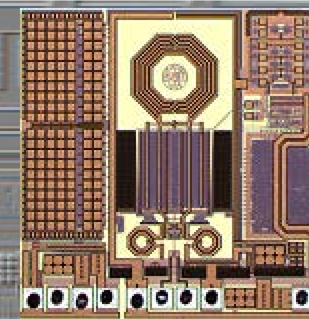

模拟集成电路设计原理

(Principle of Analog Integrated Circuit Design, INF0130025.02)

2014年11月20日

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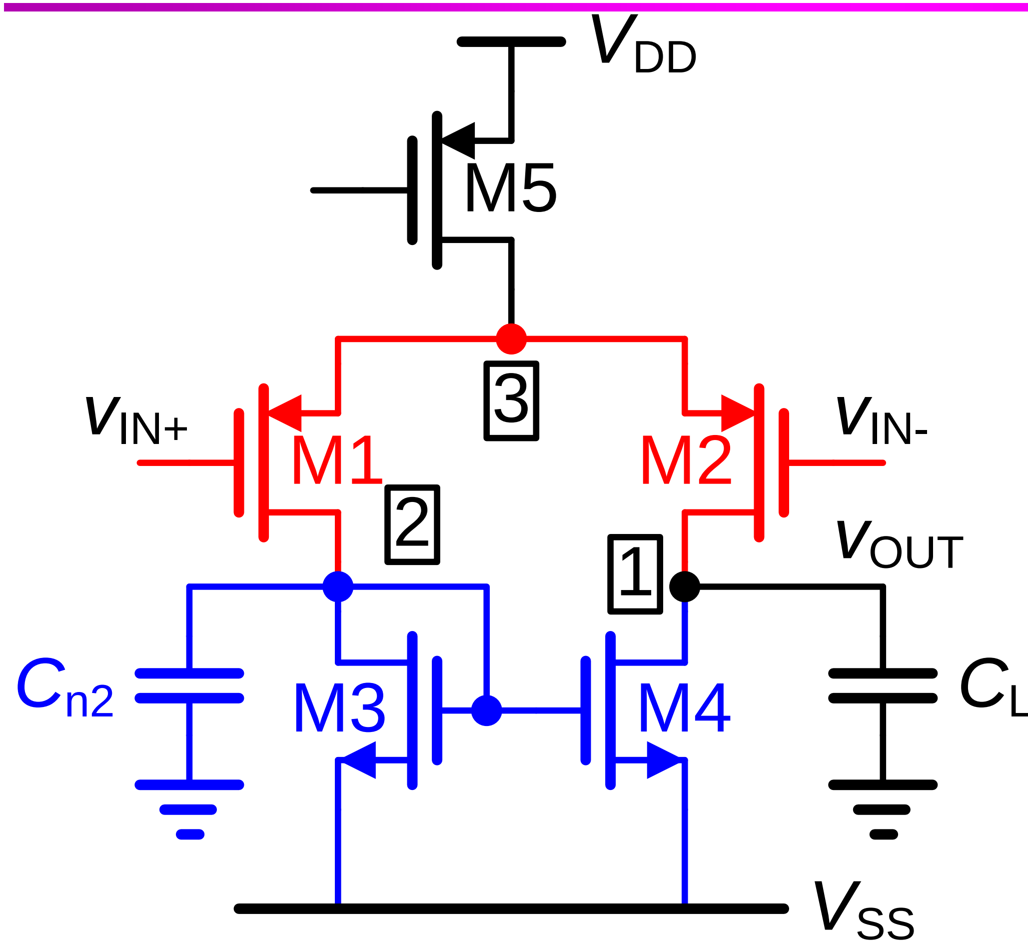
复旦大学/微电子学院/射频集成电路设计研究小组

运算放大器的重要结构

目 录

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

CMOS简单OTA



差分对

电流镜

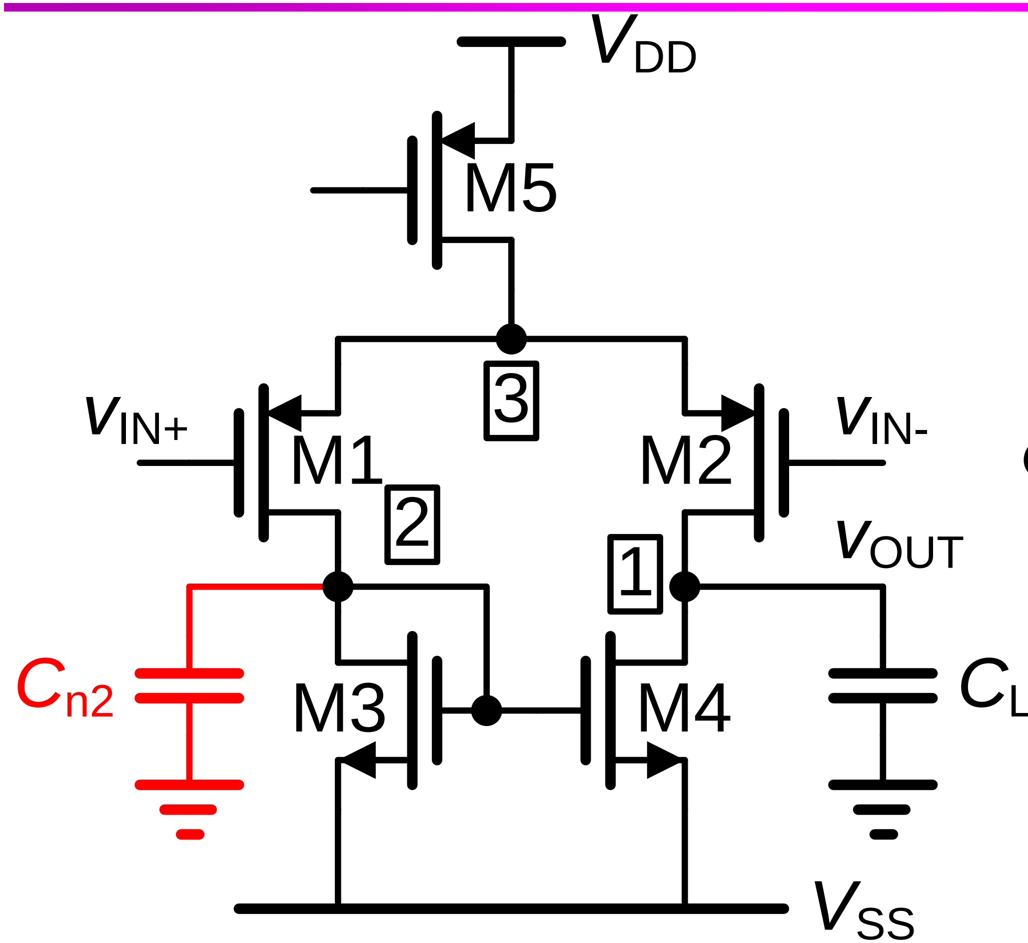
$$GBW = \frac{g_{m1}}{2\pi C_L}$$

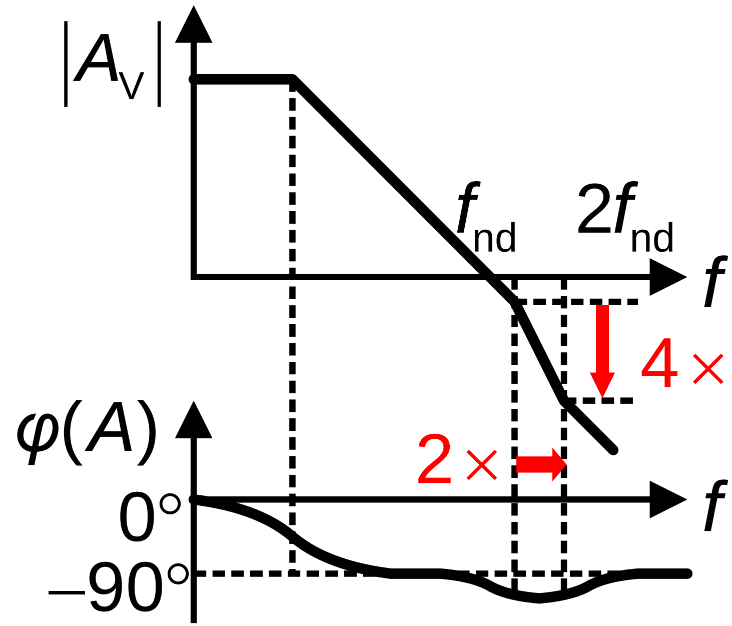
$$f_{nd} = \frac{g_{m3}}{2\pi C_{n2}}$$

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

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

CMOS简单OTA: f_{nd} & f_z

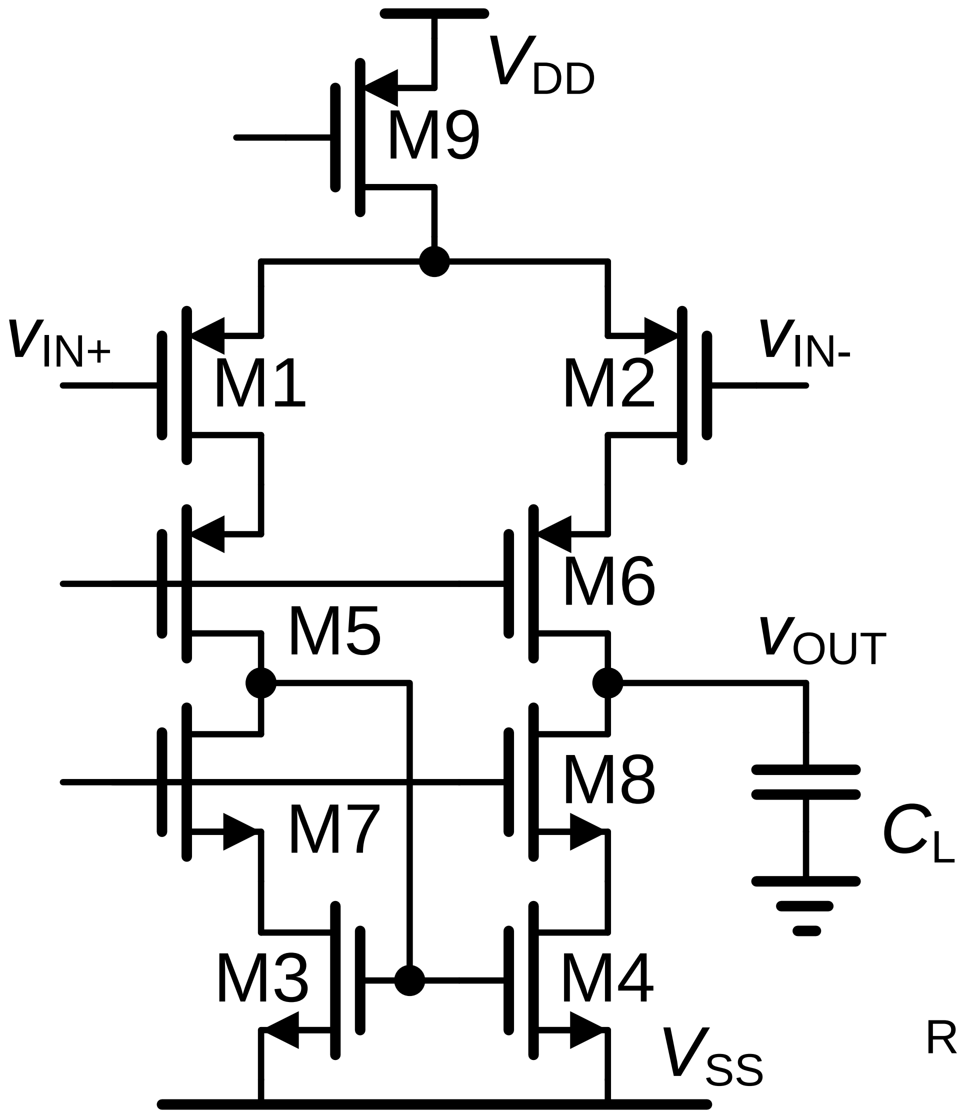




$$f_{nd} = \frac{g_{m3}}{2\pi C_{n2}}$$

$$PM = 90^\circ - \arctan\left(\frac{GBW}{f_{nd}}\right) + \arctan\left(\frac{GBW}{2f_{nd}}\right) \approx 85^\circ$$

CMOS套筒OTA

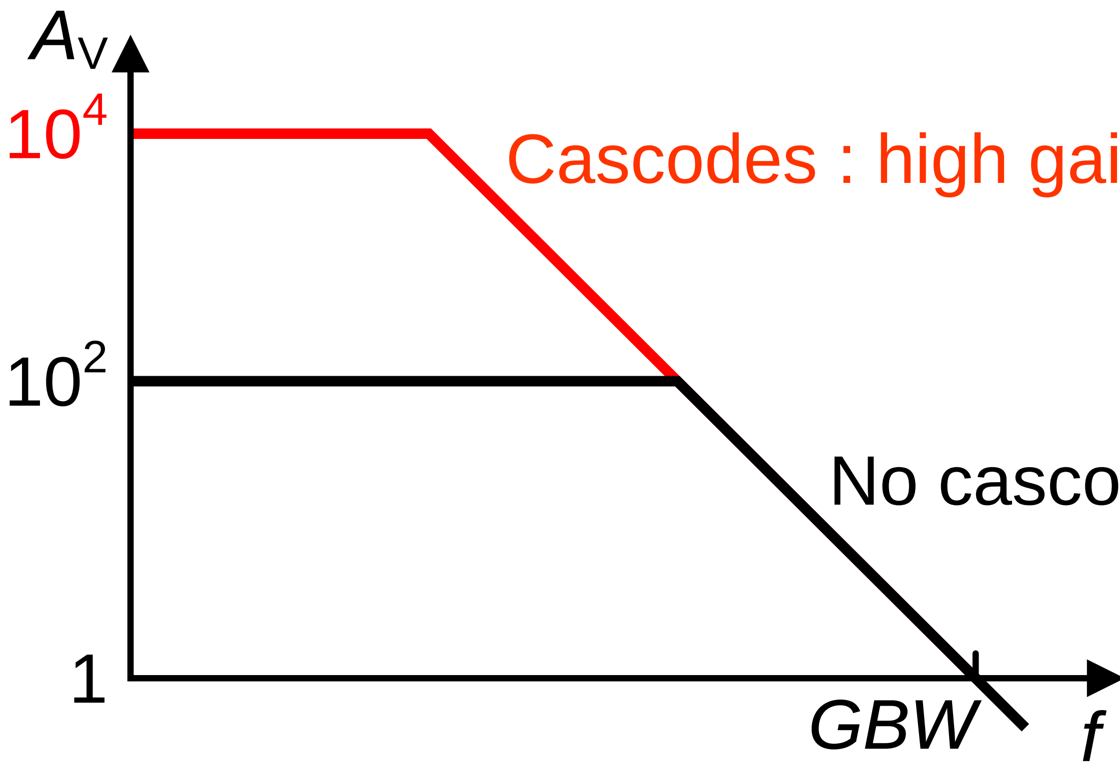


频率较低时
更大增益

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

Ref.: Gulati, JSSC Dec.98, 2010-2019

低频时共源共栅结构提升增益



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

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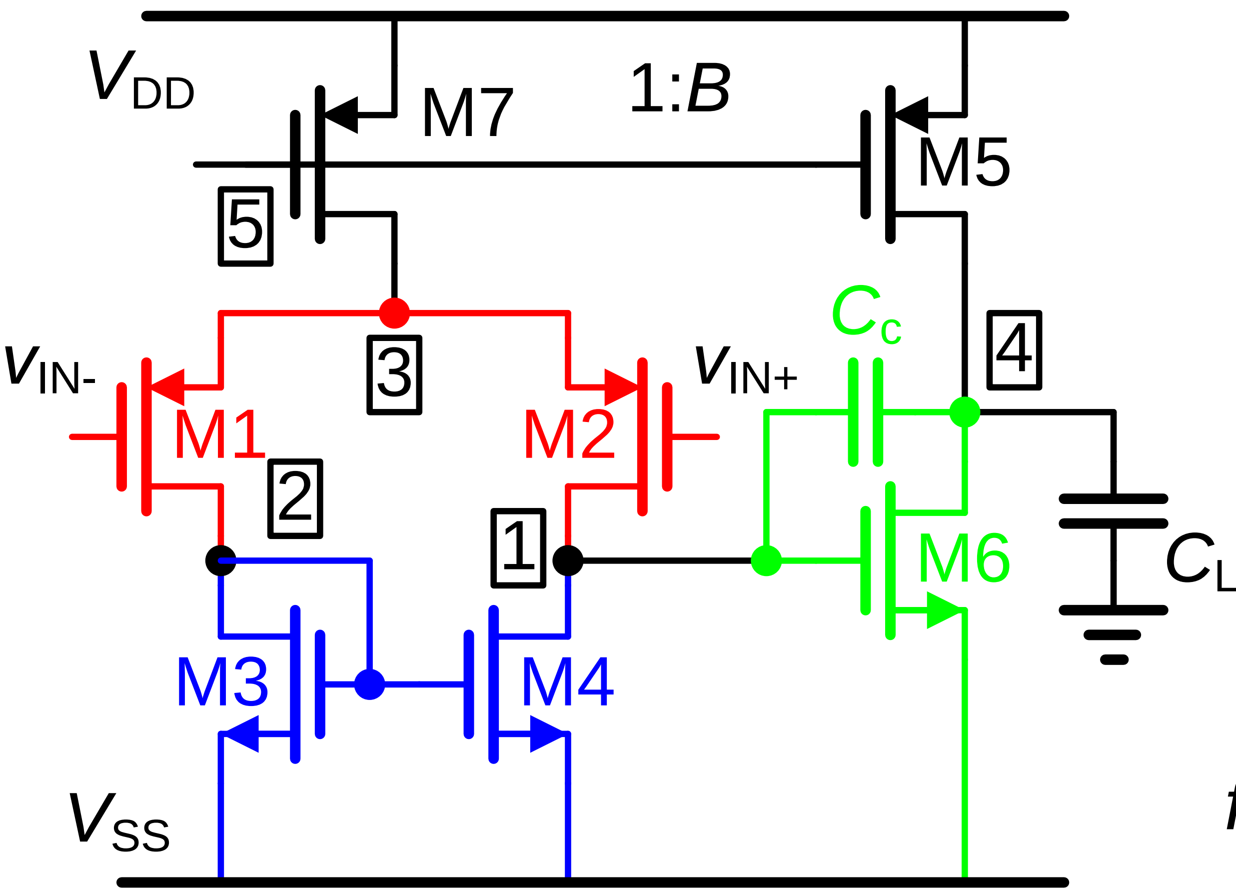
CMOS密勒OTA

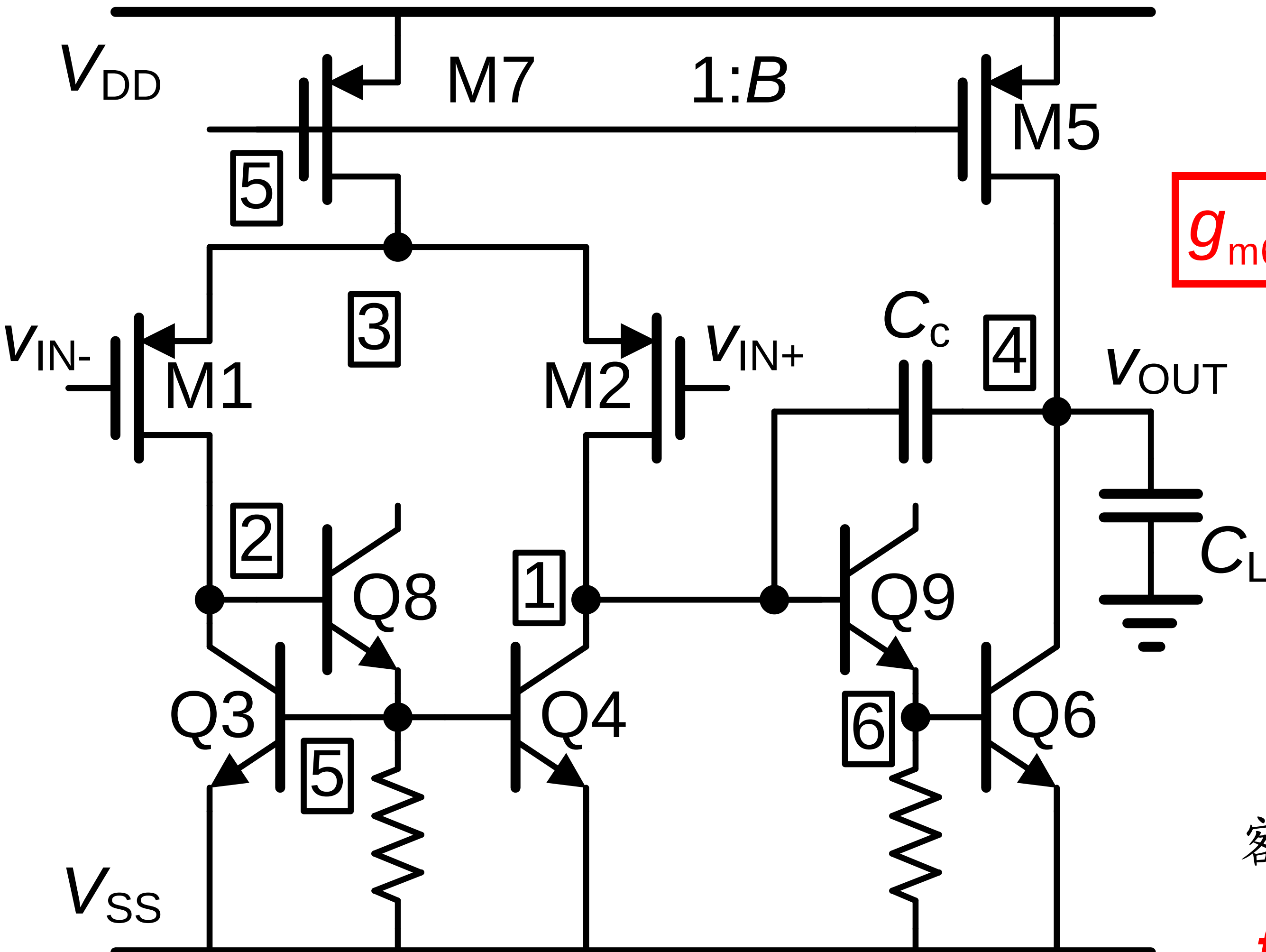


差分对
电流镜
第二级

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

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

BiCMOS密勒OTA



$g_{m6NPN} > g_{m6NMOS}$

节点1:
高阻抗

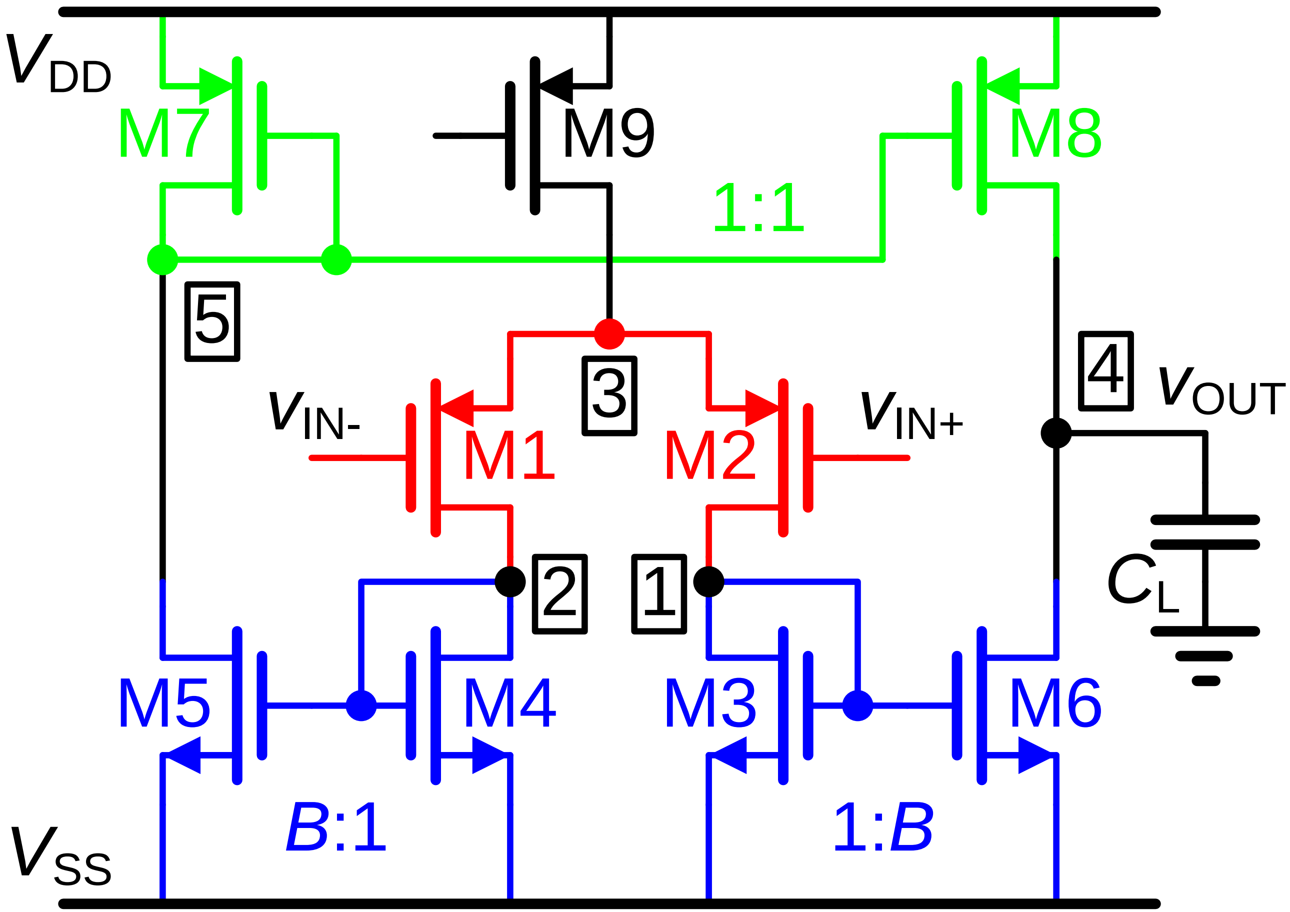
额外节点5、6

f_{nd}?

目录

- CMOS简单OTA
- CMOS密勒OTA
- CMOS对称OTA
- CMOS折叠共源共栅OTA
- 其他运放

CMOS对称OTA



差分对

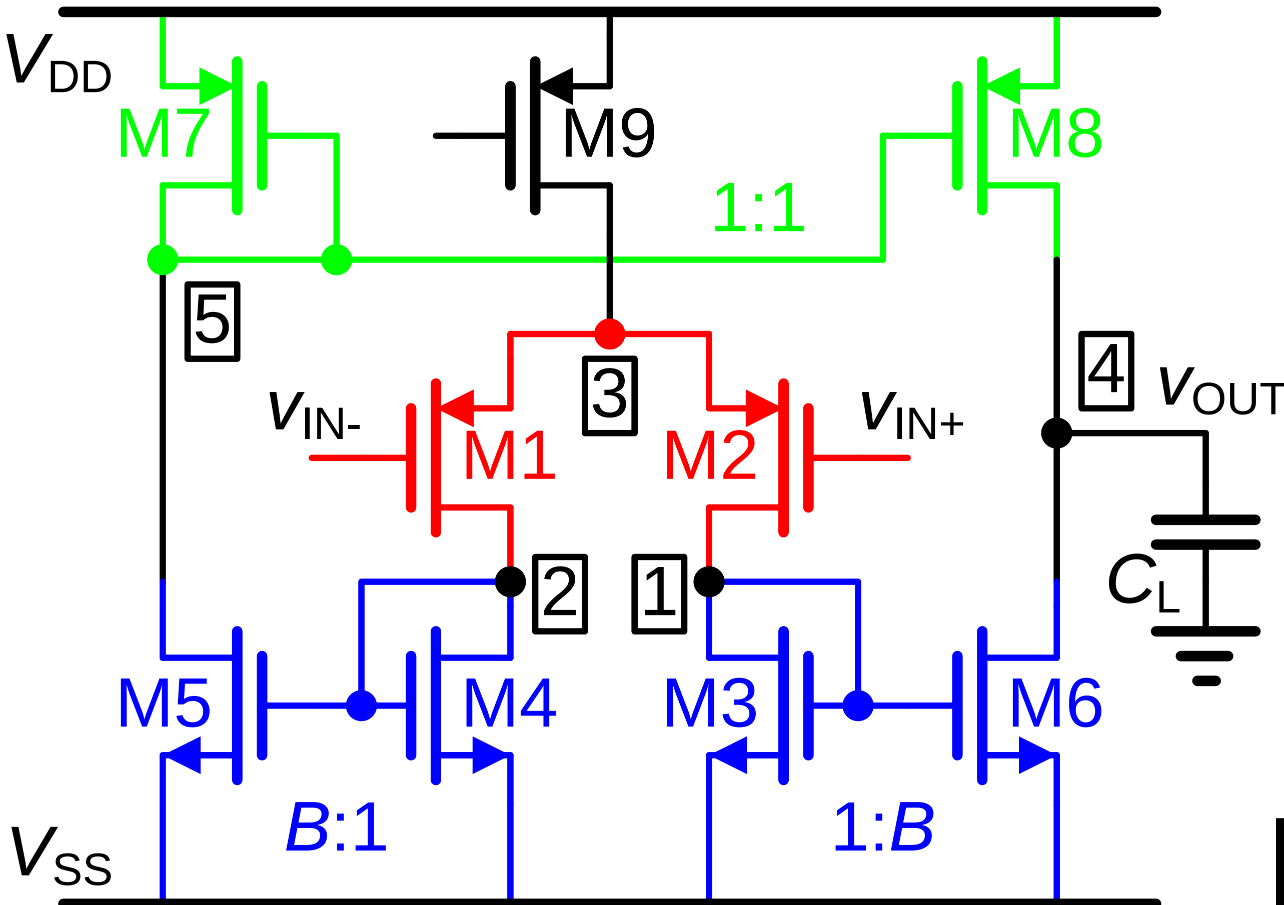
3个电流镜

对称:

节点1=节点2

轨到轨输出摆幅

CMOS对称OTA：*GBW*



$$A_V = g_{m1} B R_{n4} = \frac{2V_{En}L_6}{V_{GS1} - V_T}$$

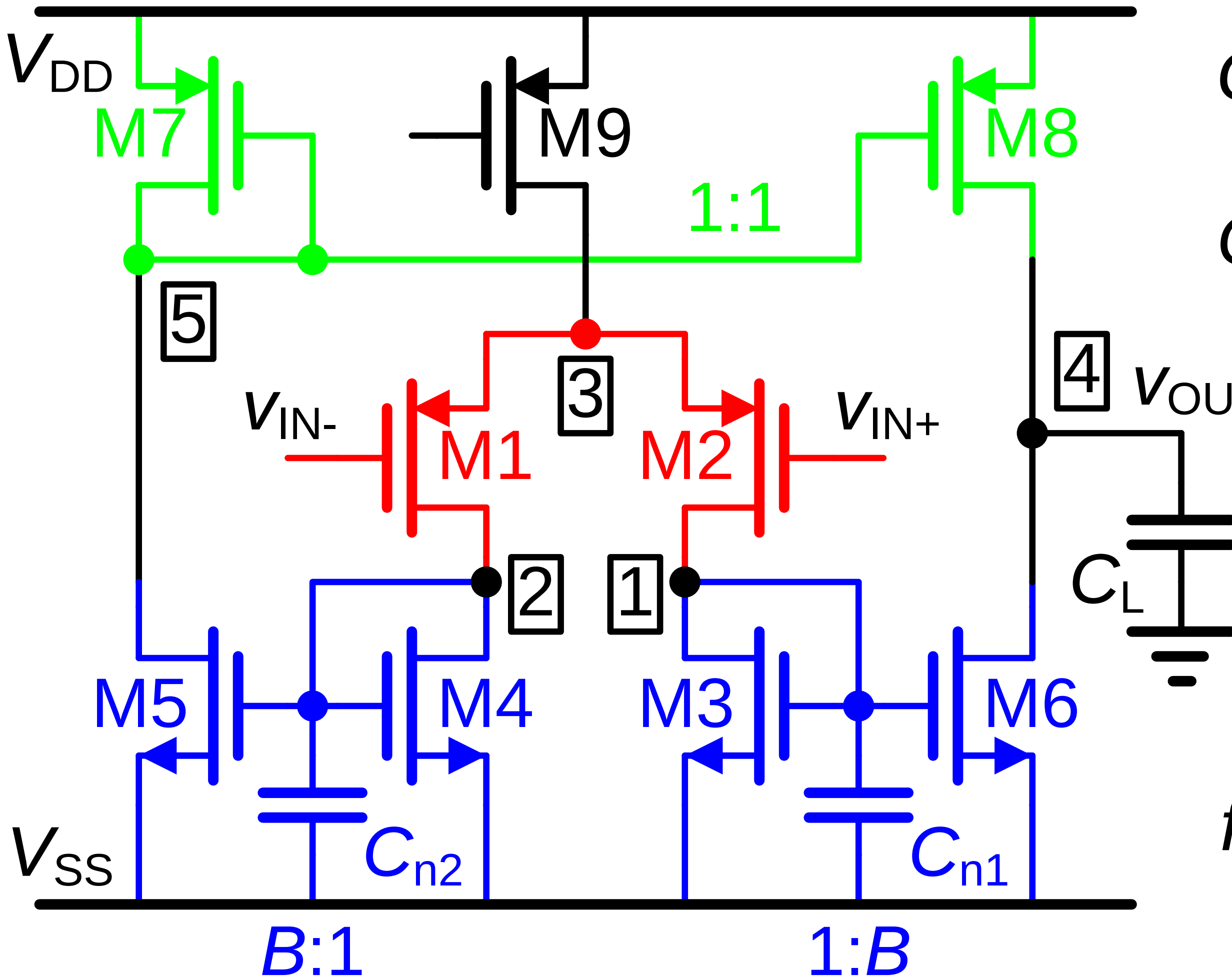
如果$L_8 > L_6$

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

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

B ？

CMOS对称OTA：$f_{nd1,2}$

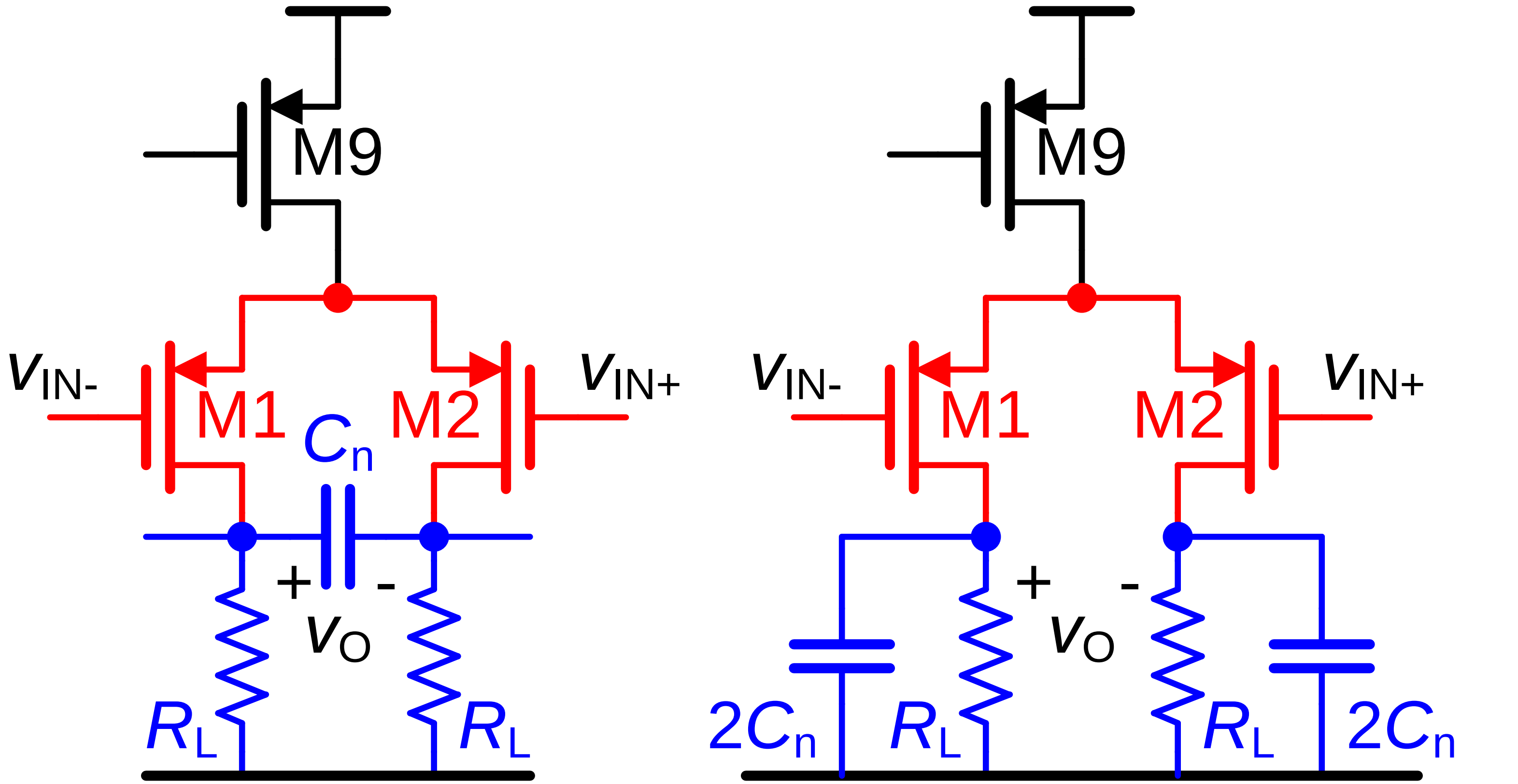


$$GBW = B\frac{g_{m1}}{2\pi C_L}$$

$$C_{n1} = (1+B)C_{GS4} + C_{DB4} + C_{DB1} \approx (3+B)C_{GS4}$$

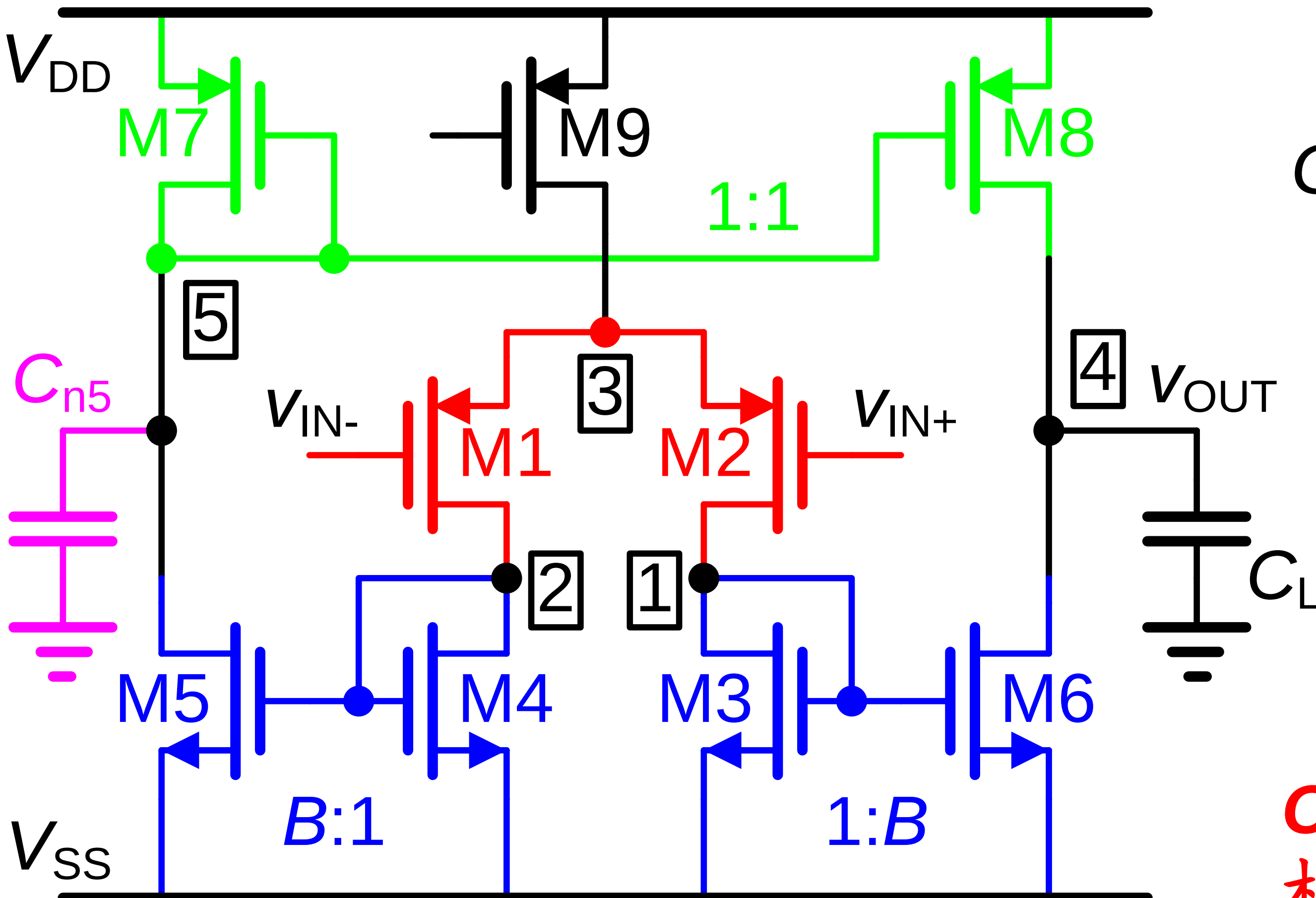
$$f_{nd} = \frac{g_{m4}}{2\pi C_{n1}} \approx \frac{f_{T4}}{3+B}$$

差分对输出端的极点



一个单极点：$f_p = \dfrac{1}{2\pi 2R_L C_n}$

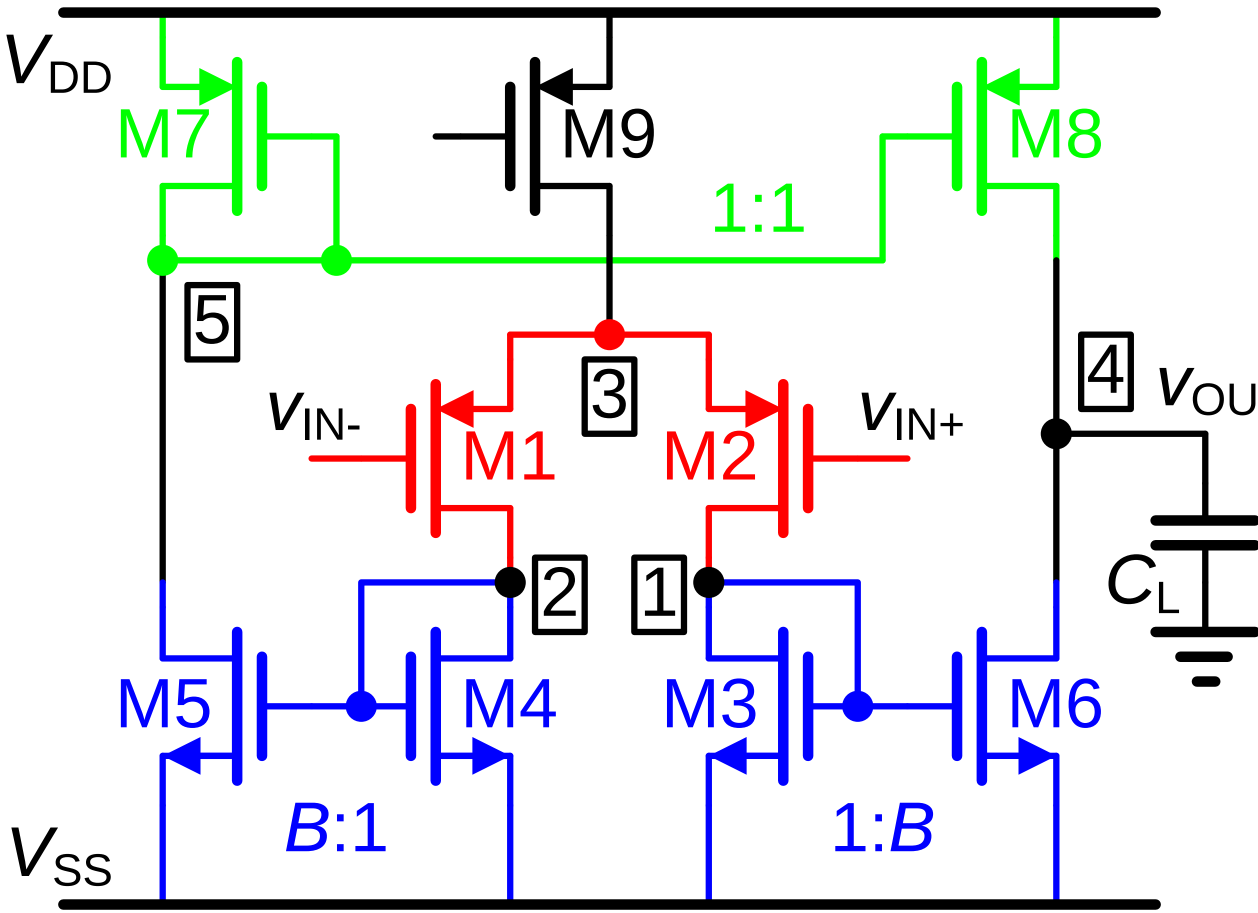
CMOS对称OTA：f_{nd5}



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

C_{n5}产生零极点对，相位恶化 3…6°

CMOS对称OTA：设计实例



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

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

$C_L = 2\ \text{pF}$

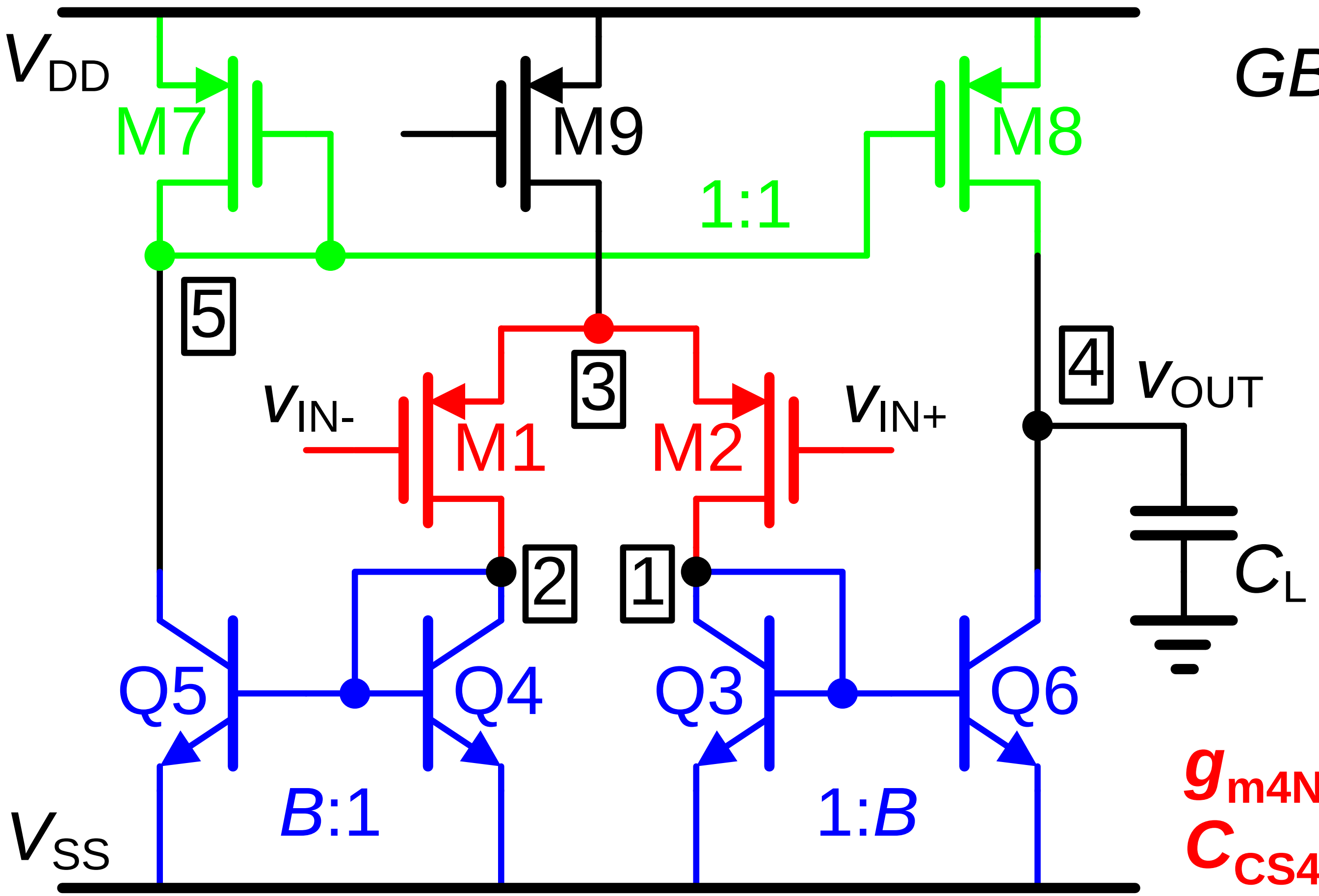
$GBW = 200\ \text{MHz}$

$V_{GS} - V_T = 0.5\ \text{V}$

$L = 1\ \mu\text{m}$

$f_{T4} = 5\ \text{GHz}$ $f_{nd} = 0.6\ \text{GHz}$ $B \approx 5$

BiCMOS对称OTA



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

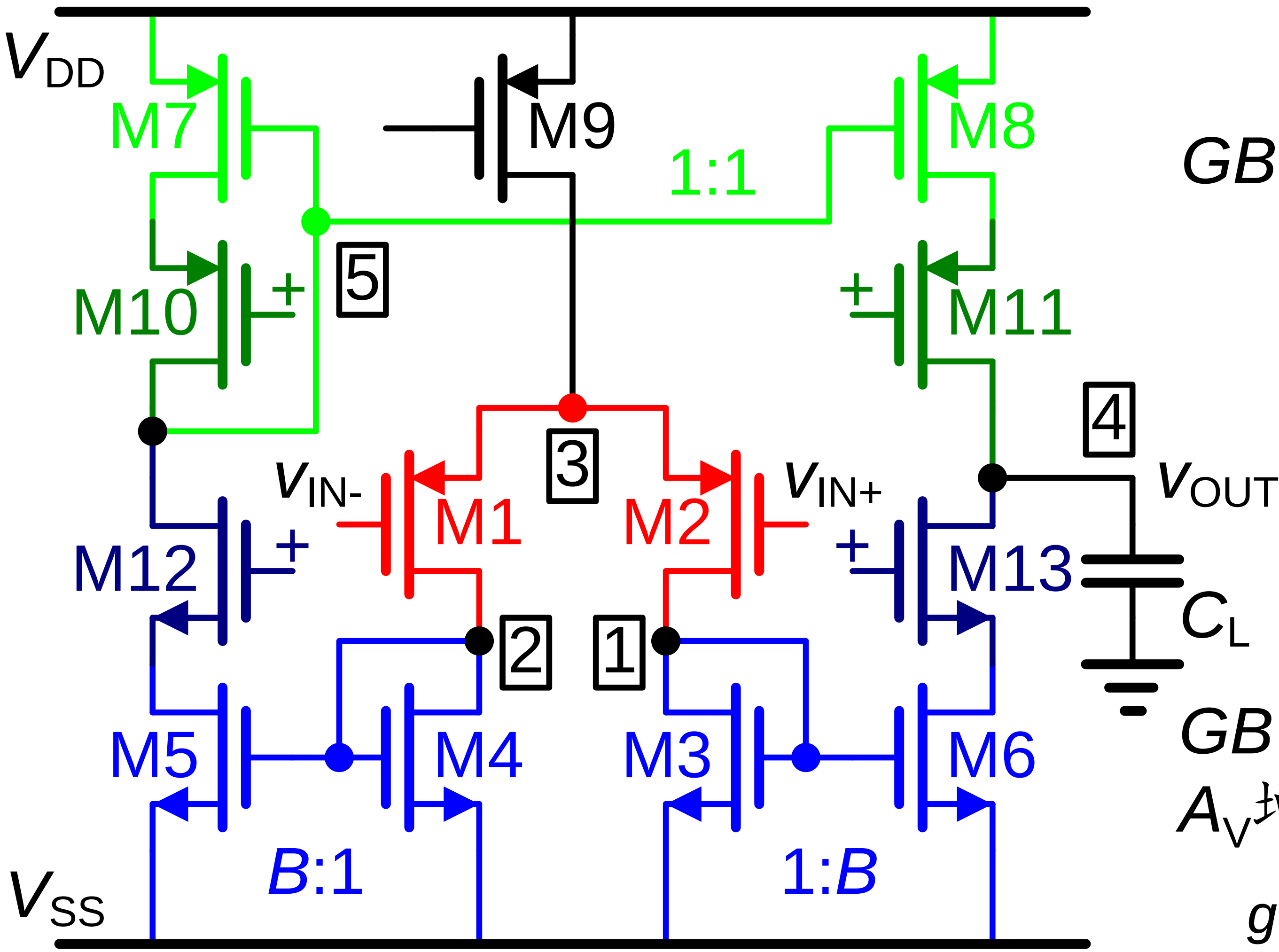
$$f_{nd} \approx \frac{f_{T4}}{3+B}$$

$g_{m4NPN} > g_{m4NMOS}$

$C_{CS4NPN} > C_{DB4NMOS}$

BiCMOS>CMOS？

接共源共栅的CMOS对称OTA

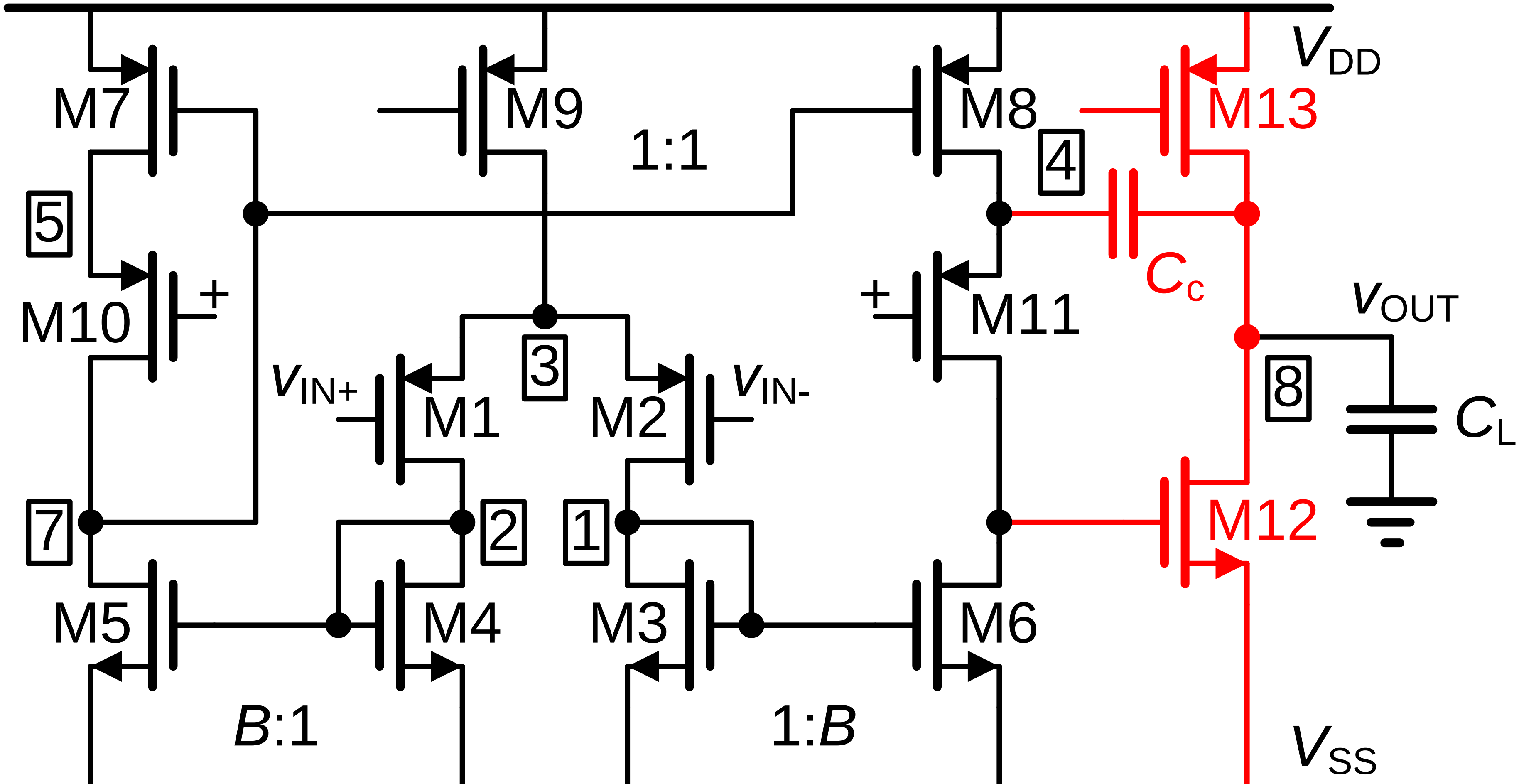


$$GBW = B\frac{g_{m1}}{2\pi C_L}$$

*GBW*相同，但是 A_V增加100倍!!!

$$g_m r_{DS} \approx 100$$

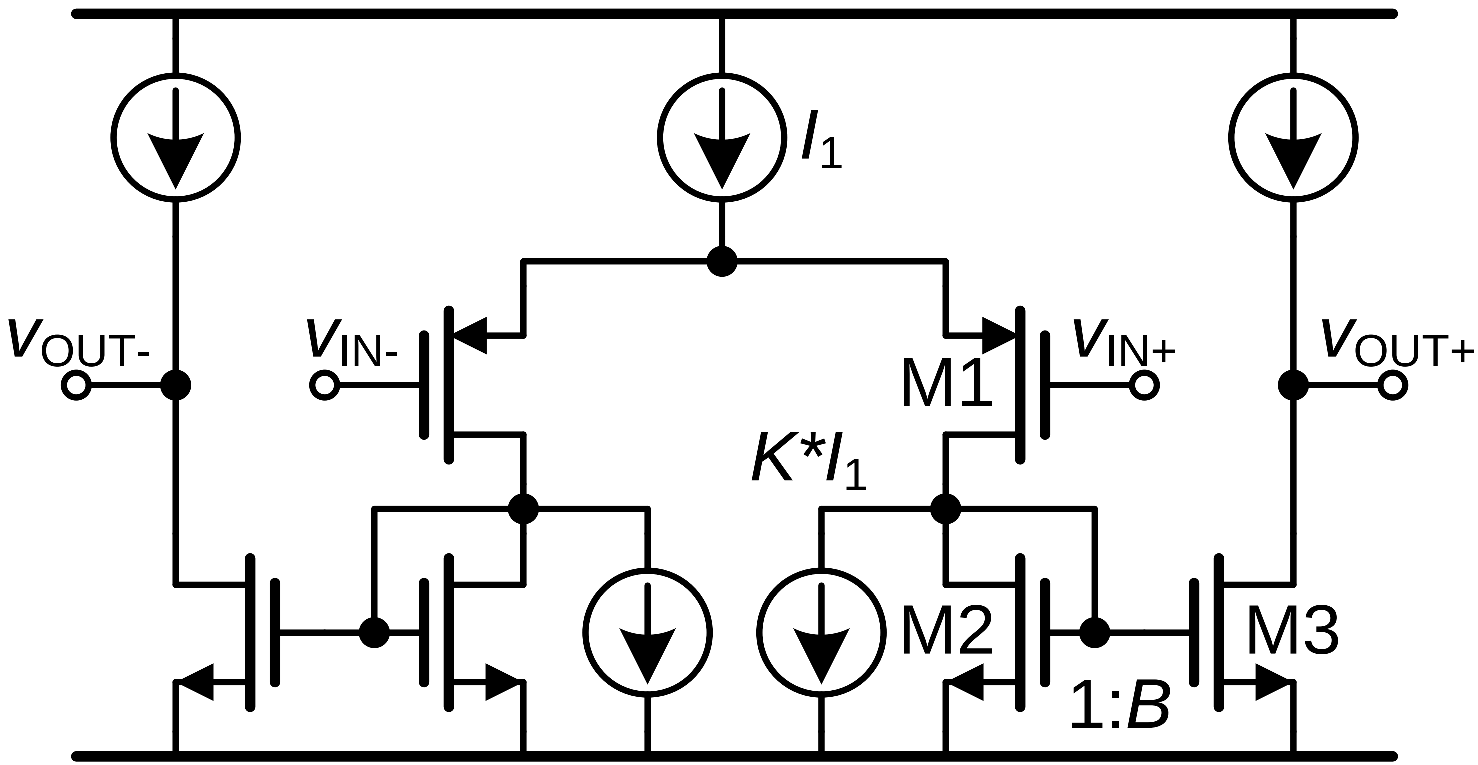
CMOS对称密勒OTA



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

没有零点！

抽取电流技术提高增益



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

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

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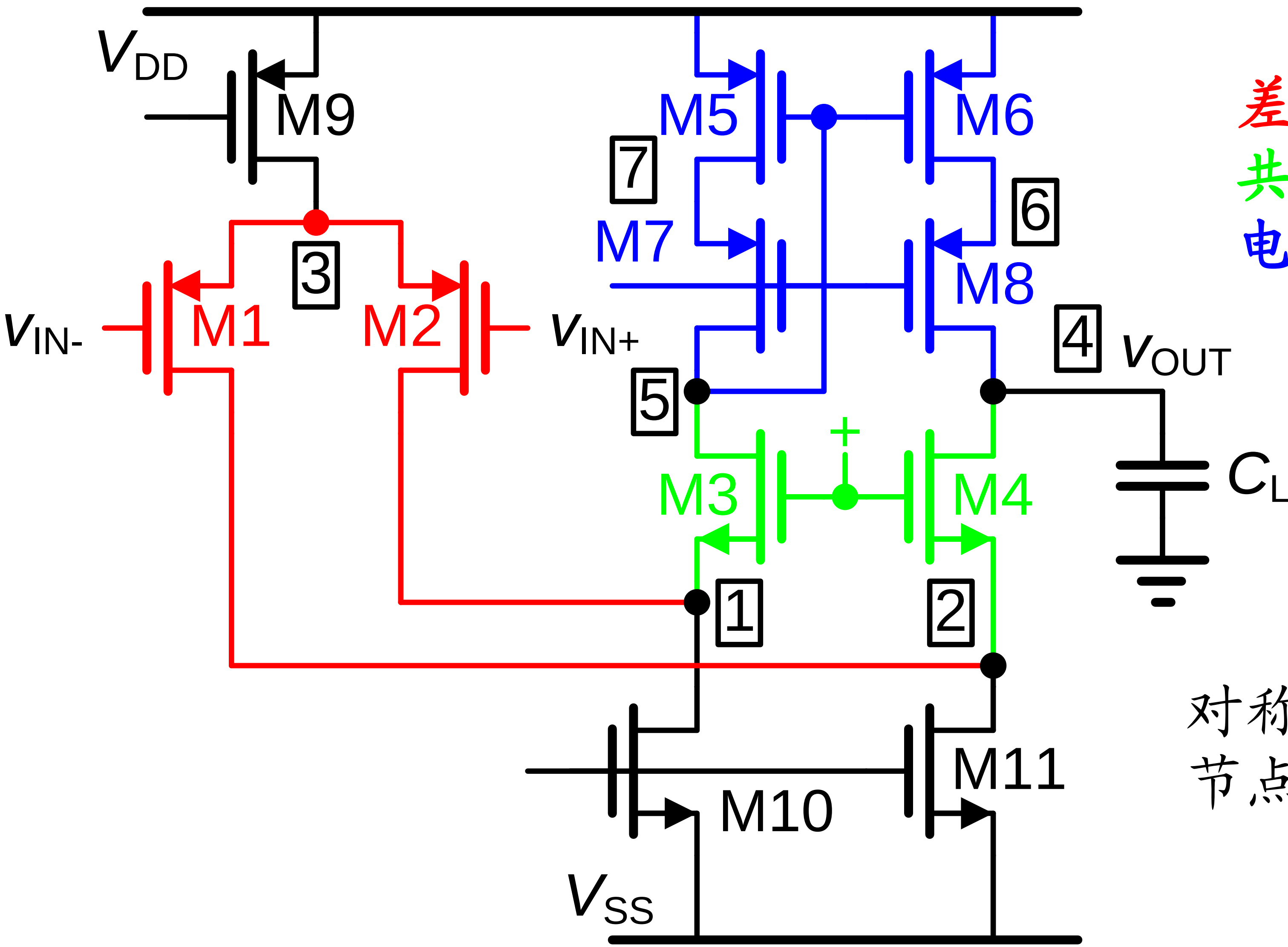
CMOS折叠共源共栅OTA



差分对

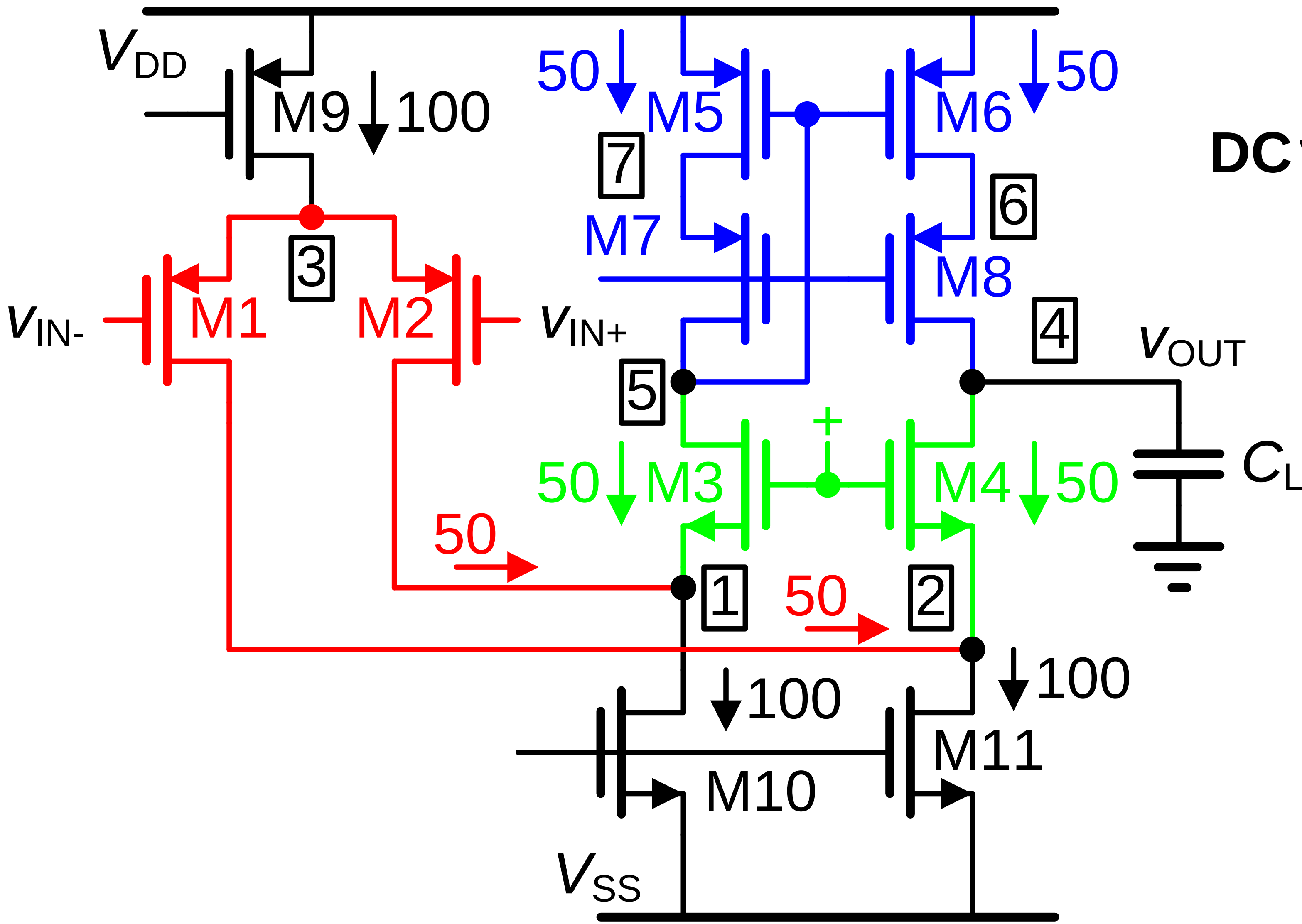
共源共栅对

电流镜

对称性：

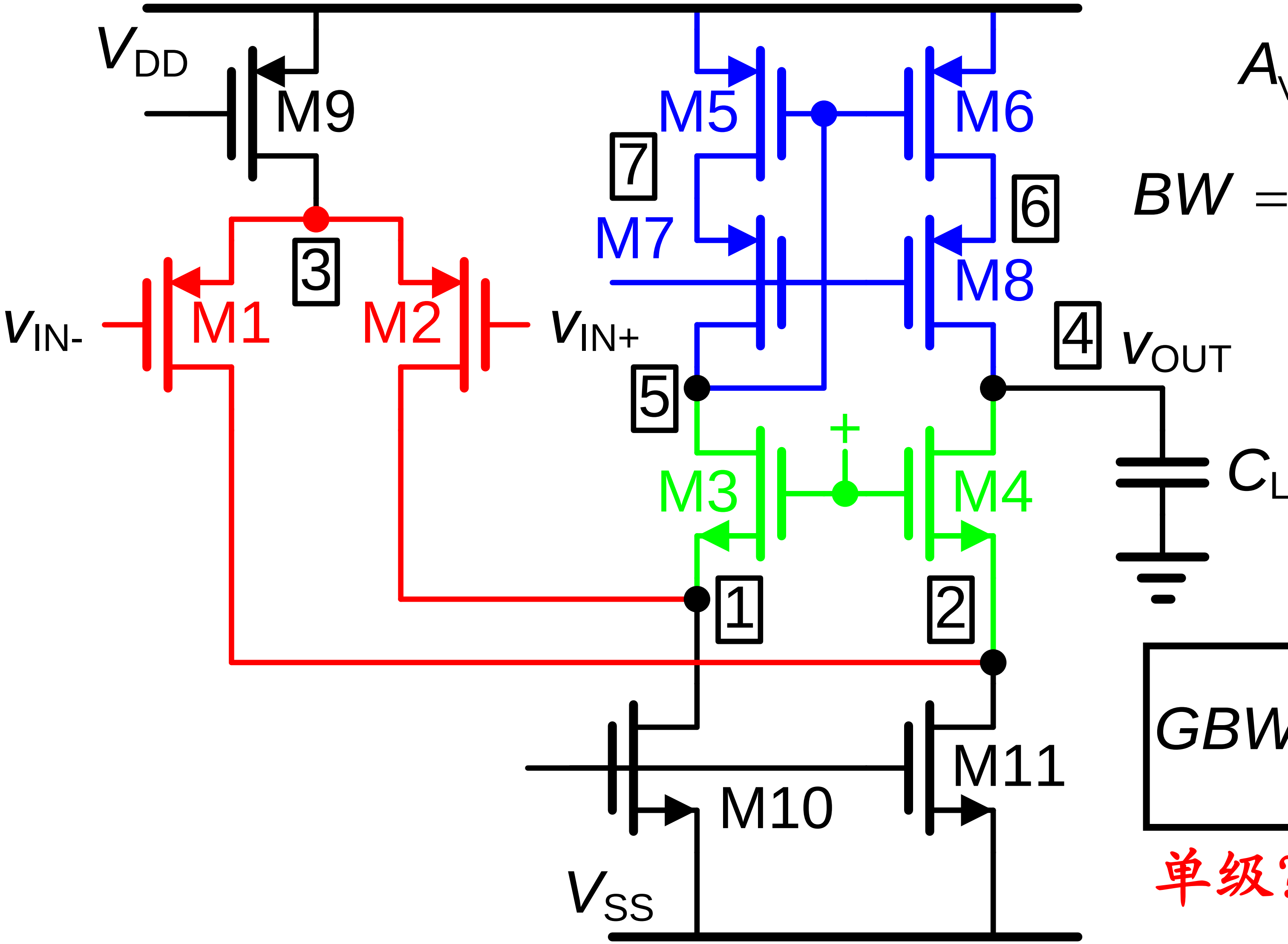
节点1=节点2

CMOS折叠共源共栅OTA：DC



DC电流

CMOS折叠共源共栅OTA：AC



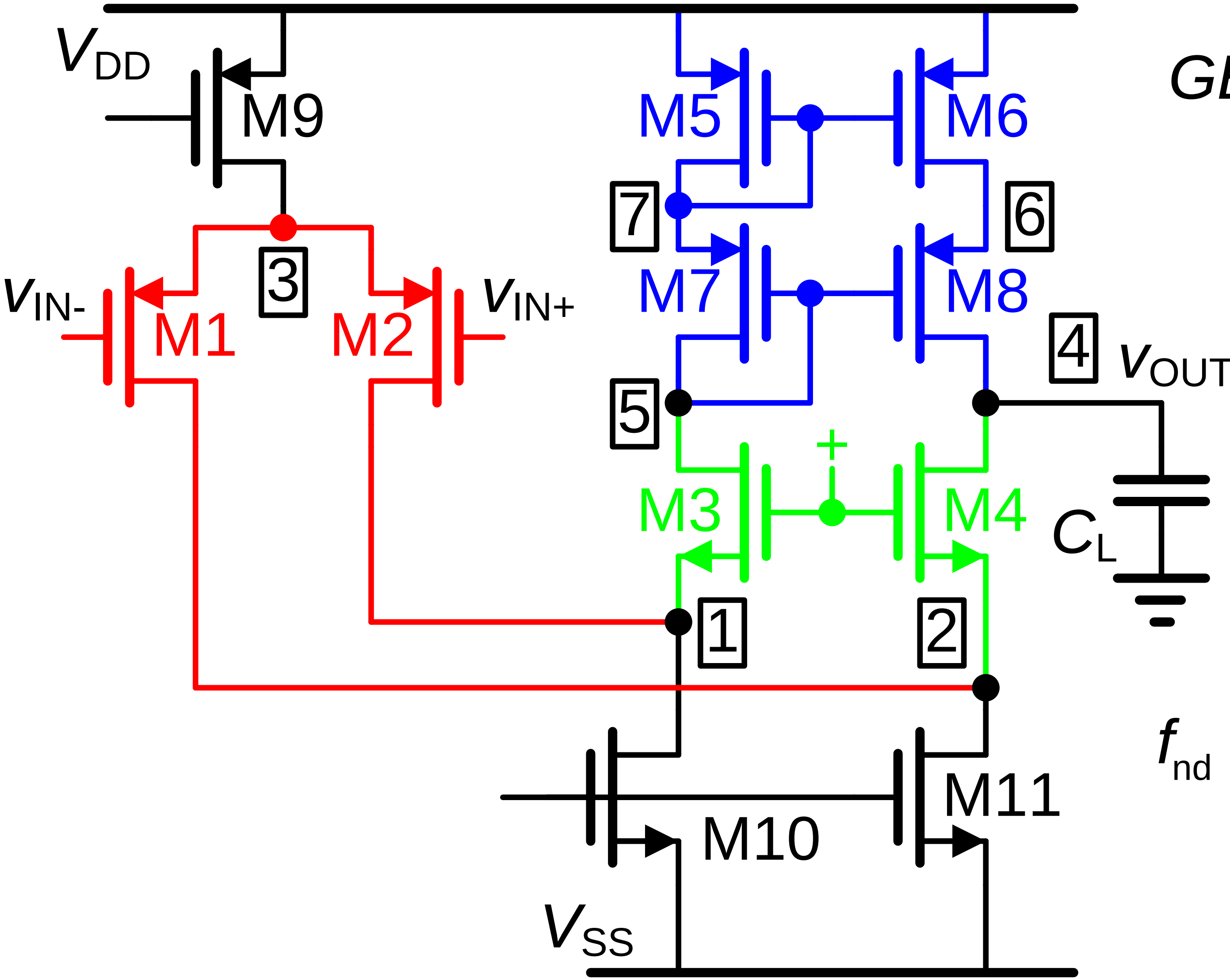
$$A_V = g_{m1} R_{n4}$$

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

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

单级？单极点？

CMOS折叠共源共栅OTA: f_{nd}

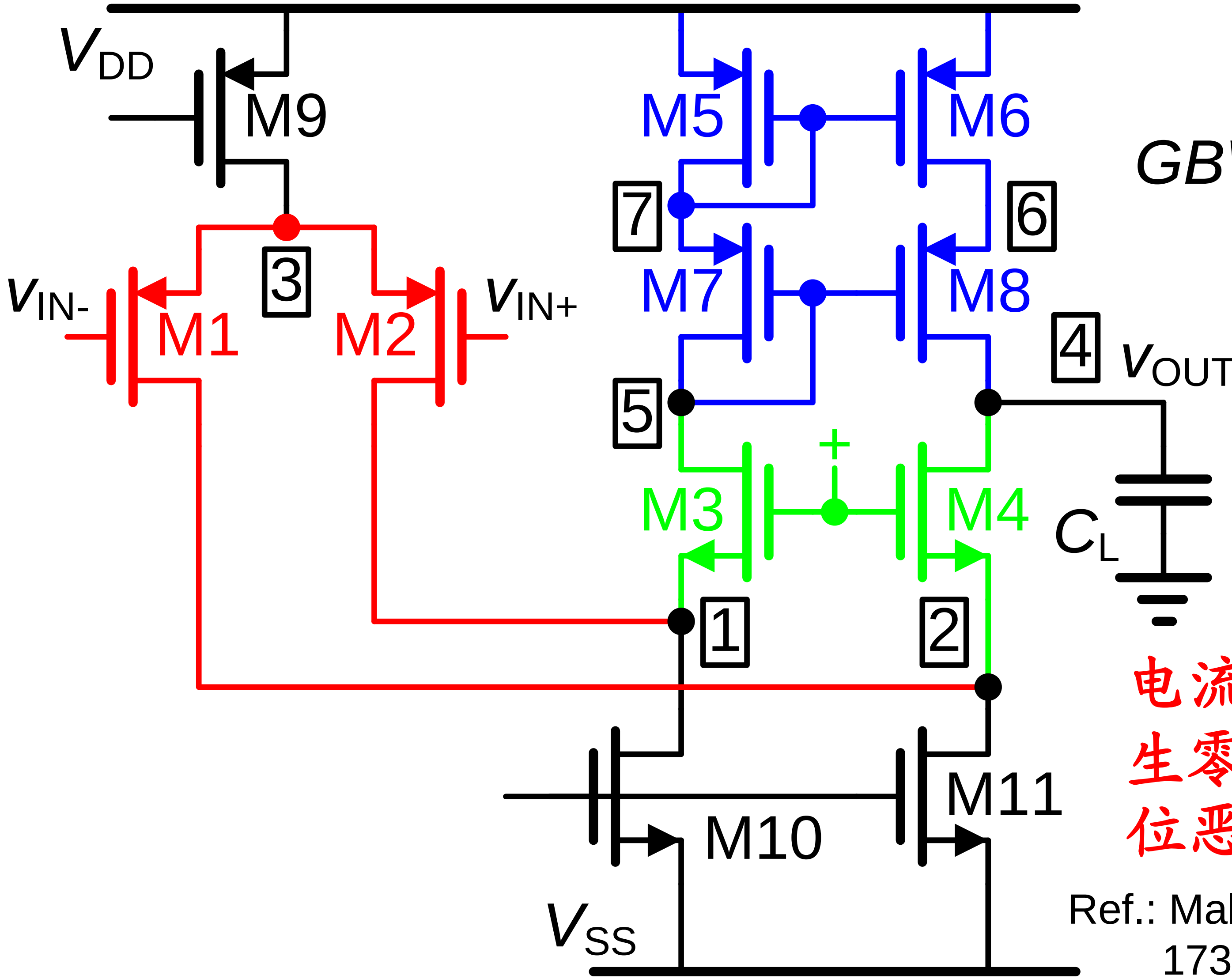


$$GBW = \frac{g_{m1}}{2\pi C_L}$$

$$C_{n1} = C_{GS3} + C_{DB2} + C_{DB10} \approx 3C_{GS3}$$

$$f_{nd} = \frac{g_{m3}}{2\pi C_{n1}} \approx \frac{f_{T3}}{3}$$ 高！

CMOS折叠共源共栅OTA: 零极点对

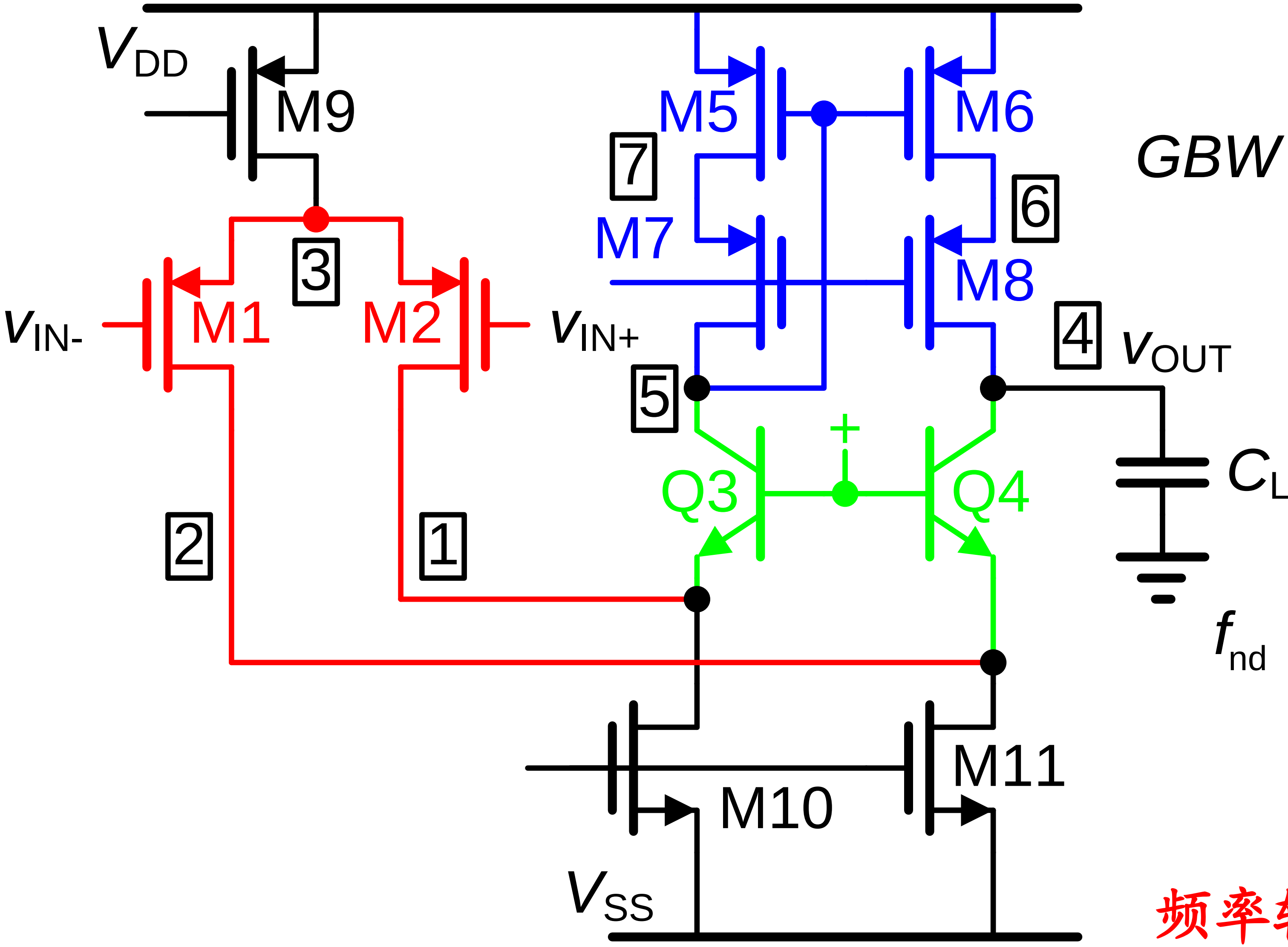


$$GBW = \frac{g_{m1}}{2\pi C_L}$$

电流镜M5-M8产生零极点对，相位恶化5…10°

Ref.: Mallya, JSSC Dec 89, 1737-1740

BiCMOS折叠共源共栅OTA

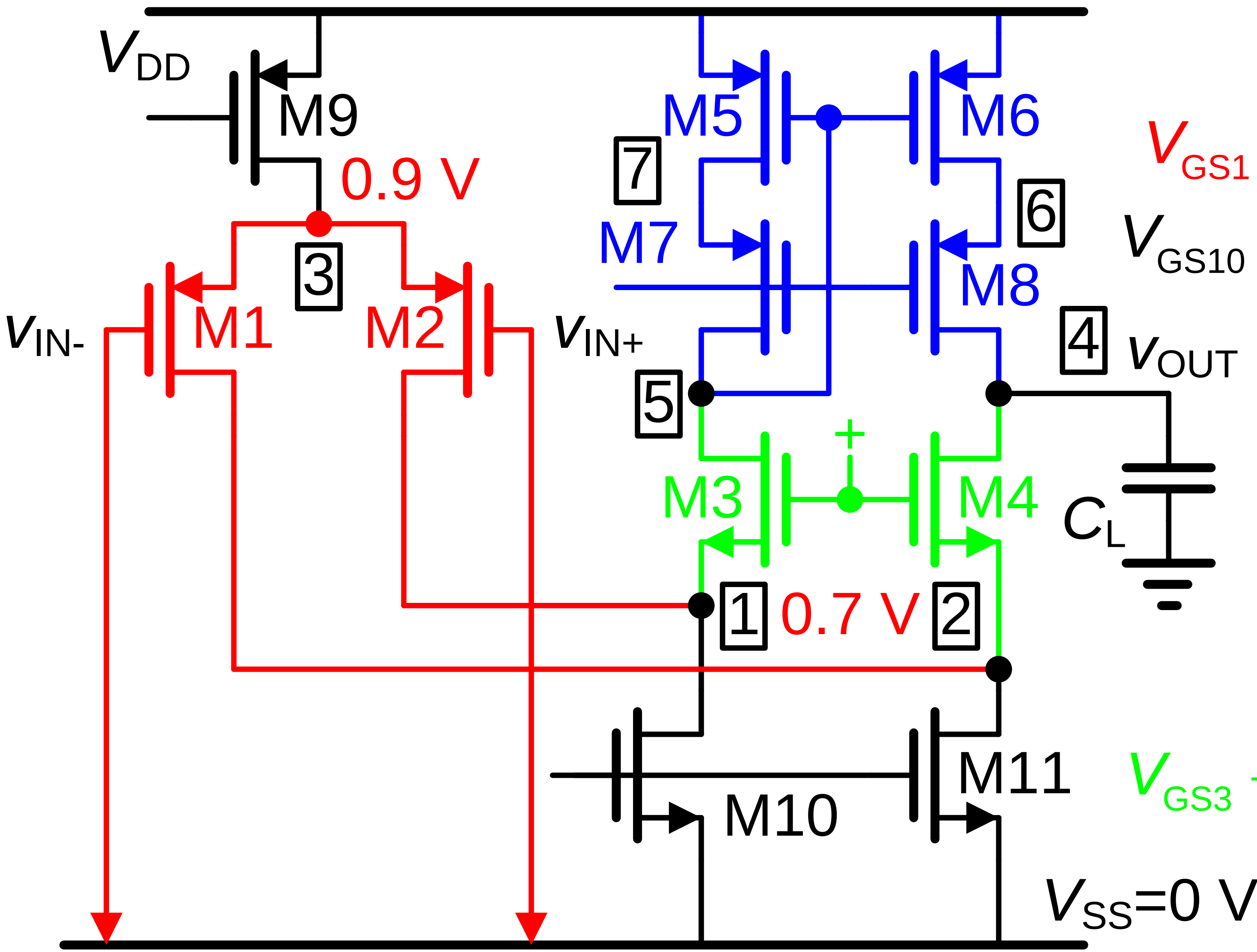


$$GBW = \frac{g_{m1}}{2\pi C_L}$$

$$f_{nd} = \frac{g_{m3}}{2\pi C_{n1}} \approx \frac{f_{T3NPN}}{3}$$

频率较高！

CMOS折叠共源共栅OTA: 输入范围



$V_T = 0.7\ V$

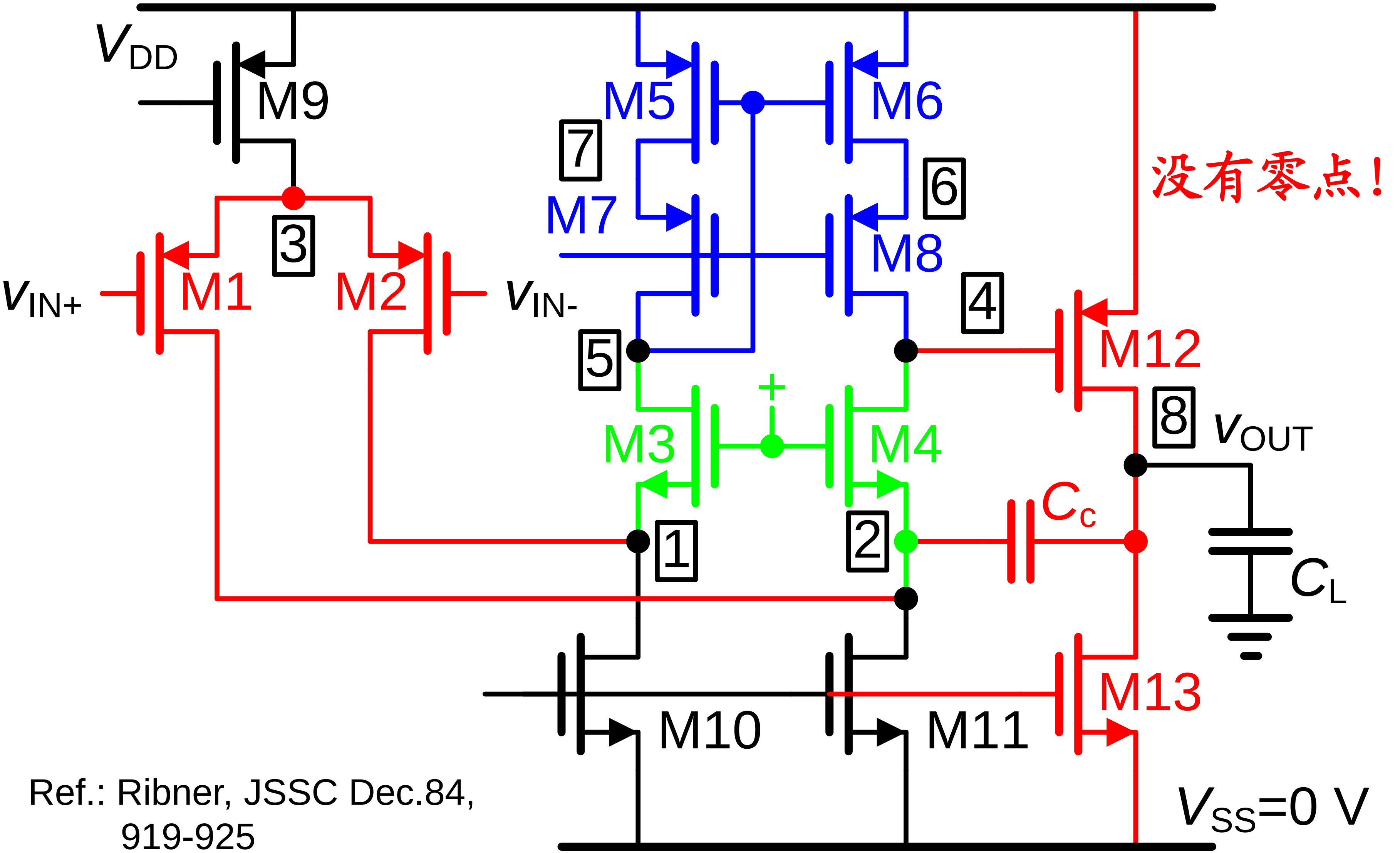
$V_{GS1} - V_T = 0.2\ V$

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

$V_+ = 1.4\ V$

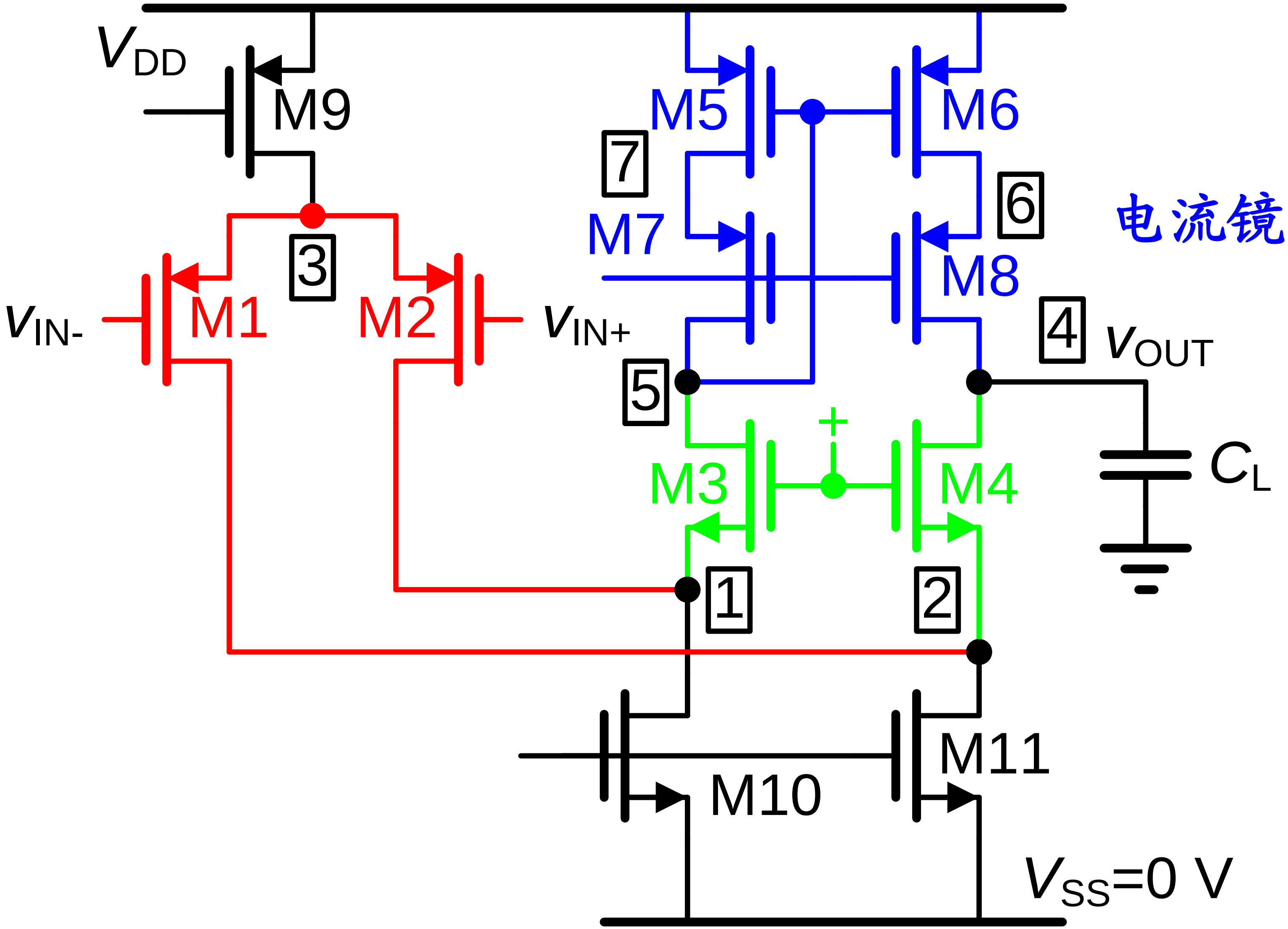
$V_{GS3} - V_T = 0.2\ V$

两级折叠共源共栅OTA

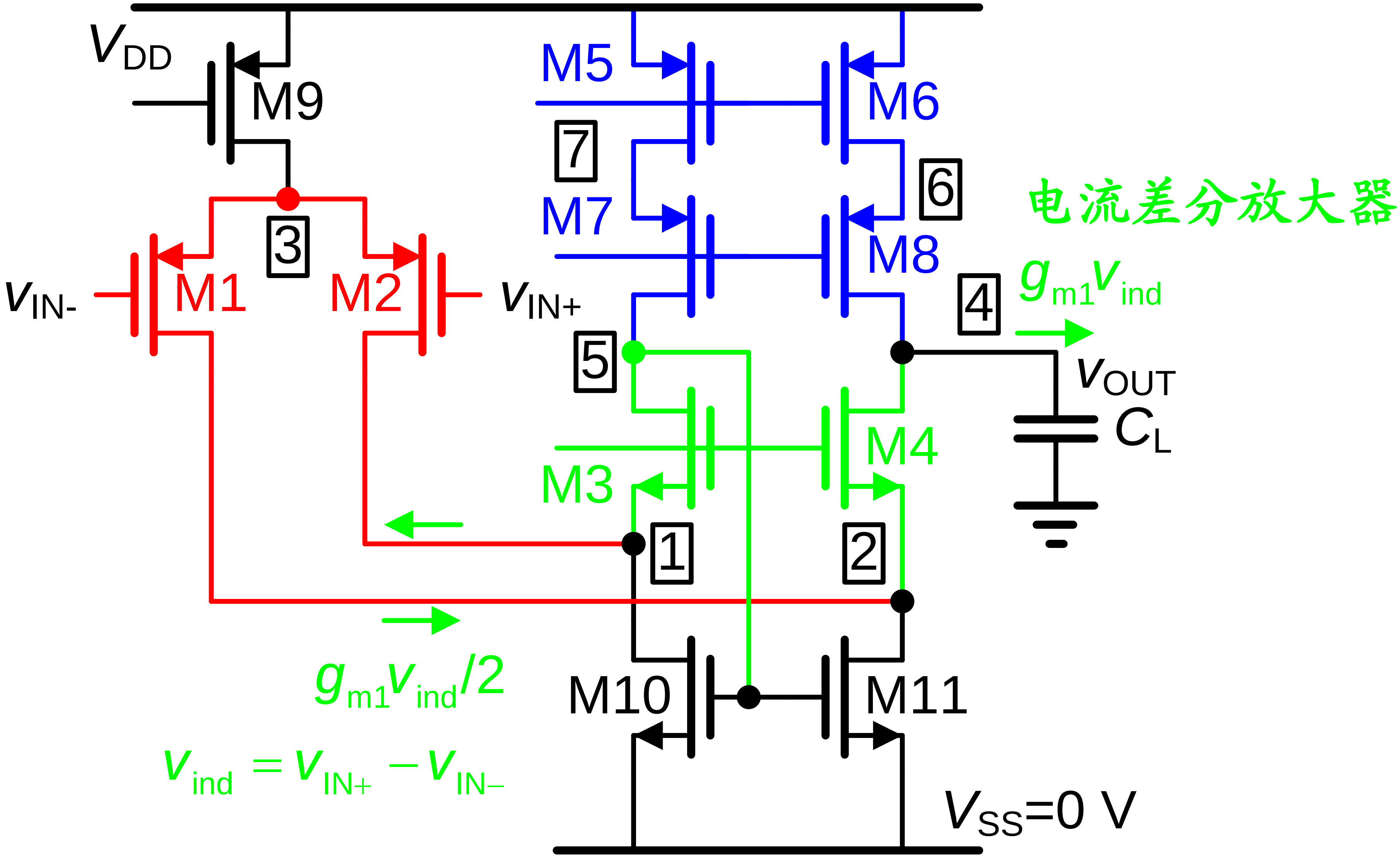


Ref.: Ribner, JSSC Dec.84, 919-925

折叠共源共栅OTA: 电流镜



折叠共源共栅OTA: 差分电流放大器



OTA(放大器)的性能比较

	I_{TOT} mA	$\overline{dv^2_{in,eq}}$ $\frac{8/3kTdf}{g_{m1}}$	Swing
简单型 (4管)	0.25	4	avg.
对称型 (B=3)	0.33	8	max.
套筒型	0.25	4	small
折叠共源共栅	0.5	8	avg.
两级密勒 (C_L/C_c=2.5)	1.1	4	max.

GBW=100 MHz　C_L= 2 pF　V_{GS}-V_T=0.2 V　全差分结构

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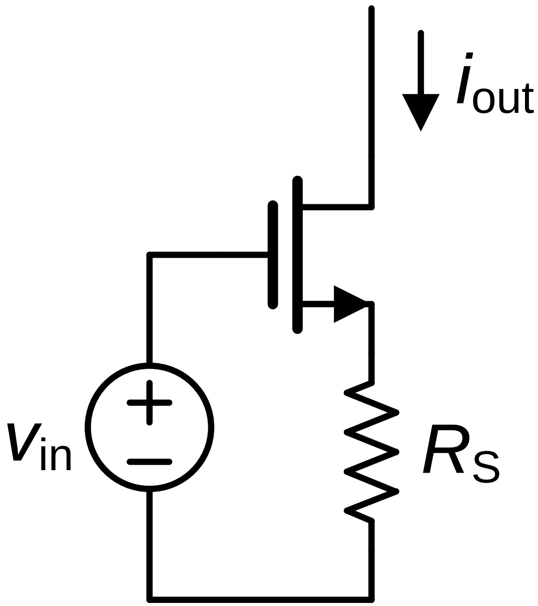
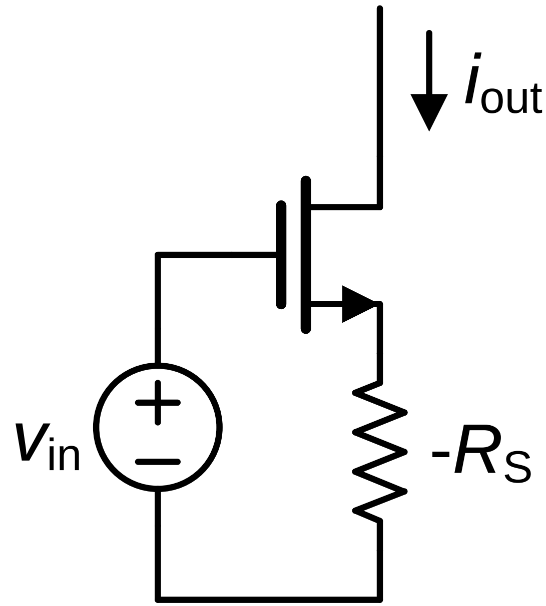
增加输入跨导 - 1

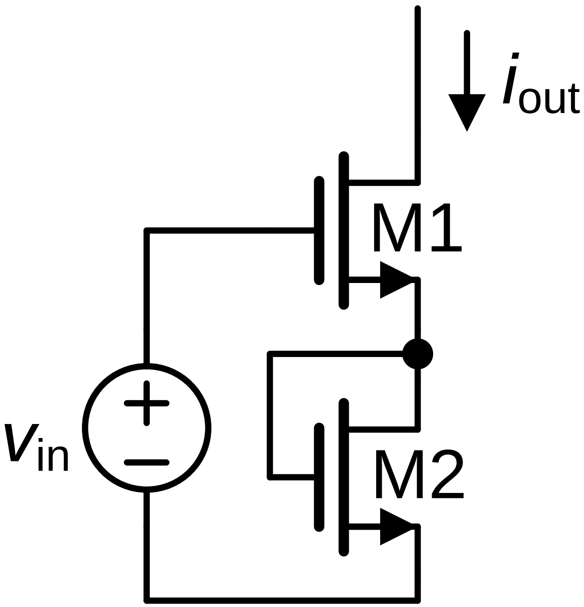


$$g_{mR} = \frac{g_m}{1+g_m R_S}$$

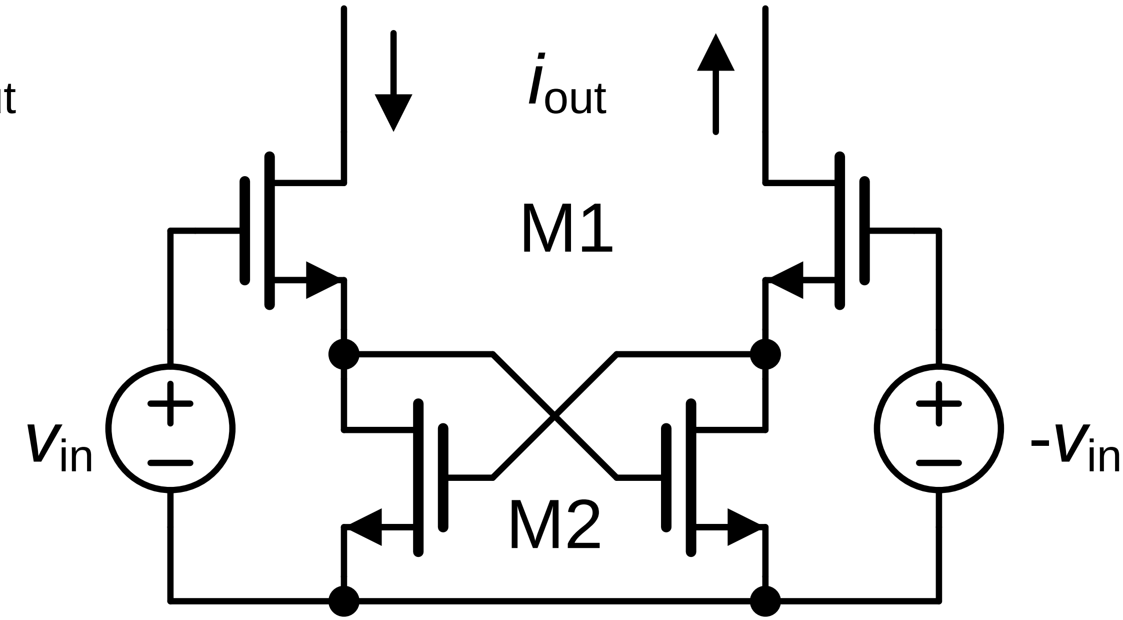


$$g_{mR} = \frac{g_m}{1-g_m R_S}$$

增加输入跨导 - 2

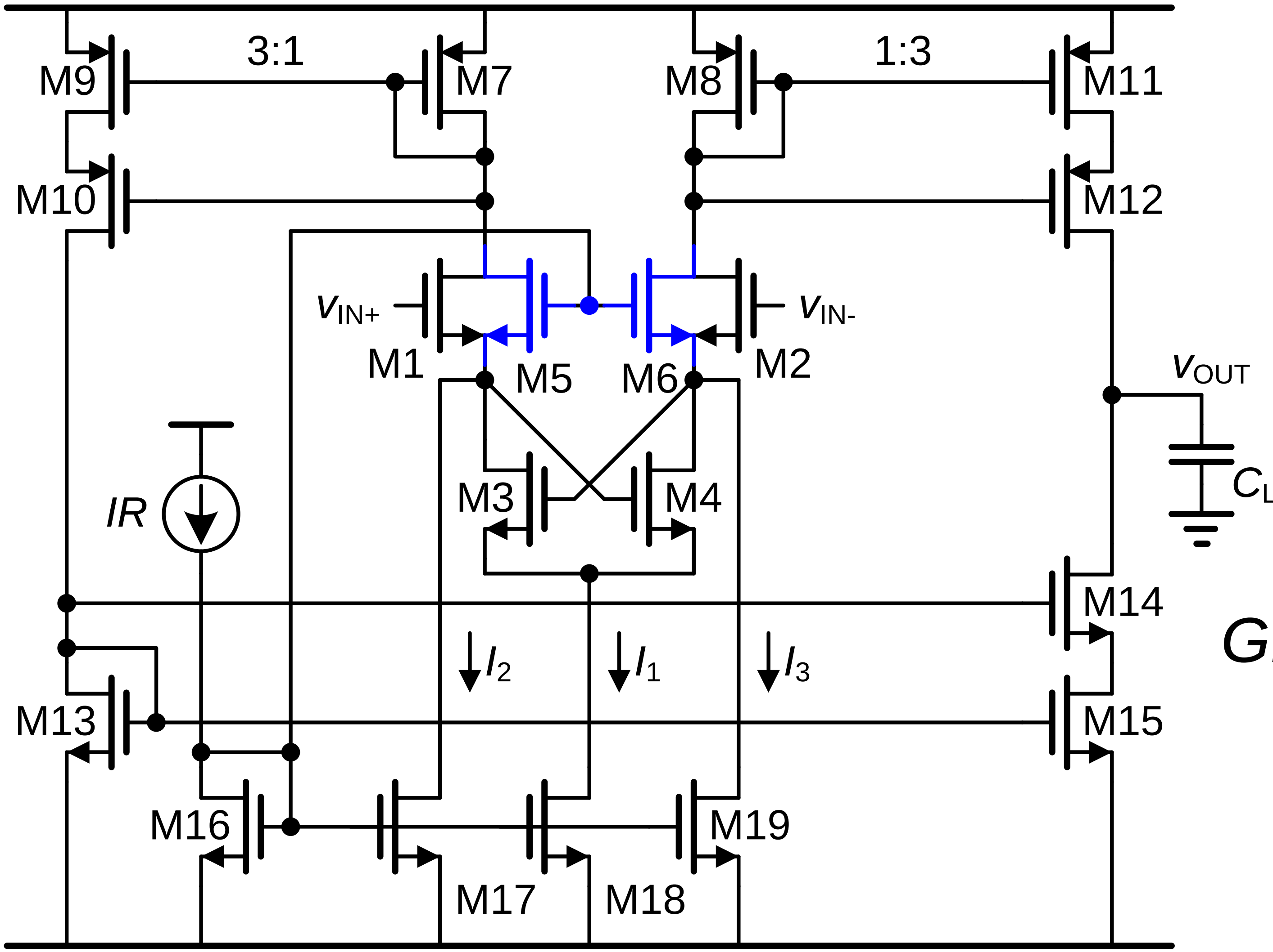


$$g_m = \frac{g_{m1}}{1 + \frac{g_{m1}}{g_{m2}}}$$



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

增加输入跨导 - 3



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

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

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

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

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