第八章 CMOS模拟集成电路

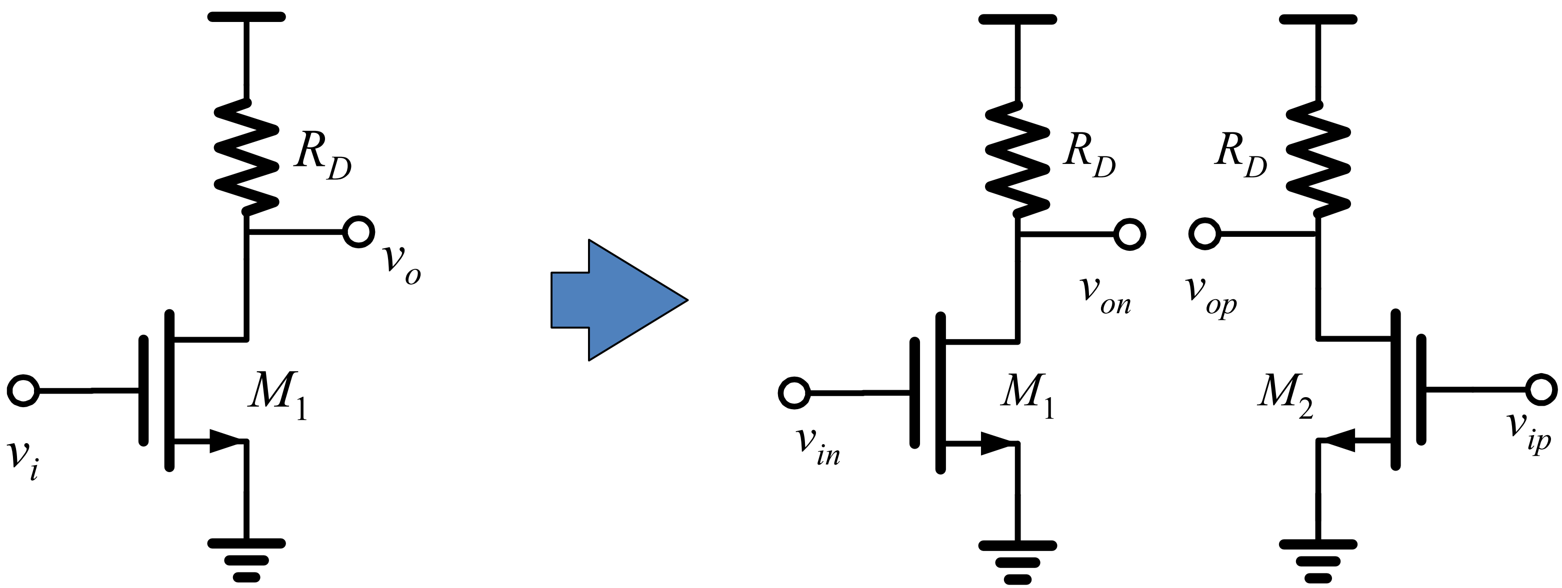
8.7 CMOS差分放大电路

CMOS差分放大电路

- 差分放大电路
- 常用于运算放大器的输入级

差分输出的差分放大器

◆ 电阻负载NMOS共源放大器



增益

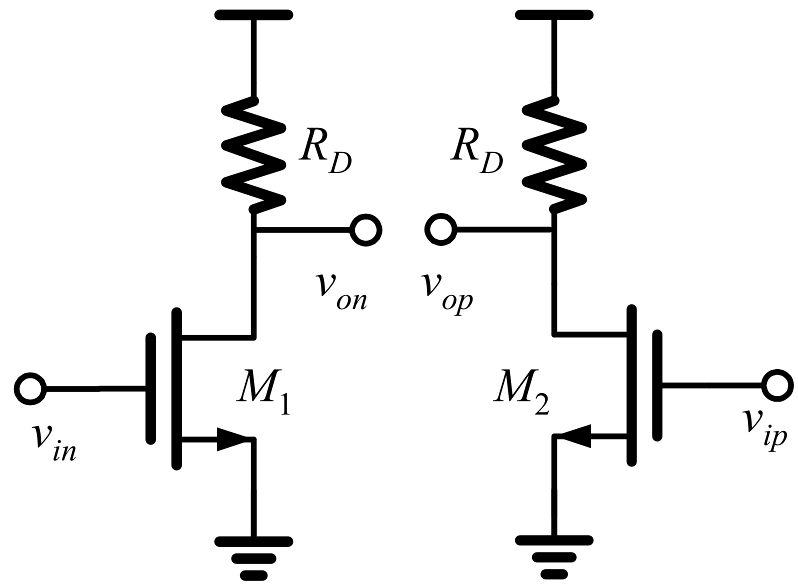
$$v_{op} = A_{v2} v_{ip} = -g_{m2}\left(r_{ds2} \parallel R_D\right) v_{ip}$$

$$v_{on} = A_{v1} v_{in} = -g_{m1}\left(r_{ds1} \parallel R_D\right) v_{in}$$

- 如果 $A_{v1} = A_{v2}$

$$v_{op} - v_{on} = A_v\left(v_{ip} - v_{in}\right)$$

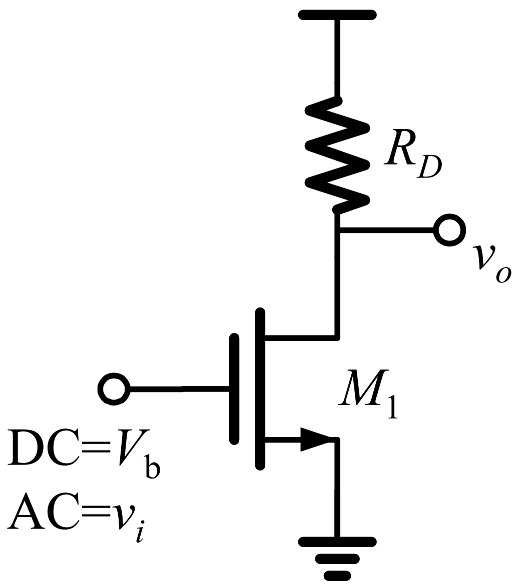
$$A_v = -g_{m1}\left(r_{ds1} \parallel R_D\right)$$



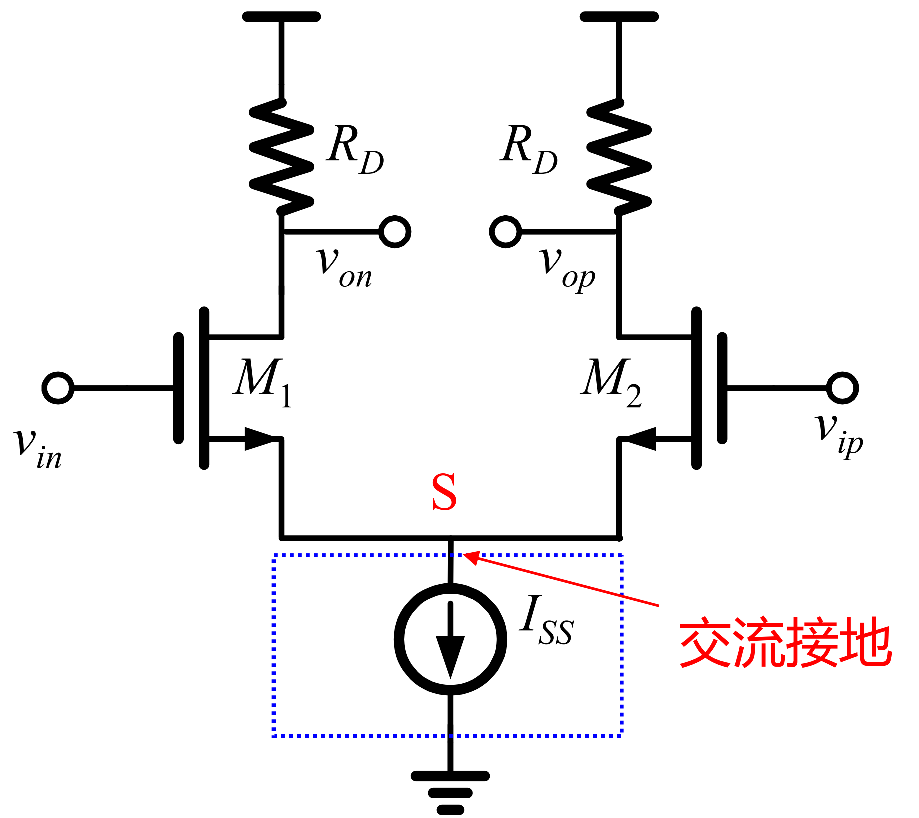
差分输入差分输出放大器

偏置电路

共源放大器
电压偏置



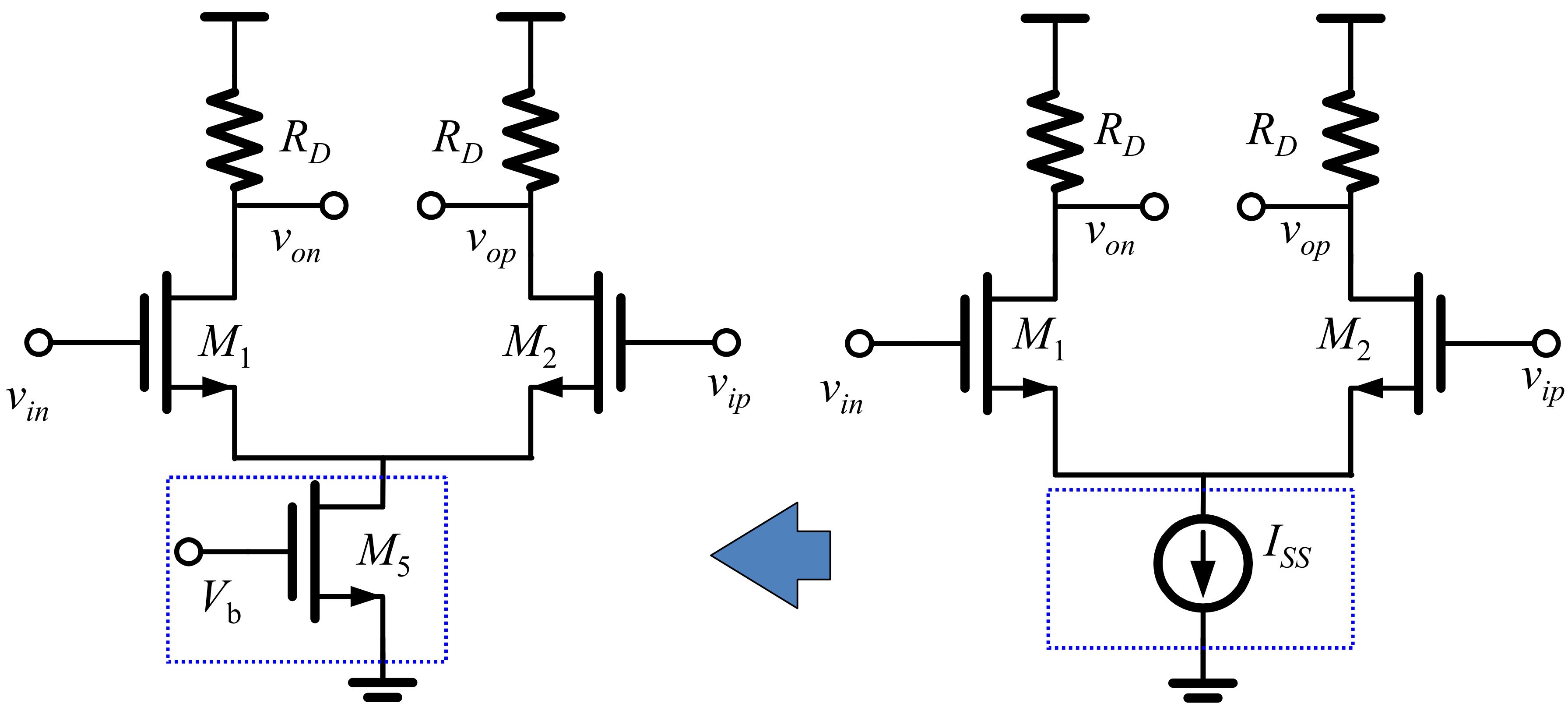
差分放大器
电流偏置



偏置电路

电路实现

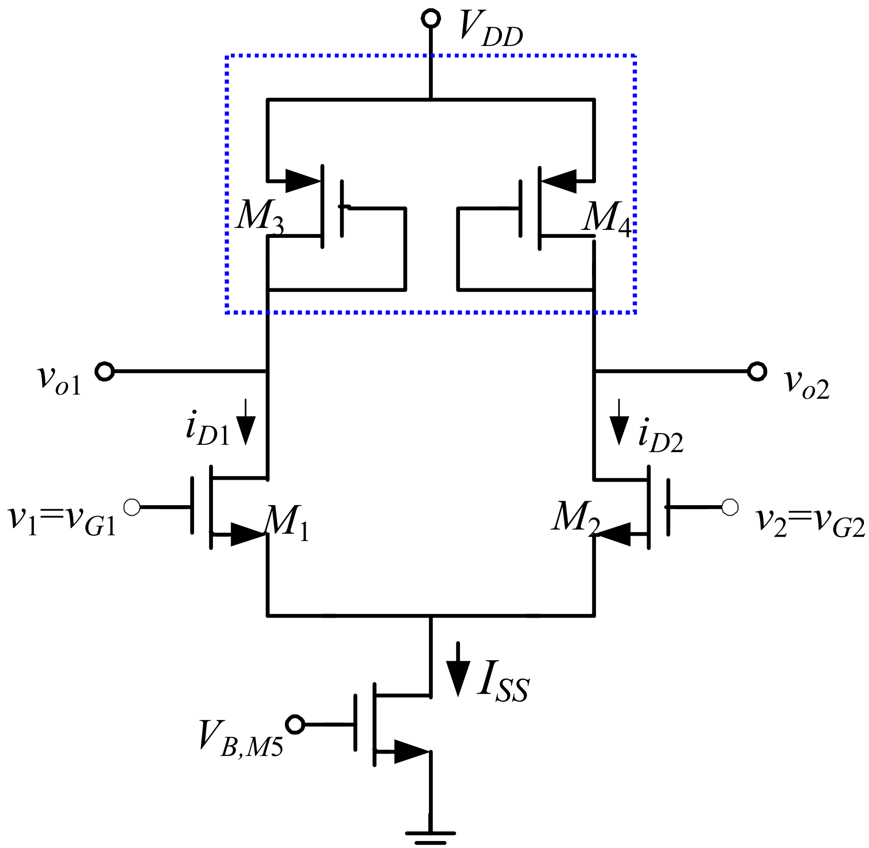
差分放大器
电流偏置



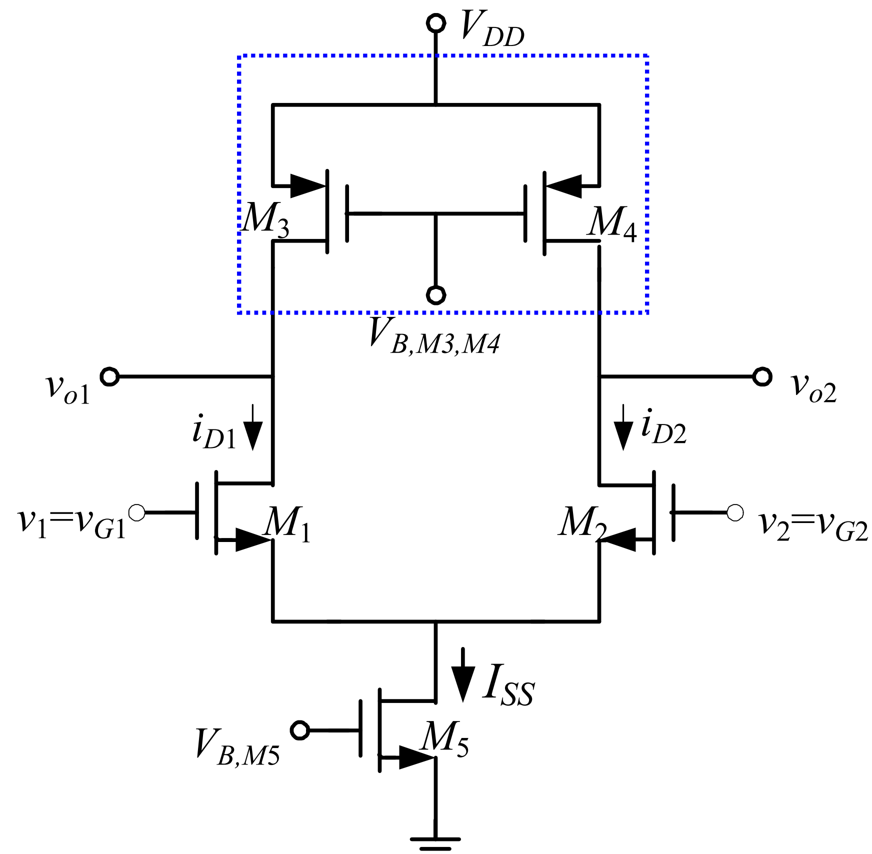
负载

- 采用有源负载

PMOS二极管负载

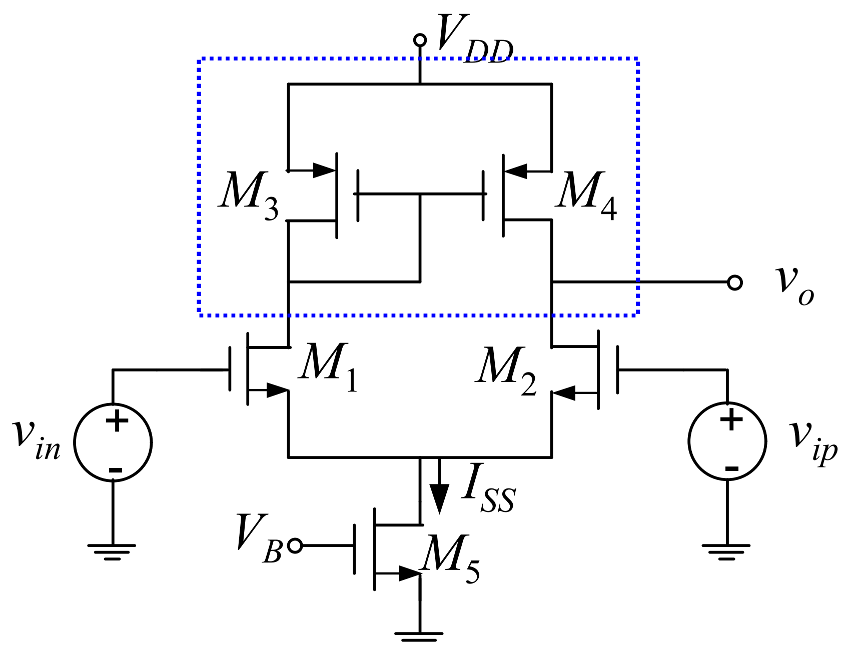


PMOS电流源负载



单端输出的差分放大器

- PMOS电流镜负载
  - 电路结构不对称



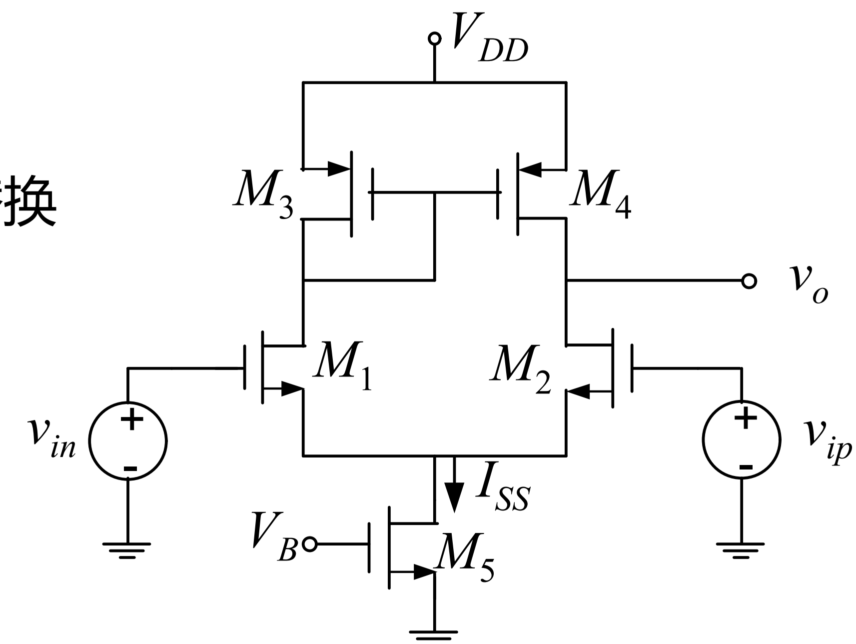
增益

分析方法

1，小信号等效电路模型

- M1~M4，用小信号等效电路替换
- M1/M2：必须考虑背栅效应
- M5：用电阻r_{ds5}替换

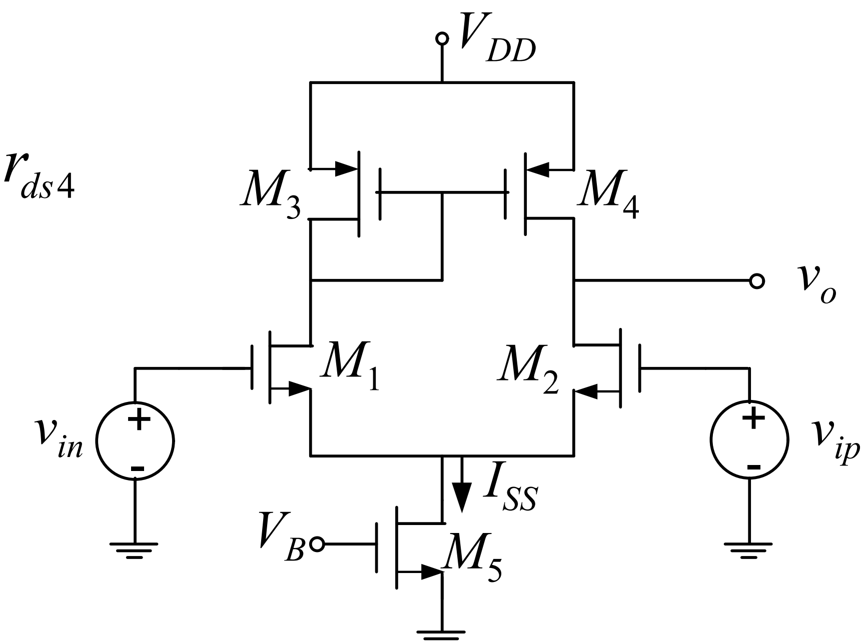
2，列写电路方程求解



增益

- 假设两侧电路参数相同

$$g_{m1}=g_{m2},\quad r_{ds1}=r_{ds2},\quad r_{ds3}=r_{ds4}$$



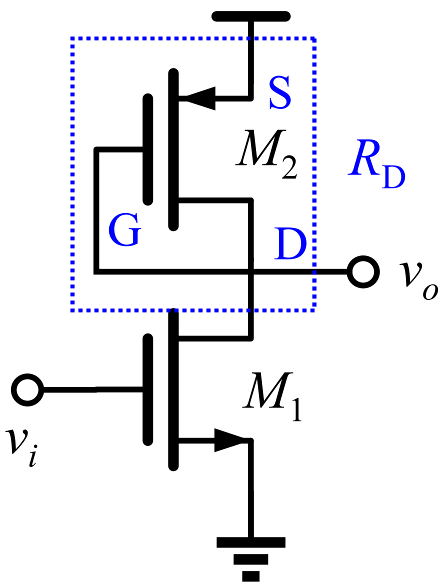
- 如果 $2r_{ds2} \gg \dfrac{1}{g_{m4}} \parallel r_{ds4}$

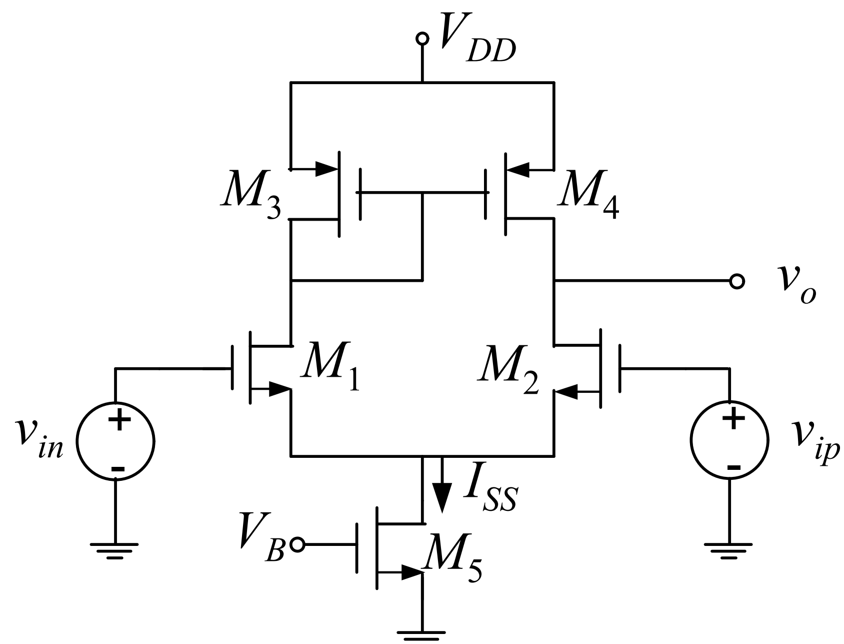
$$v_o = A_v\left(v_{ip}-v_{in}\right)$$

$$A_v = -g_{m2}\left(r_{ds2} \parallel r_{ds4}\right)$$

- 形式与PMOS电流源负载的NMOS共源放大器增益一样

增益





NMOS共源放大器

$$A_v = -g_{m1}\left(r_{ds1} \parallel r_{ds2}\right)$$

NMOS差分放大器

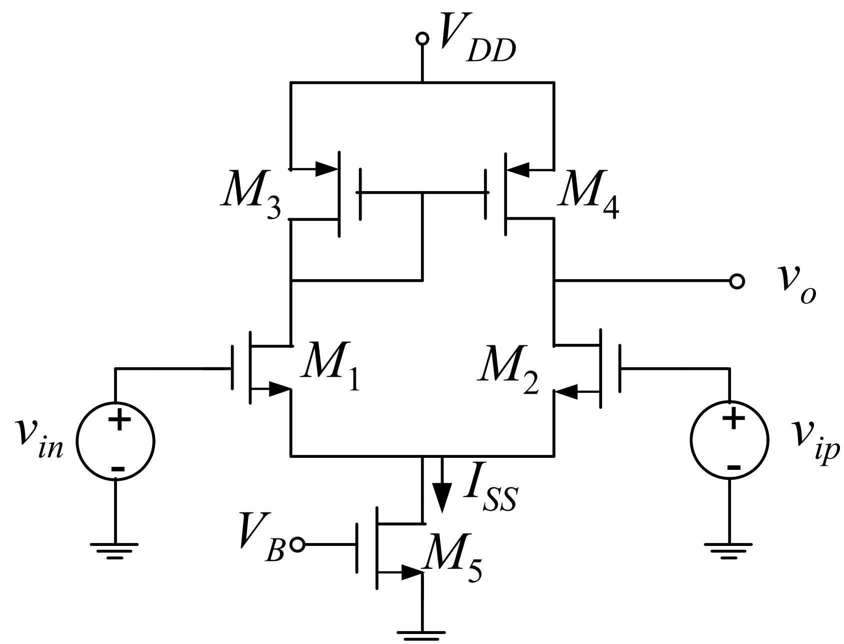
$$A_v = -g_{m2}\left(r_{ds2} \parallel r_{ds4}\right)$$

差分放大器仿真

- VDD=+5V
- 所有MOS管：L=1u, W=10um

- 偏置电流：200uA
  - 对应偏置电压：1.29V

- 共模输入电压V_{IC}：2V
- 差分输入电压v_{id}

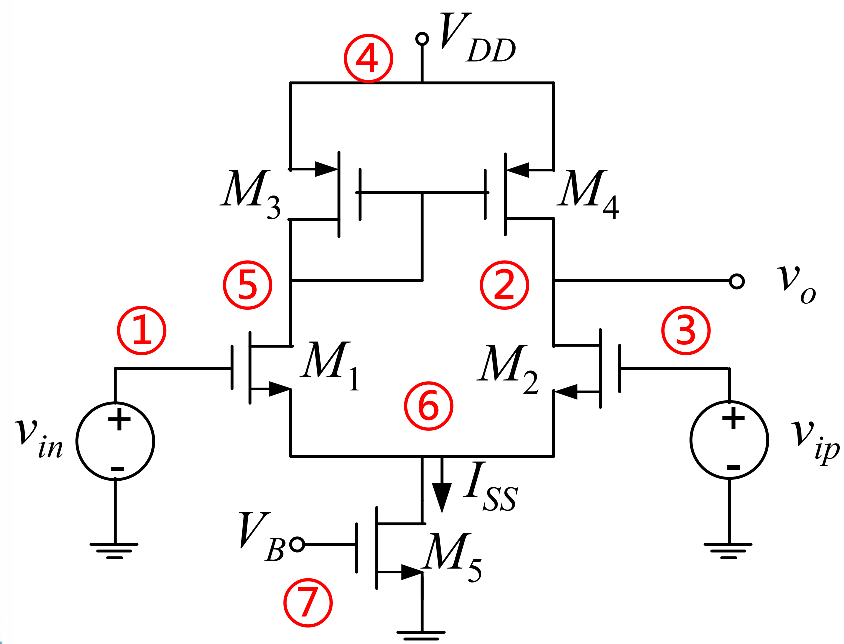


$$v_{ip} = V_{IC} + \frac{v_{id}}{2}$$

$$v_{in} = V_{IC} - \frac{v_{id}}{2}$$

OP仿真与DC仿真

```
.title DIFF_AMP_DC
* with current mirror load
M1 5 1 6 0 n08 W=10U L=1U
M2 2 3 6 0 n08 W=10U L=1U
M3 5 5 4 4 p08 W=10U L=1U
M4 2 5 4 4 p08 W=10U L=1U
M5 6 7 0 0 n08 W=10U L=1U
Vbias 7 0 DC=1.29

VDD 4 0 DC=5

 PARAM VCM=2 Vid=0
Vin 1 0 DC=VCM-Vid/2
Vip 3 0 DC=VCM+Vid/2

.OP                    *直流工作点仿真
.DC Vid -1 1 0.01      *直流扫描仿真
.probe v(2) v(1)

.option post probe

*.MODEL 语句省略

.end
```



$$v_{ip} = V_{IC} + \frac{v_{id}}{2}$$

$$v_{in} = V_{IC} - \frac{v_{id}}{2}$$

增益估算

subckt					
element	0:m1	0:m2	0:m3	0:m4	0:m5
model	0:n08	0:n08	0:p08	0:p08	0:n08
region	Saturati	Saturati	Saturati	Saturati	Saturati
id	101.8672u	101.8672u	-101.8672u	-101.8672u	203.7343u
ibs	-7.5211f	-7.5211f	0.	0.	0.
ibd	-36.9031f	-36.9031f	13.0969f	13.0969f	-7.5211f
vgs	1.2479	1.2479	-1.3097	-1.3097	1.2900
vds	2.9382	2.9382	-1.3097	-1.3097	752.1113m
vbs	-752.1113m	-752.1113m	0.	0.	0.
vth	847.3503m	847.3503m	-700.0000m	-700.0000m	700.0000m
vdsat	400.5384m	400.5384m	-609.6867m	-609.6867m	590.0000m
vod	400.5384m	400.5384m	-609.6867m	-609.6867m	590.0000m
beta	1.2699m	1.2699m	548.0886u	548.0886u	1.1706m
gam eff	400.0000m	400.0000m	570.0000m	570.0000m	400.0000m
gm	508.6511u	508.6511u	334.1623u	334.1623u	690.6248u
gds	3.6462u	3.6462u	4.7803u	4.7803u	7.9114u
gmb	84.4209u	84.4209u	106.4774u	106.4774u	165.0909u

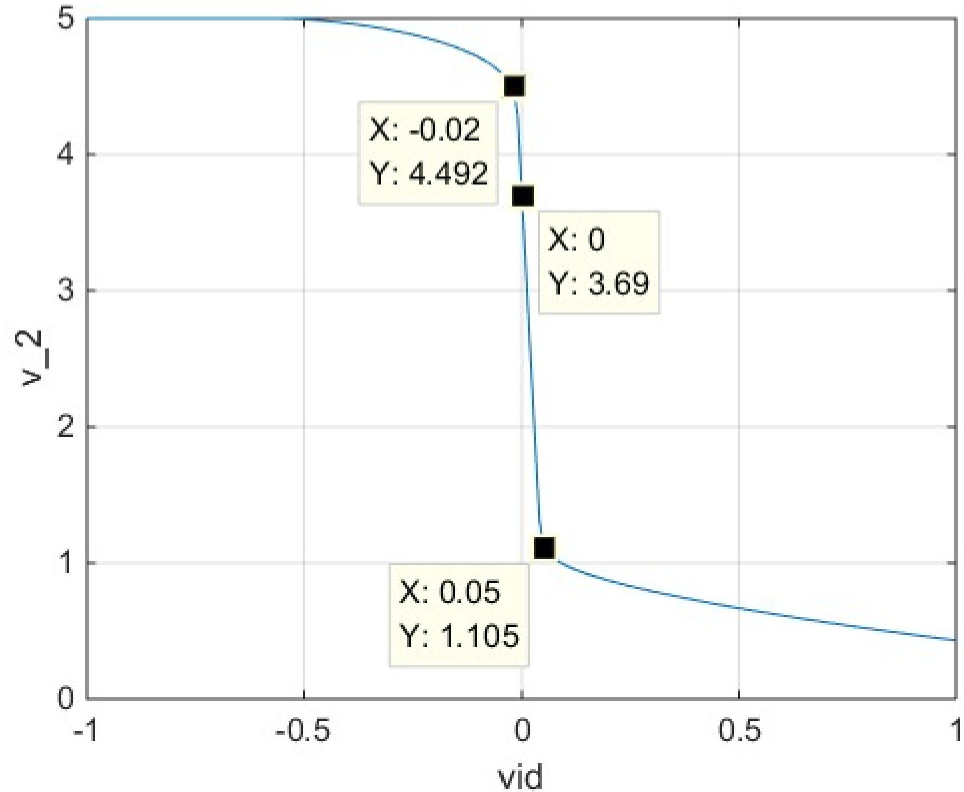
$$A_v = -\frac{g_{m2}}{g_{ds2} + g_{ds4}} = -\frac{509}{3.65 + 4.78} = -60$$

- 35.6dB

直流转移特性

- 输出电压摆幅
  - 1.1~4.5V

M4进入线性区



M2进入线性区

AC仿真

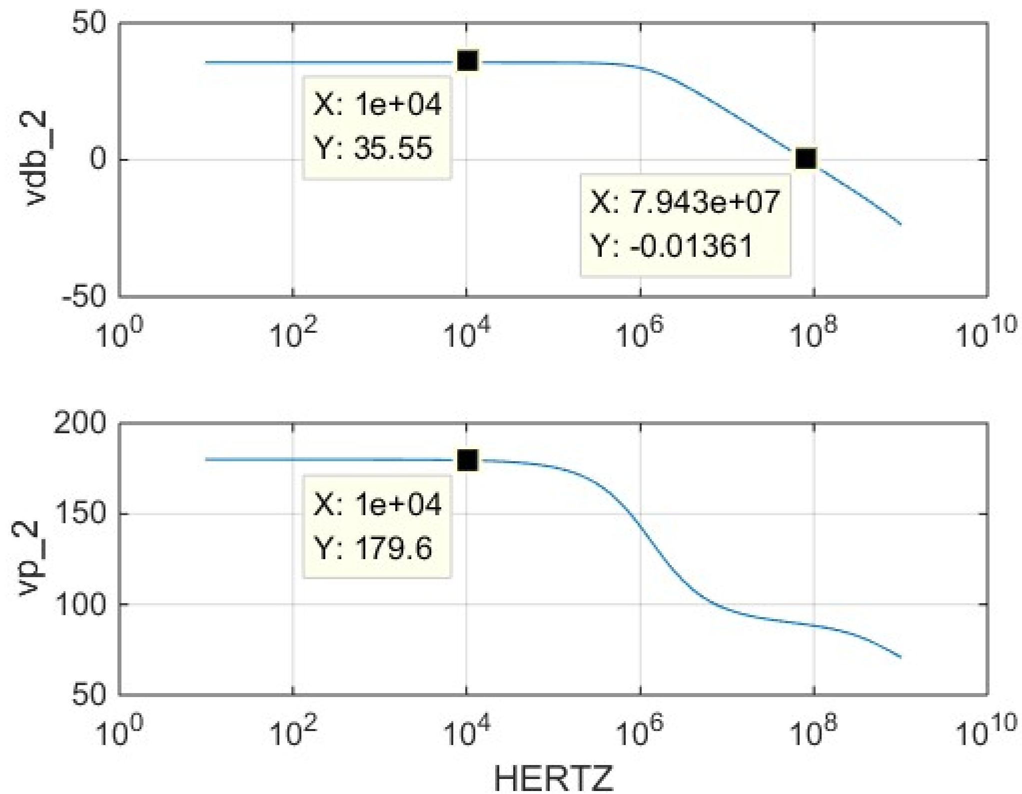
- 输出接1pF的电容
  - 后级电路负载效应

- 共模输入电压：2V
- 差分输入信号：1V

```
.title DIFF_AMP_AC
* with current mirror load
M1 5 1 6 0 n08 W=10U L=1U
M2 2 3 6 0 n08 W=10U L=1U
M3 5 5 4 4 p08 W=10U L=1U
M4 2 5 4 4 p08 W=10U L=1U
M5 6 7 0 0 n08 W=10U L=1U
Vbias 7 0 DC=1.29

VDD 4 0 DC=5
CL 2 0 1P

.PARAM VCM=2 Vid=1
Vin 1 0 DC=VCM AC=Vid/2 180
Vip 3 0 DC=VCM AC=Vid/2

.OP                              *直流工作点仿真
.AC dec 10 10 1g                 *交流仿真
.probe vdb(2) vp(2)

.option post probe

*.MODEL 语句省略

.end
```

开环增益

- 反相放大
- 直流增益
  - 35.6分贝
- 单位增益带宽
  - 79MHz



差分放大器共模抑制比

- 差模增益

$$A_{vd} = -g_{m2}\left(r_{ds2} \parallel r_{ds4}\right)$$

- 共模增益

$$\boxed{A_{vc} = ?}$$

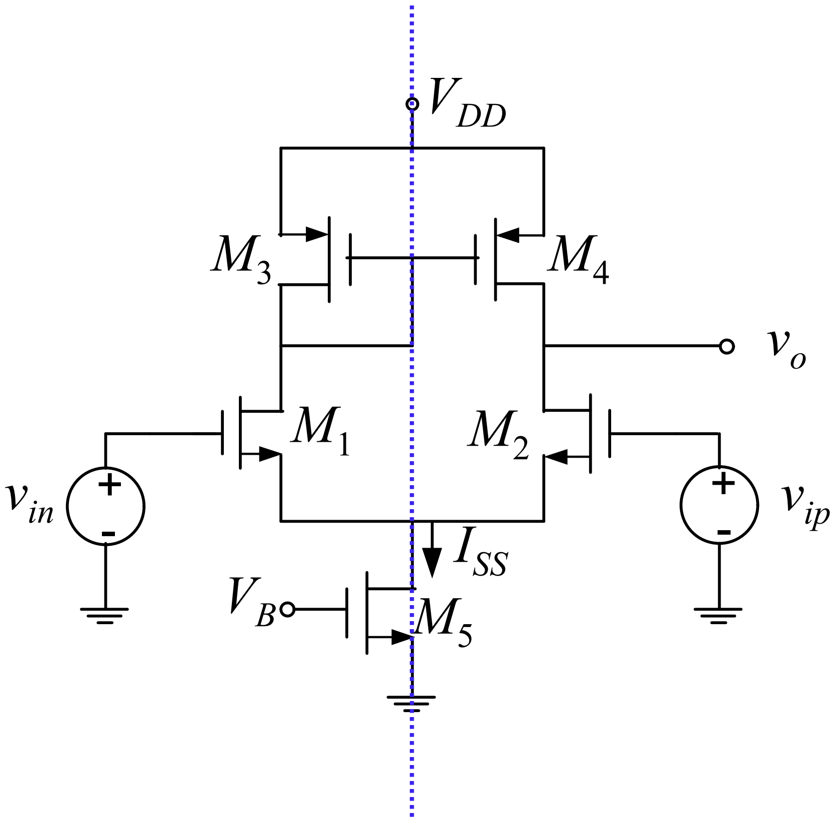
- 共模抑制比

$$CMRR = \left|\frac{A_{vd}}{A_{vc}}\right|$$

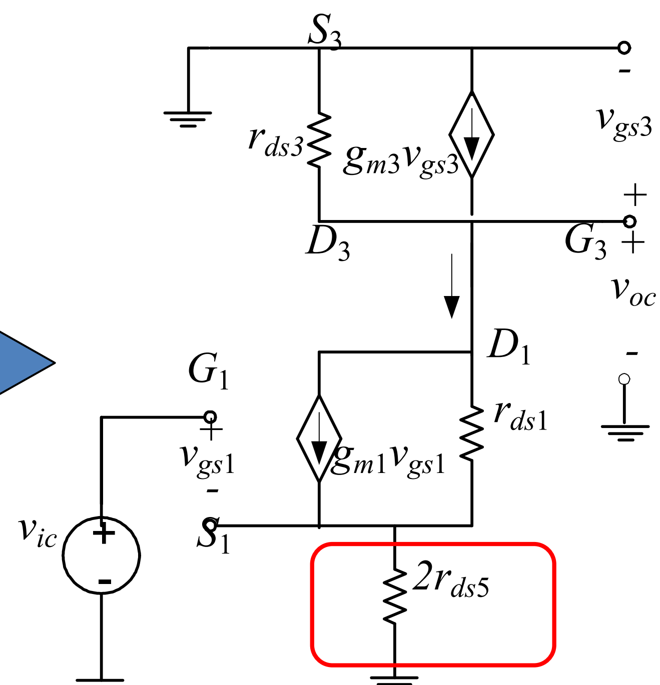
$$CMRR = 20\lg\left|\frac{A_{vd}}{A_{vc}}\right| \quad (dB)$$

共模增益

- 共模条件下，差分输入信号：0V
  - 电路特性完全对称，可以用半边电路技术分析



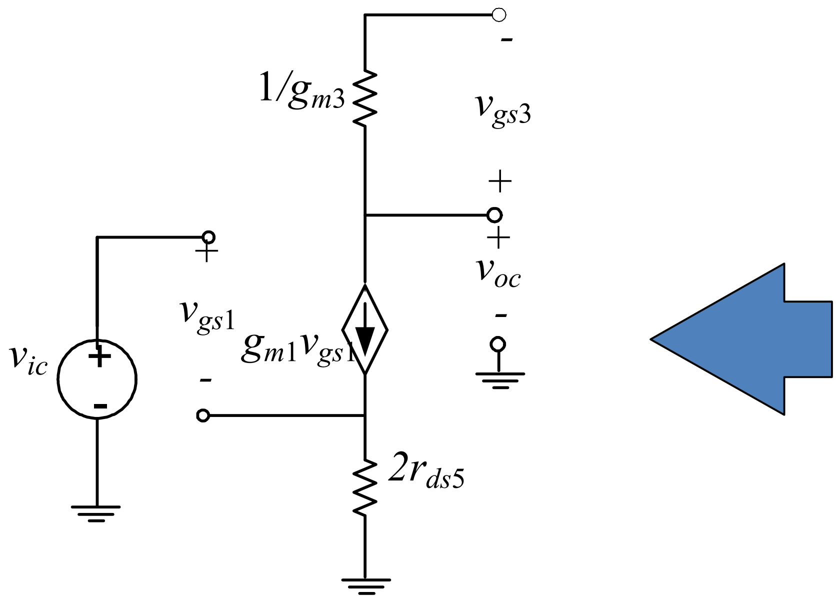
半边等效电路



M5：用电阻$2r_{ds5}$替换

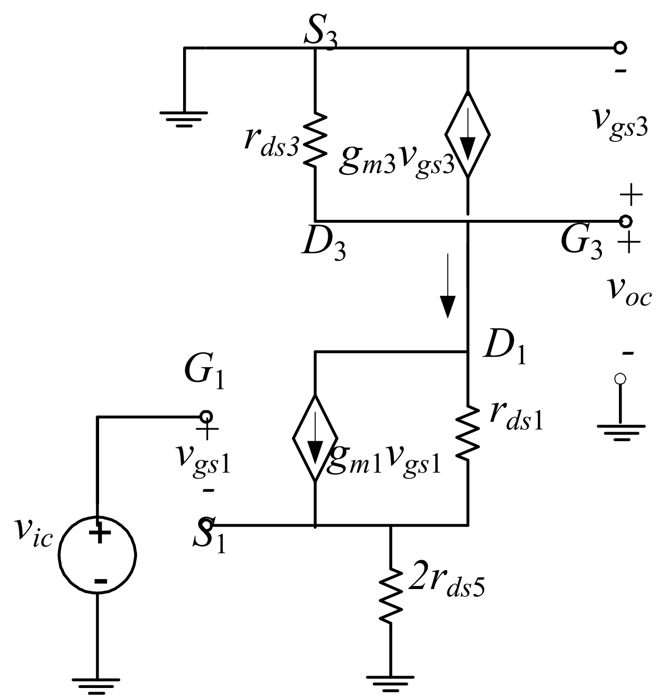
共模增益

$$A_{vc}=\frac{v_o}{v_{ic}}=-\frac{g_{m1}/g_{m3}}{1+2g_{m1}r_{ds5}}\approx-\frac{1}{2g_{m3}r_{ds5}}$$



忽略r_{ds1}和r_{ds3}简化电路

半边等效电路



共模抑制比

- 差模增益

$$A_{vd} = -g_{m2}\left(r_{ds2} \parallel r_{ds4}\right)$$

- 共模增益

$$A_{vc} = \frac{v_o}{v_{ic}} = -\frac{g_{m1} / g_{m3}}{1 + 2g_{m1}r_{ds5}} \approx -\frac{1}{2g_{m3}r_{ds5}}$$

- 共模抑制比

$$\boxed{CMRR = \left|\frac{A_{vd}}{A_{vc}}\right| = \frac{2g_{m1}g_{m3}}{(g_{ds2} + g_{ds4})g_{ds5}}}$$

共模增益估算

subckt					
element	0:m1	0:m2	0:m3	0:m4	0:m5
model	0:n08	0:n08	0:p08	0:p08	0:n08
region	Saturati	Saturati	Saturati	Saturati	Saturati
id	101.8672u	101.8672u	-101.8672u	-101.8672u	203.7343u
ibs	-7.5211f	-7.5211f	0.	0.	0.
ibd	-36.9031f	-36.9031f	13.0969f	13.0969f	-7.5211f
vgs	1.2479	1.2479	-1.3097	-1.3097	1.2900
vds	2.9382	2.9382	-1.3097	-1.3097	752.1113m
vbs	-752.1113m	-752.1113m	0.	0.	0.
vth	847.3503m	847.3503m	-700.0000m	-700.0000m	700.0000m
vdsat	400.5384m	400.5384m	-609.6867m	-609.6867m	590.0000m
vod	400.5384m	400.5384m	-609.6867m	-609.6867m	590.0000m
beta	1.2699m	1.2699m	548.0886u	548.0886u	1.1706m
gam eff	400.0000m	400.0000m	570.0000m	570.0000m	400.0000m
gm	508.6511u	508.6511u	334.1623u	334.1623u	690.6248u
gds	3.6462u	3.6462u	4.7803u	4.7803u	7.9114u
gmb	84.4209u	84.4209u	106.4774u	106.4774u	165.0909u

$$A_{vc} = -\frac{1}{2g_{m3}r_{ds5}} = -\frac{7.9}{2\times 334} = -0.0118$$

- -38.6dB

共模抑制比估算

- 差模增益
  - 35.6dB
- 共模增益
  - -38.6dB
- 共模抑制比

$$CMRR = \left| \frac{A_{vd}}{A_{vc}} \right| = 35.6 - (-38.6) = 74.2 \quad dB$$

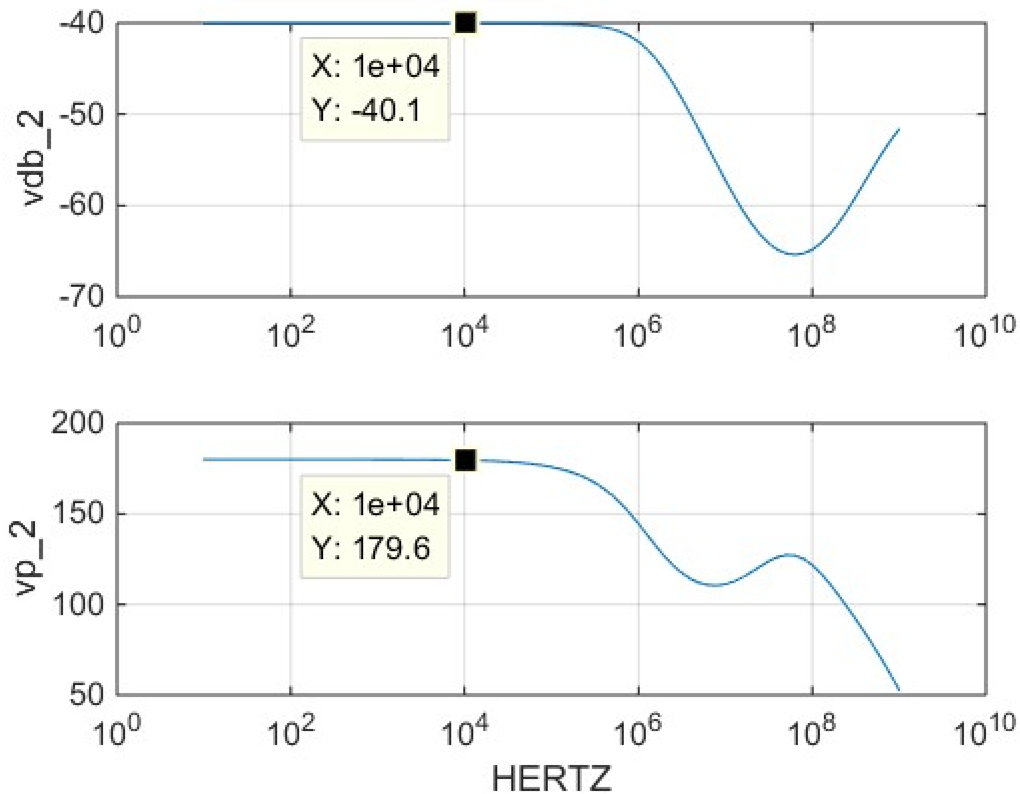
共模增益仿真

- M1/M2栅极连在一起
  - 差分输入电压：0V
- 共模输入电压
  直流2V，加交流分量

```
.title DIFF_AMP_AC
* with current mirror load
M1 5 1 6 0 n08 W=10U L=1U
M2 2 1 6 0 n08 W=10U L=1U
M3 5 5 4 4 p08 W=10U L=1U
M4 2 5 4 4 p08 W=10U L=1U
M5 6 7 0 0 n08 W=10U L=1U
Vbias 7 0 DC=1.29

VDD 4 0 DC=5
CL 2 0 1P

.PARAM VCM=2
Vin 1 0 DC=VCM AC=1

.OP                                    *直流工作点仿真
.AC dec 10 10 1g                       *交流仿真
.probe vdb(2) vp(2)

.option post probe

*.MODEL 语句省略

.end
```

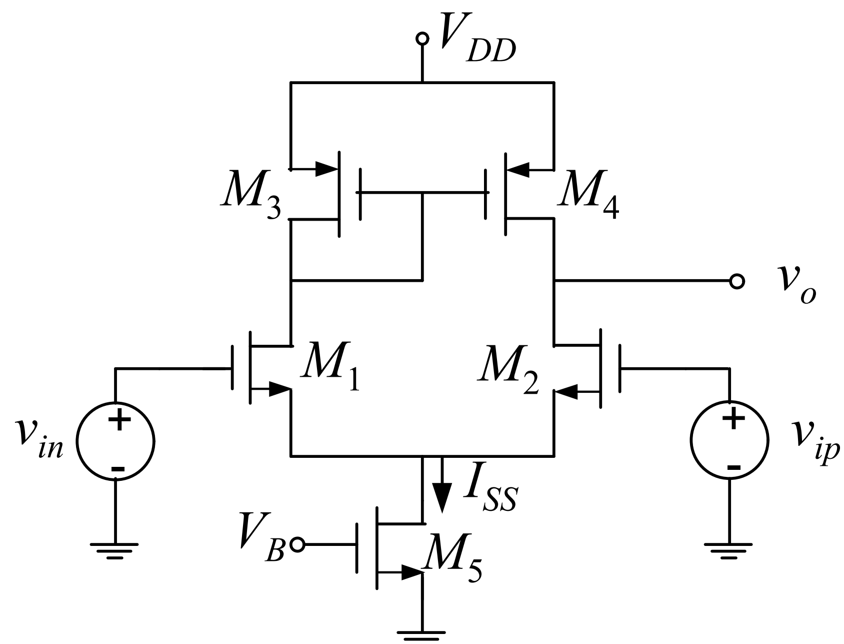
共模增益仿真

- 共模增益
  - -40.1dB
- 共模抑制比
  - 75.7dB



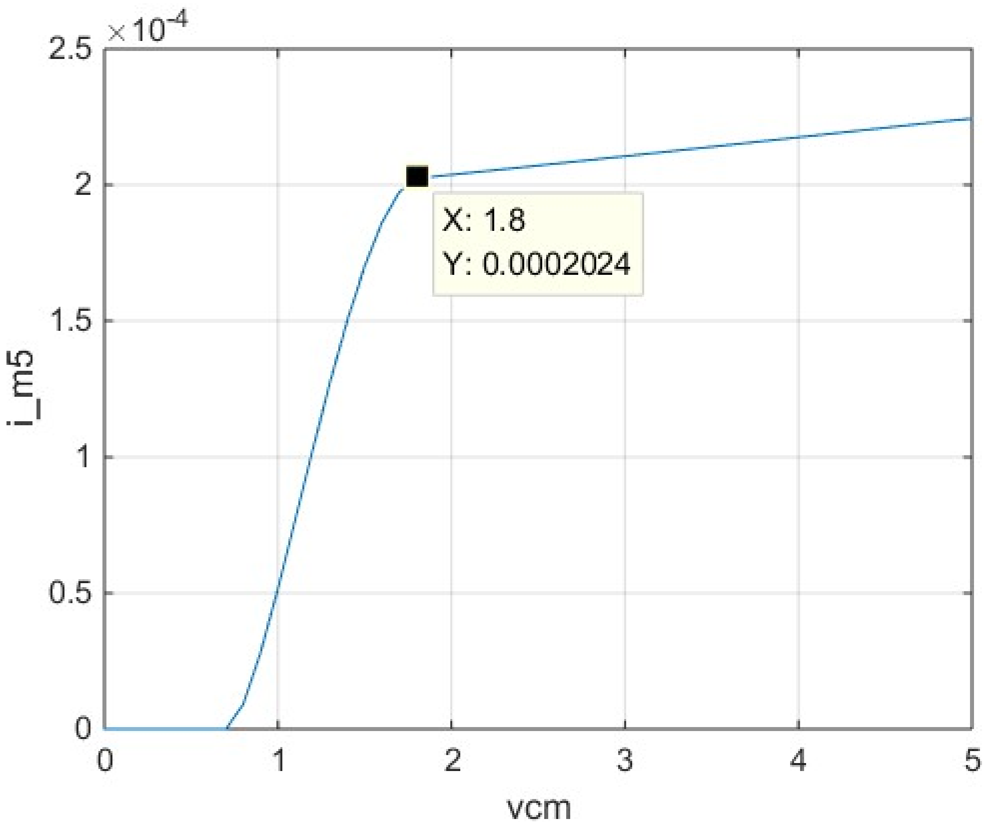
输入共模范围ICMR

- 输入共模电压的范围
  - 差分放大器正常工作
  - 差模增益、共模抑制比等指标可以得到保证
- 共模输入电压太小
  - M5进入线性区
- 共模输入电压太大
  - 无法保证M1~M4都工作在饱和区



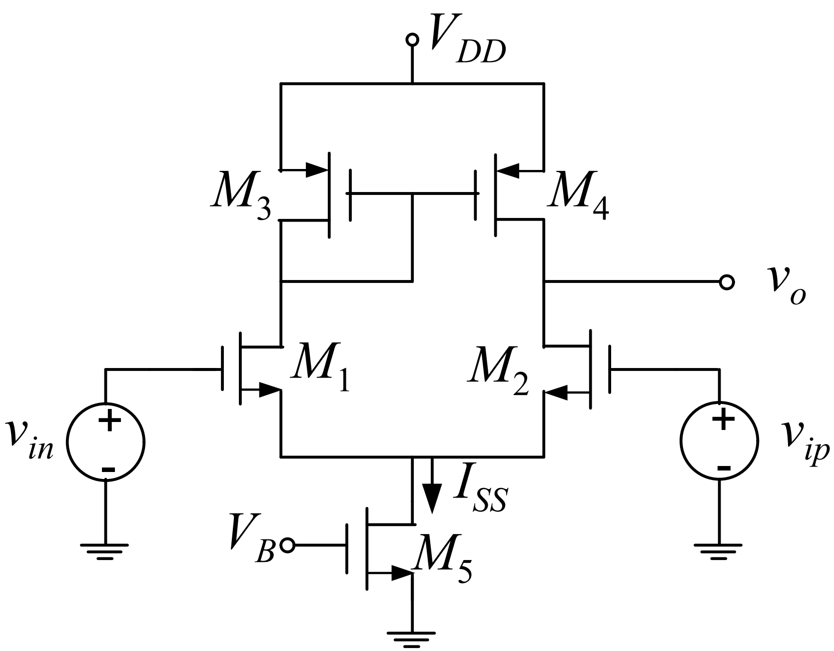
输入共模范围

- 最小共模输入电压
  - 1.8V
- 最大共模输入电压
  - 4.8V



另一种差分放大电路结构

PMOS电流镜负载
NMOS差分放大器



NMOS电流镜负载
PMOS差分放大器