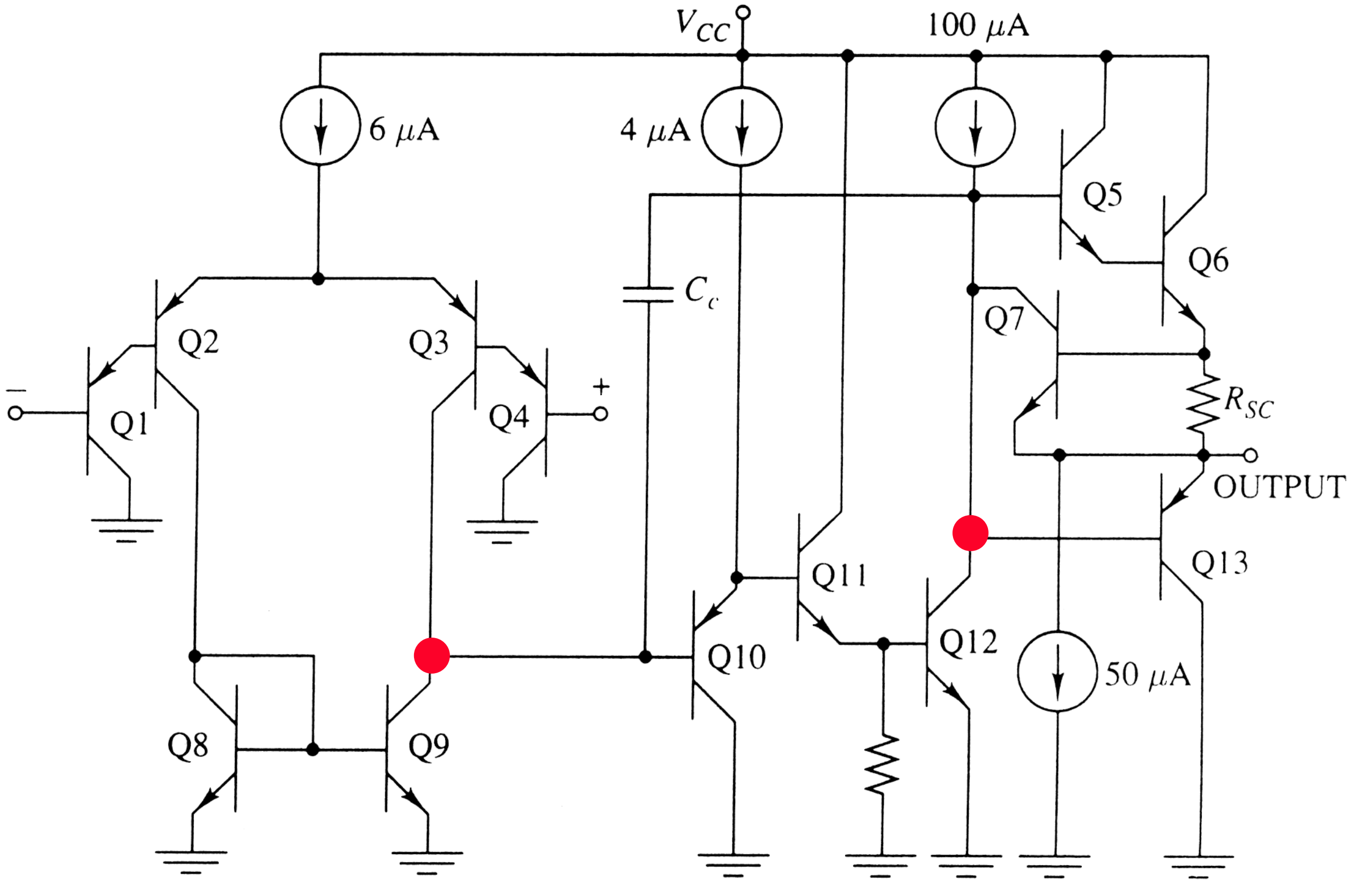


$$i = g_{m1} v_{in}$$

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

Ref.Nakamura, JSSC April 1992, pp.563-568

Bipolar opamp LM-124



GBW = 0.5 MHz

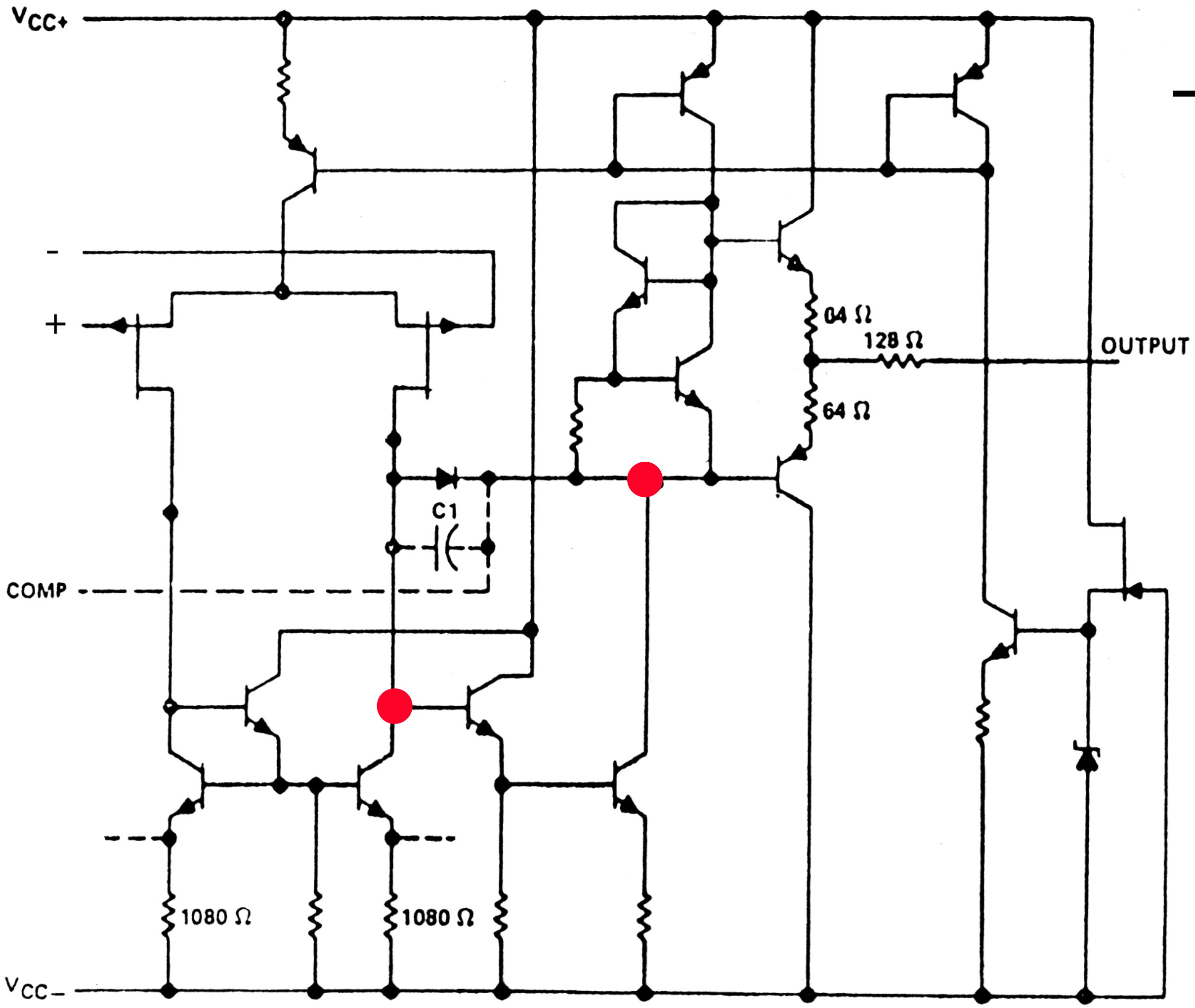
SR = 0.4 V/μs

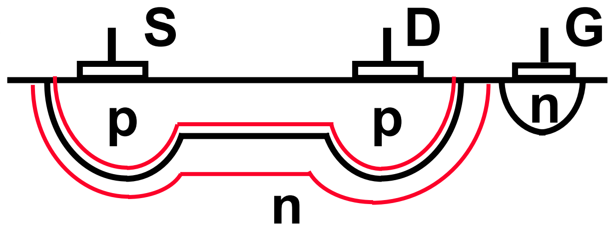
I_1 = 3 μA

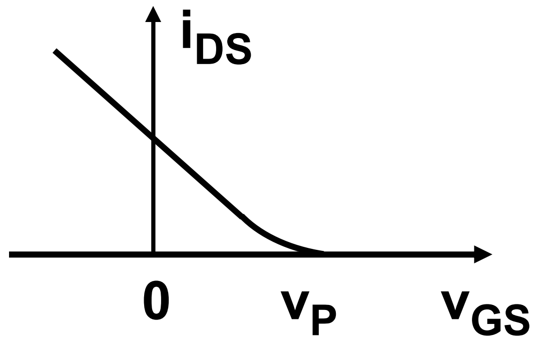
I_{TOT} = 650 μA

68 $nV_{RMS}/\sqrt{Hz}$

BiFET opamp TL-070







GBW = 3 MHz

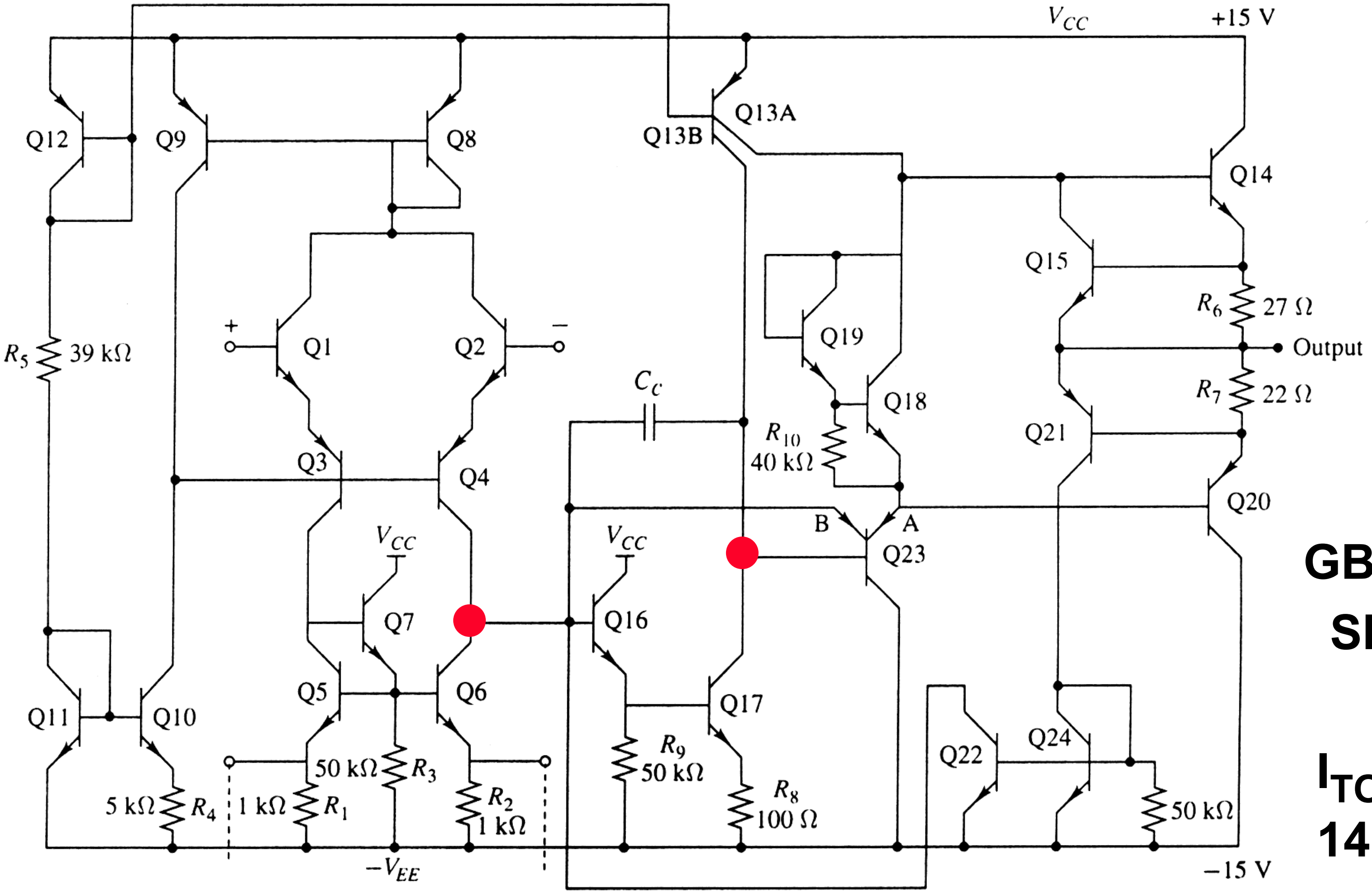
SR = 13 V/μs

I_1 = 100 μA

I_{TOT} = 1400 μA

18 $nV_{RMS}/\sqrt{Hz}$

Bipolar 2-stage opamp 741



GBW = 0.8 MHz

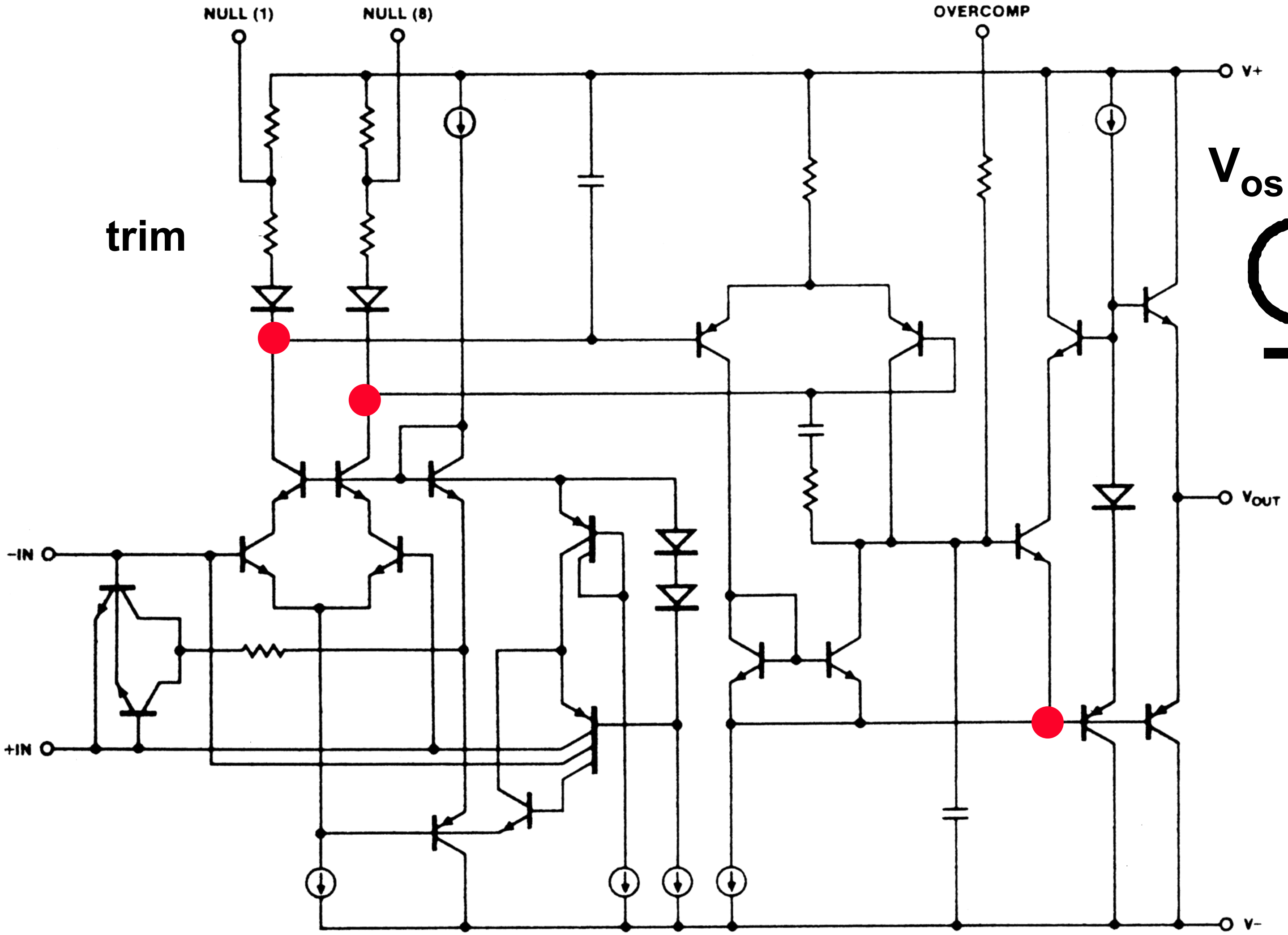
SR = 0.7 V/μs

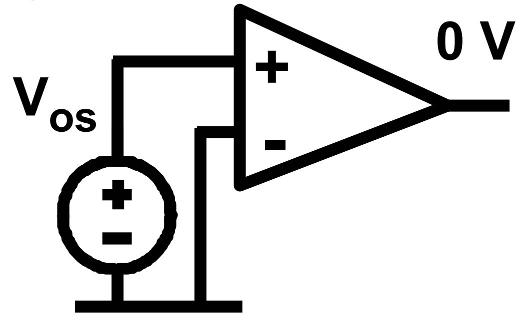
I_1 = 10 μA

I_{TOT} = 1100 μA

14 $nV_{RMS}/\sqrt{Hz}$

Two-stage opamp OP-97





GBW = 0.8 MHz

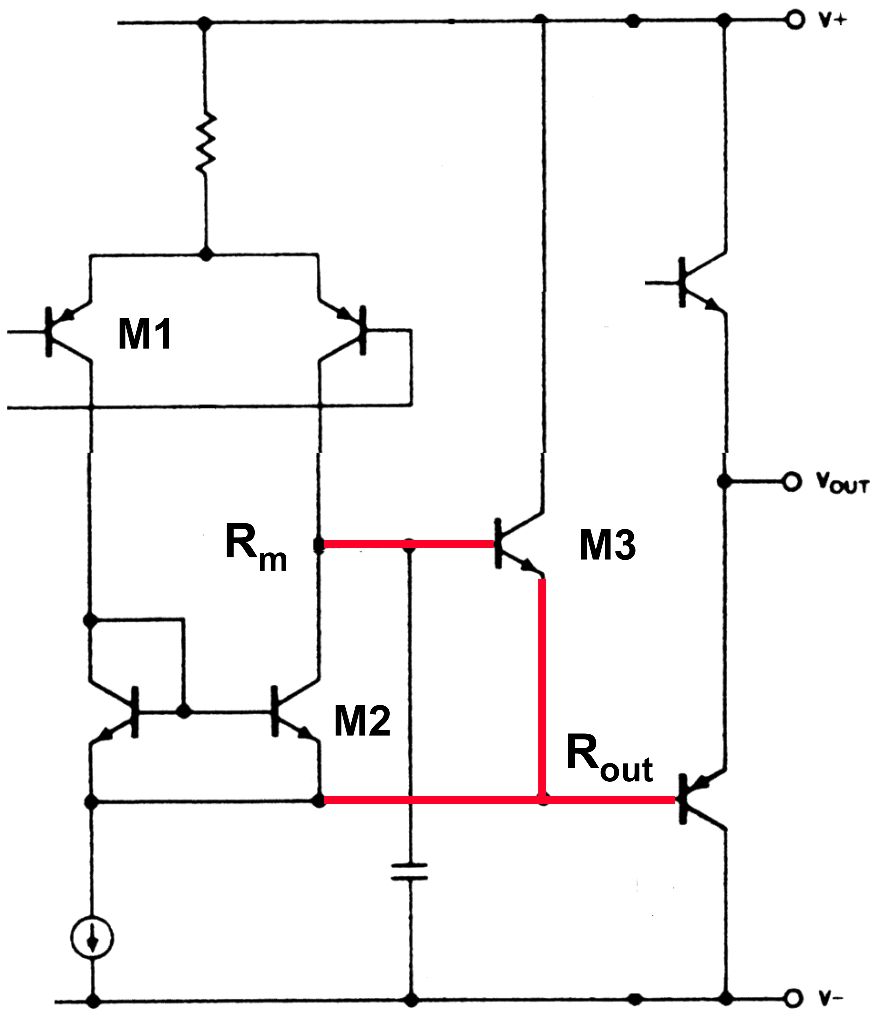
SR = 0.1 V/µs

I_{TOT} = 600 µA

25 µV offset

30 pA input

Bootstrap for high gain A_{v2}



R_m -> x β_3

R_{out} -> x $\frac{1}{\beta_3}$

$A_{v2} \approx g_{m1} r_{o2} \times \beta_3$

Same GBW !

Ref.De Man JSSC June 77, pp.217-222

Table of contents

- Simple CMOS OTA
- CMOS Miller OTA
- Symmetrical CMOS OTA
- Folded cascode OTA
- Other opamps