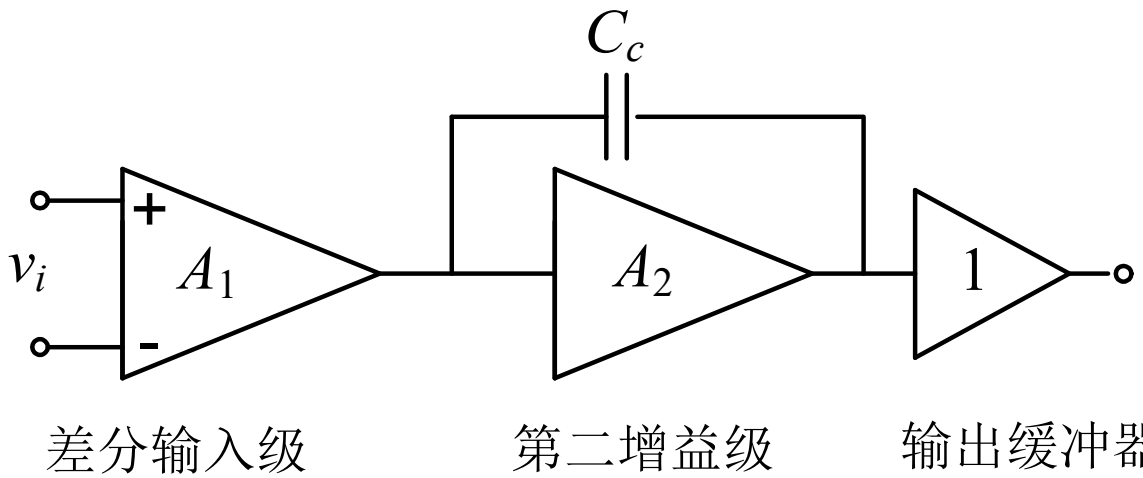
第八章 CMOS模拟集成电路

8.8 CMOS二级运放电路

CMOS二级运放电路

- 单级运算放大器
  - 结构简单，响应速度快，功耗低
  - 常用于设计高速宽带运放
  - 增益相对较低
- 二级运算放大器
  - 两个放大级级连，提高增益

二级运放原理框图



1. 差分输入单端输出级
2. 有源负载共源放大级
3. 输输出缓冲器
   - 用于驱动电阻负载

- 电容Cc，密勒补偿电容

二级运放电路

- 0.8um CMOS工艺
- ±2.5V双电源供电
- 所有MOS管，L=1um

差分输入级

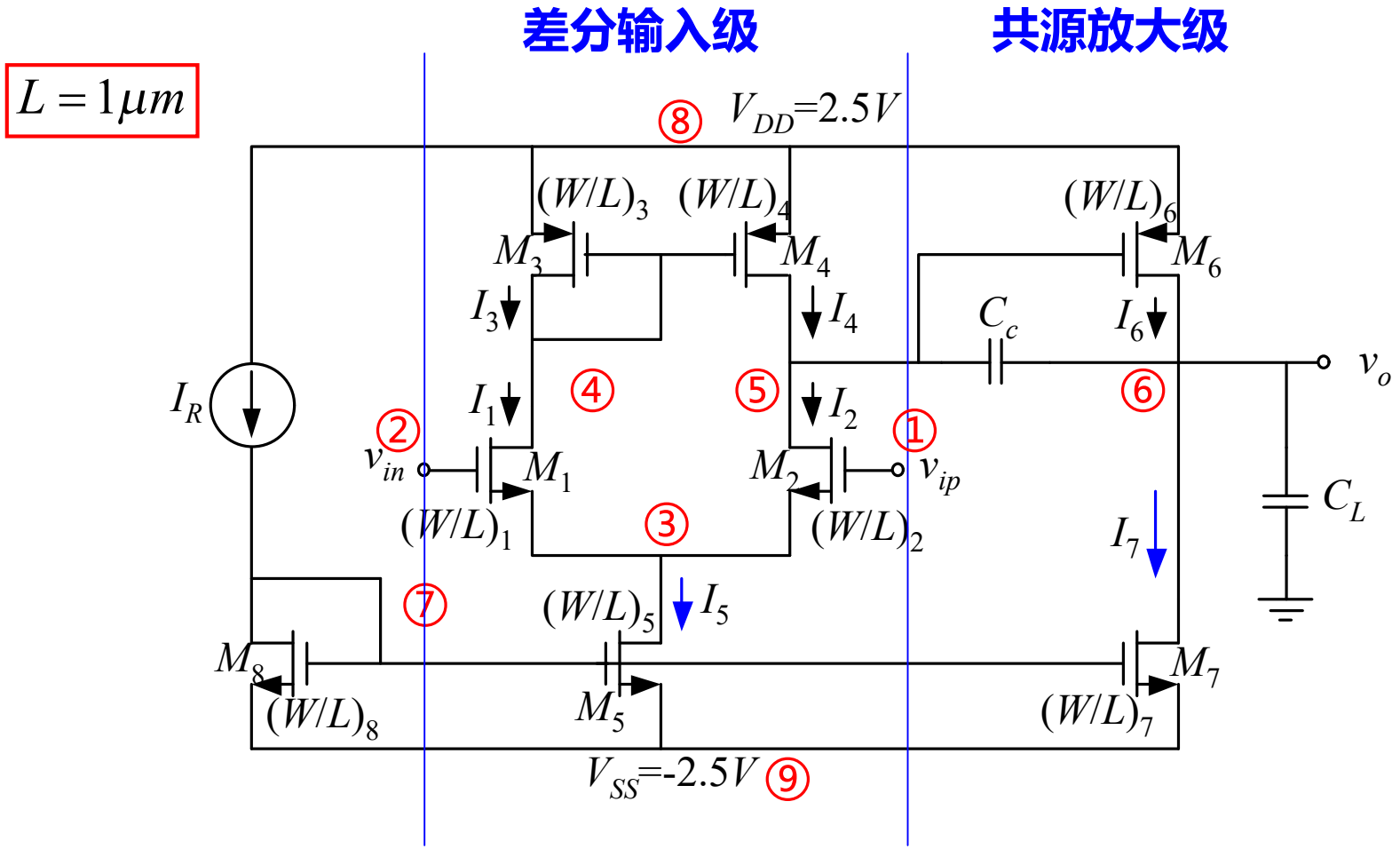
- M1/M2：差分输入；
- M3/M4：电流镜有源负载
- M5：偏置电流源

共源放大级

- M6：共源放大
- M7：偏置电流源

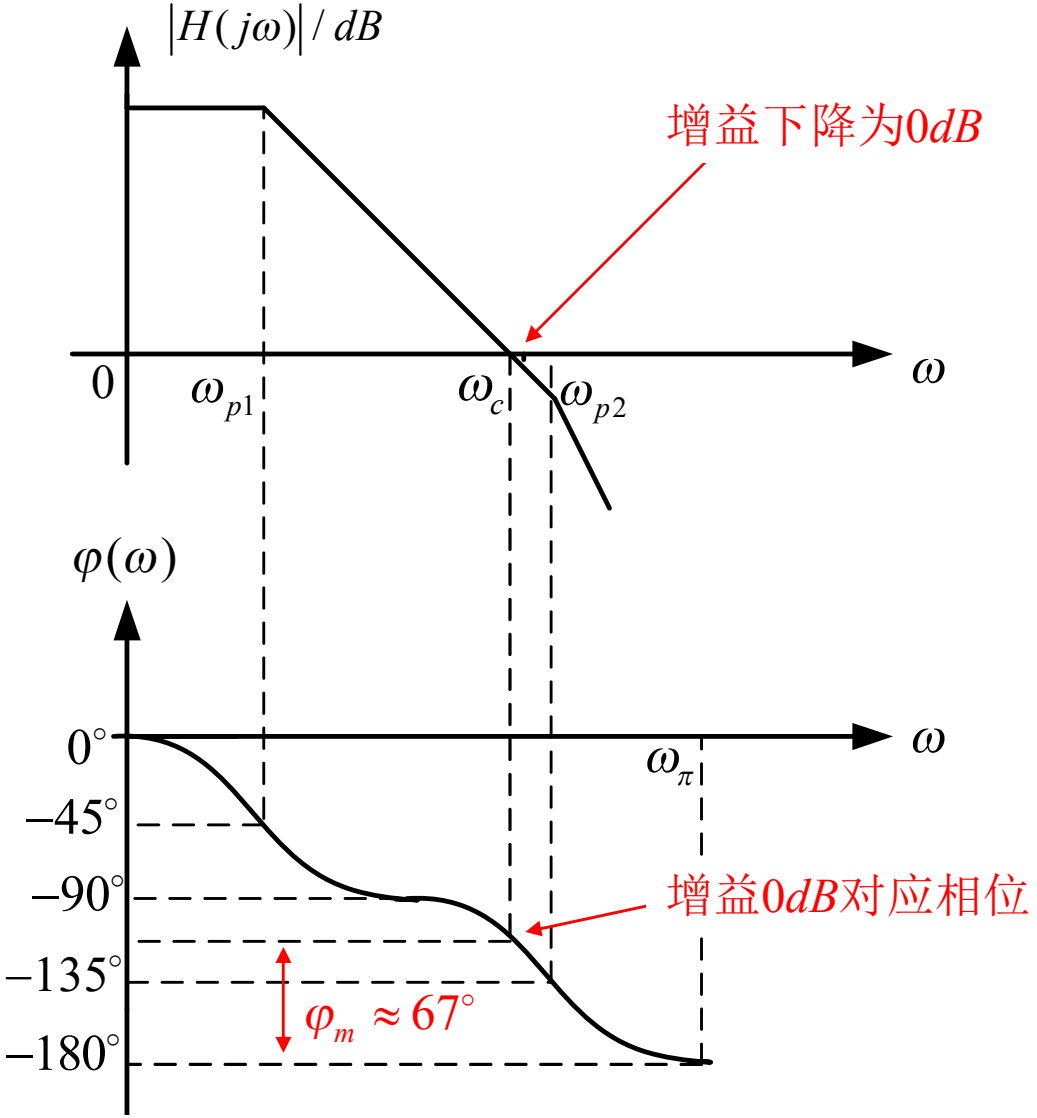
- 电容C_L：负载
- 电容C_C：密勒补偿电容，改善相位裕度

二级运放电路


差分输入级
共源放大级
$L=1\mu m$
⑧ V_{DD}=2.5V
$(W/L)_3$
$(W/L)_4$
$(W/L)_6$
M_3
M_4
M_6
I_3
I_4
C_c
I_6
v_o
I_R
I_1
④
⑤
I_2
⑥
②
①
v_{in}
M_1
M_2
v_{ip}
C_L
$(W/L)_1$
③
$(W/L)_2$
I_7
⑦
$(W/L)_5$
I_5
M_8
M_5
M_7
$(W/L)_8$
$(W/L)_7$
V_{SS}=-2.5V ⑨

电容C_C作用

- 相位裕度 φ_m
- 足够大的相位裕度，保证反馈系统稳定工作
- 一般要求>约60度



二级运放指标

- 增益：>5000（74dB）
- 单位增益带宽（增益带宽积）：>10MHz
- 共模抑制比：>80dB
- 输出电压摆幅：±2V
- 输入共模范围：-1~2V
- 负载电容：10pF
- 压摆率：>15V/μs
- 功耗：<2mW

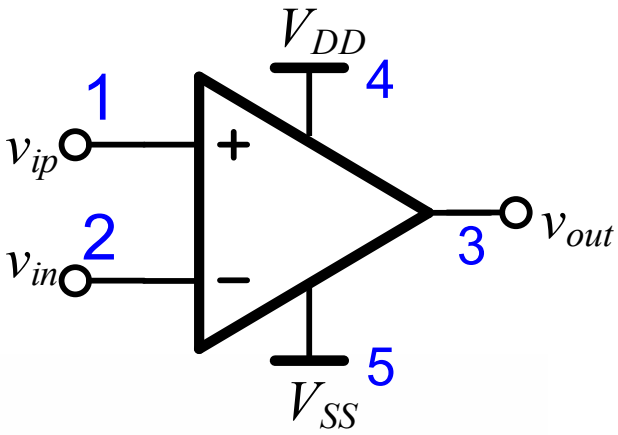
二级运放电路参数

- 利用设计方程，根据指标，可以确定电路的参数
  - 采用P.E.Allen《CMOS模拟集成电路设计》的方法

MOS管	W/L(μm/μm)	I_D(μA)
M_1/M_2	8/1	22.5
M_3/M_4	23/1	22.5
M_5	4/1	45
M_6	190/1	187
M_7	17/1	187
M_8	4/1	45

二级运放网表文件

标号为引脚序号



- OPA.cdl

```
.SUBCKT OPAMP 1 2 6 8 9
* 1 vip  * 2 vin  * 6 vout  * 8 VDD  * 9 VSS

M1 4 2 3 3 n08 W = 8U   L = 1U AD = 48P   AS = 48P   PD = 28U PS = 28U
M2 5 1 3 3 n08 W = 8U   L = 1U AD = 48P   AS = 48P   PD = 28U PS = 28U
M3 4 4 8 8 p08 W = 23U  L = 1U AD = 138P  AS = 138P  PD = 58U PS = 58U
M4 5 4 8 8 p08 W = 23U  L = 1U AD = 138P  AS = 138P  PD = 58U PS = 58U
M5 3 7 9 9 n08 W = 4U   L = 1U AD = 24P   AS = 24P   PD = 20U PS = 20U
M6 6 5 8 8 p08 W = 190U L = 1U AD = 1140P AS = 1140P PD = 392U PS =392U
M7 6 7 9 9 n08 W = 17U  L = 1U AD = 102P  AS = 102P  PD = 46U PS = 46U
M8 7 7 9 9 n08 W = 4U   L = 1U AD = 24P   AS = 24P   PD = 20U PS = 20U
CC 5 6 3.0P
IBIAS 8 7 45U

*.MODEL 语句省略

.ENDS
```

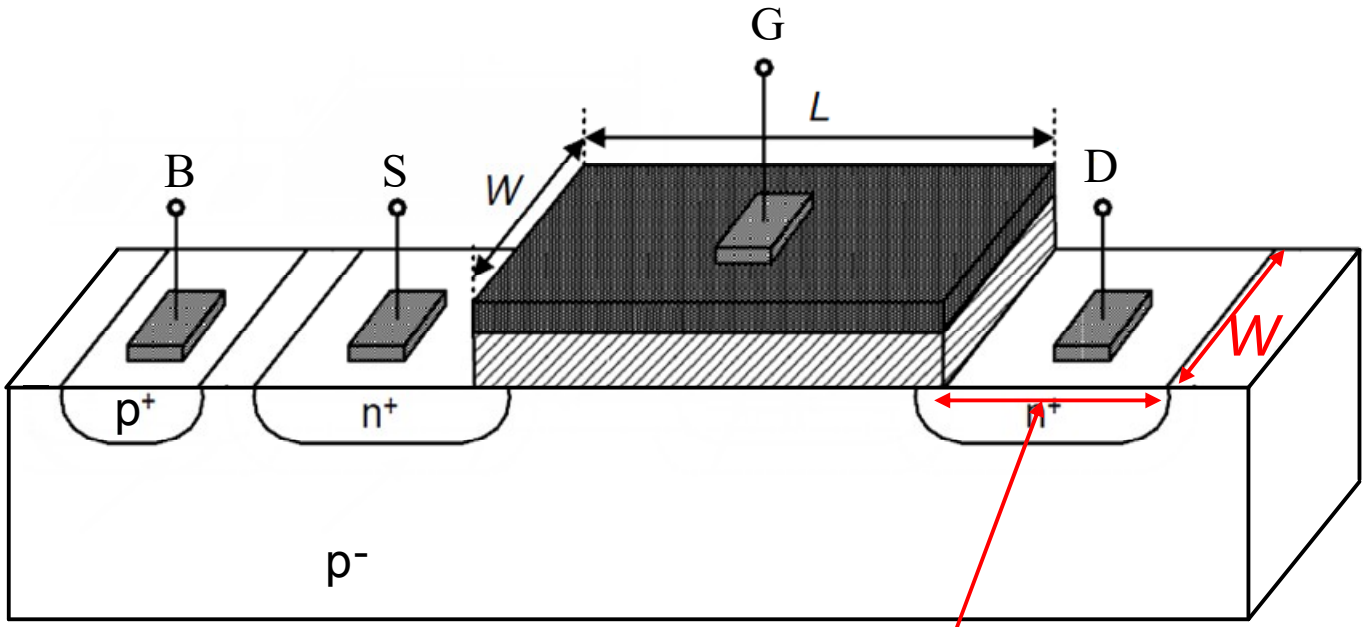
AD/AS/PD/PS参数

- 用于计算MOS管的寄生电容

- AS/AD：源极/漏极的面积
- PS/PD ： 源极/漏极的周长

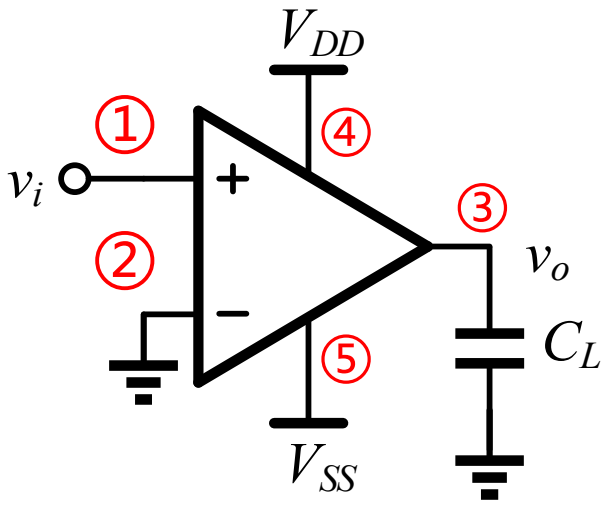
例如：

- AD =漏极的宽度*长度
- PD= 2*(漏极的宽度+长度)



开环测试电路

- 共模输入电压：0V
- 差分输入电压：
  全部接在同相输入端




```
.title OPAMP_open_loop

.include 'OPA.cdl'

X1 1 2 3 4 5 OPAMP
* 1 vip  * 2 vin  * 3 vout  * 4 VDD  * 5 VSS
VDD 4 0 DC  2.5
VSS 0 5 DC  2.5
vvip 1 0 DC 0 AC 1.0
vvin 2 0 DC 0
CL 3 0 10P

.OP                                  * 直流工作点仿真

.DC vvip -0.005 0.005 100U * 直流扫描仿真
.probe dc v(3)

.AC dec 10 10 1g                     * 交流仿真
.probe ac vdb(3) vp(3)

.option post probe

.end
```

MOS管工作区

subckt								
element	0:m1	0:m2	0:m3	0:m4	0:m5	0:m6	0:m7	0:m8
model	0:n08	0:n08	0:p08	0:p08	0:n08	0:p08	0:n08	0:n08
region	Saturati	Saturati	Saturati	Saturati	Saturati	Saturati	Saturati	Saturati
id	22.8882u	22.8882u	-22.8882u	-22.8882u	45.7764u	-202.3046u	202.3046u	45.0000u
ibs	0.	0.	0.	0.	0.	0.	0.	0.
ibd	-25.2142f	-25.2142f	8.9245f	8.9245f	-15.8613f	23.5413f	-26.4587f	-11.3520f
vgs	913.8709m	913.8709m	-892.4533m	-892.4533m	1.1352	-892.4533m	1.1352	1.1352
vds	2.5214	2.5214	-892.4533m	-892.4533m	1.5861	-2.3541	2.6459	1.1352
vbs	0.	0.	0.	0.	0.	0.	0.	0.
vth	700.0000m	700.0000m	-700.0000m	-700.0000m	700.0000m	-700.0000m	700.0000m	700.0000m
vdsat	213.8709m	213.8709m	-192.4533m	-192.4533m	435.2008m	-192.4533m	435.2008m	435.2008m
vod	213.8709m	213.8709m	-192.4533m	-192.4533m	435.2008m	-192.4533m	435.2008m	435.2008m
beta	1.0008m	1.0008m	1.2359m	1.2359m	483.3842u	10.9241m	2.1363m	475.1855u
gam eff	400.0000m	400.0000m	570.0000m	570.0000m	400.0000m	570.0000m	400.0000m	400.0000m
gm	214.0375u	214.0375u	237.8572u	237.8572u	210.3692u	2.1024m	929.7072u	206.8011u
gds	831.6506n	831.6506n	1.0955u	1.0955u	1.7218u	9.0500u	7.3177u	1.7218u
gmb	51.1648u	51.1648u	75.7908u	75.7908u	50.2878u	669.9006u	222.2425u	49.4349u
cdtot	26.1579f	26.1579f	73.8743f	73.8743f	16.6178f	449.6269f	51.7618f	18.2092f
cgtot	17.3109f	17.3109f	48.8817f	48.8817f	8.9057f	399.7531f	35.7045f	8.9000f
cstot	62.0939f	62.0939f	139.4014f	139.4014f	33.3270f	1.1211p	126.8196f	33.3270f
cbtot	72.9264f	72.9264f	168.2634f	168.2634f	42.5562f	1.1930p	144.9203f	44.1533f
cgs	14.4939f	14.4939f	41.8214f	41.8214f	7.2470f	345.4809f	30.7996f	7.2470f
cgd	1.8242f	1.8242f	5.1256f	5.1256f	900.1977a	43.2298f	3.8832f	894.4556a

功耗估算

subckt								
element	0:m1	0:m2	0:m3	0:m4	0:m5	0:m6	0:m7	0:m8
model	0:n08	0:n08	0:p08	0:p08	0:n08	0:p08	0:n08	0:n08
region	Saturati	Saturati	Saturati	Saturati	Saturati	Saturati	Saturati	Saturati
id	22.8882u	22.8882u	-22.8882u	-22.8882u	45.7764u	-202.3046u	202.3046u	45.0000u
ibs	0.	0.	0.	0.	0.	0.	0.	0.
ibd	-25.2142f	-25.2142f	8.9245f	8.9245f	-15.8613f	23.5413f	-26.4587f	-11.3520f
vgs	913.8709m	913.8709m	-892.4533m	-892.4533m	1.1352	-892.4533m	1.1352	1.1352
vds	2.5214	2.5214	-892.4533m	-892.4533m	1.5861	-2.3541	2.6459	1.1352

- 差分输入级：
  5V*45.8uA
- 共源放大级：
  5V*202.3uA
- 参考电流源：
  5V*45uA
- 总功耗：~1.5mW

增益估算

subckt element	0:m1	0:m2	0:m3	0:m4	0:m5	0:m6	0:m7	0:m8
model	0:n08	0:n08	0:p08	0:p08	0:n08	0:p08	0:n08	0:n08
region	Saturati	Saturati	Saturati	Saturati	Saturati	Saturati	Saturati	Saturati
id	22.8882u	22.8882u	-22.8882u	-22.8882u	45.7764u	-202.3046u	202.3046u	45.0000u
ibs	0.	0.	0.	0.	0.	0.	0.	0.
ibd	-25.2142f	-25.2142f	8.9245f	8.9245f	-15.8613f	23.5413f	-26.4587f	-11.3520f
vgs	913.8709m	913.8709m	-892.4533m	-892.4533m	1.1352	-892.4533m	1.1352	1.1352
vds	2.5214	2.5214	-892.4533m	-892.4533m	1.5861	-2.3541	2.6459	1.1352
vbs	0.	0.	0.	0.	0.	0.	0.	0.
vth	700.0000m	700.0000m	-700.0000m	-700.0000m	700.0000m	-700.0000m	700.0000m	700.0000m
vdsat	213.8709m	213.8709m	-192.4533m	-192.4533m	435.2008m	-192.4533m	435.2008m	435.2008m
vod	213.8709m	213.8709m	-192.4533m	-192.4533m	435.2008m	-192.4533m	435.2008m	435.2008m
beta	1.0008m	1.0008m	1.2359m	1.2359m	483.3842u	10.9241m	2.1363m	475.1855u
gam eff	400.0000m	400.0000m	570.0000m	570.0000m	400.0000m	570.0000m	400.0000m	400.0000m
gm	214.0375u	214.0375u	237.8572u	237.8572u	210.3692u	2.1024m	929.7072u	206.8011u
gds	831.6506n	831.6506n	1.0955u	1.0955u	1.7218u	9.0500u	7.3177u	1.7218u
gmb	51.1648u	51.1648u	75.7908u	75.7908u	50.2878u	669.9006u	222.2425u	49.4349u

增益估算

$$A_{v1} = -\frac{g_{m2}}{g_{ds2} + g_{ds4}} = -\frac{214}{0.83 + 1.10} = -111$$

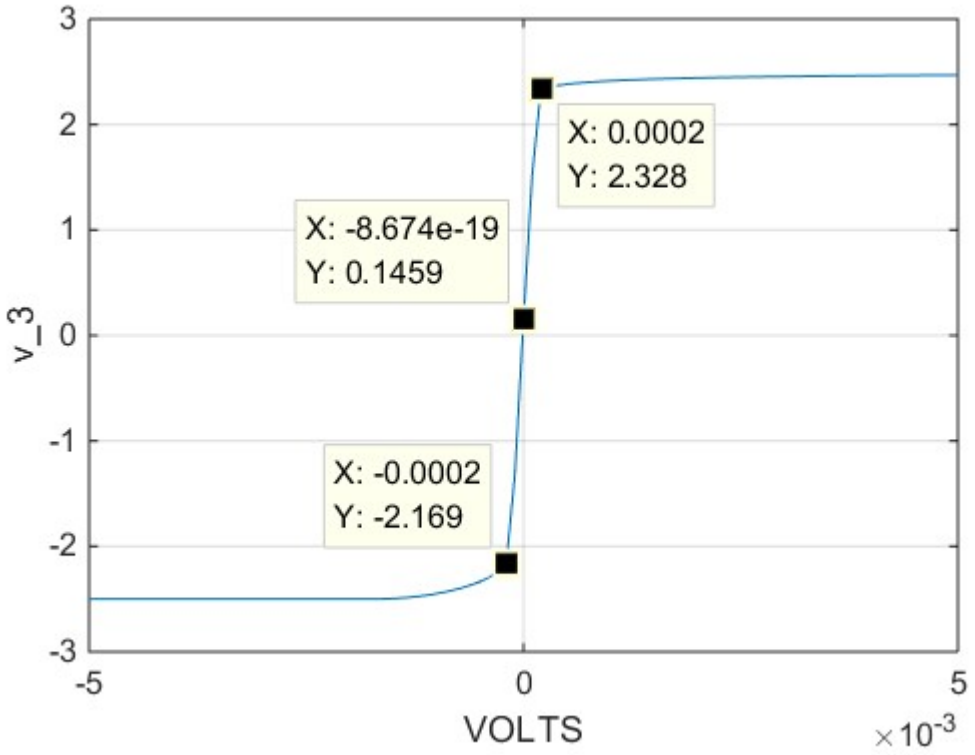
$$A_{v2} = -g_{m6}\frac{1}{g_{ds6} + g_{ds7}} = -\frac{2.1 \times 10^3}{9.05 + 7.32} = -128$$

$$A_v = A_{v1}A_{v2} = 14208$$

- ~83dB

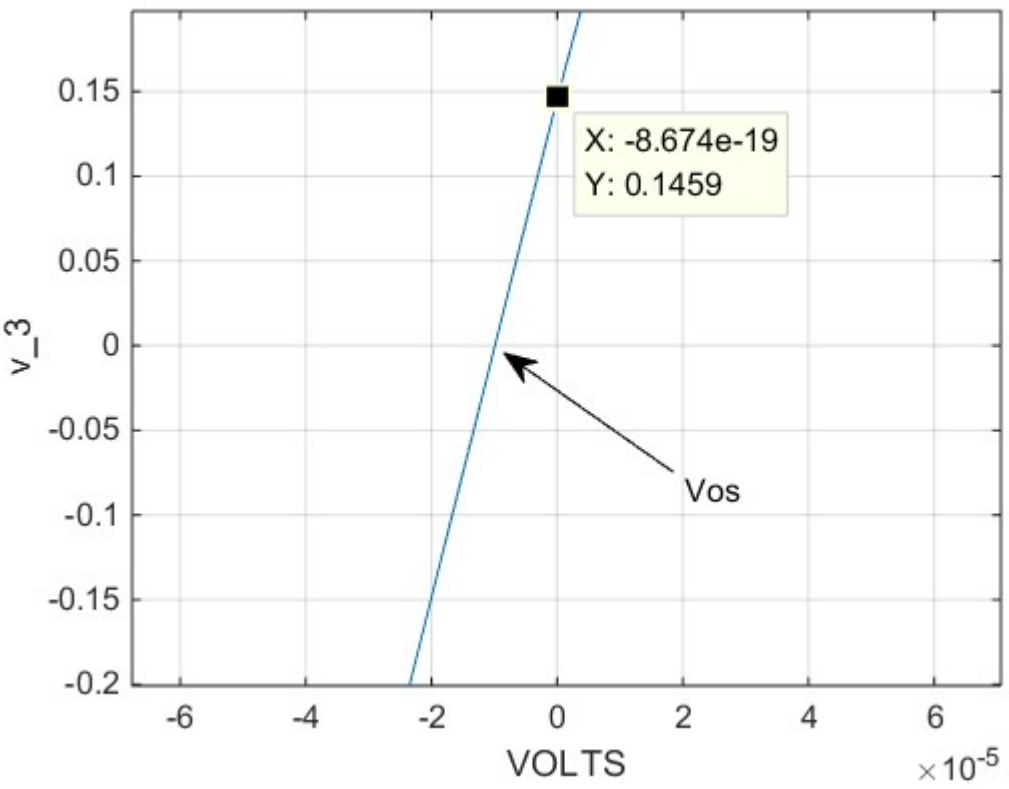
输出电压摆幅

- 输出电压摆幅
  - -2.2~2.3V



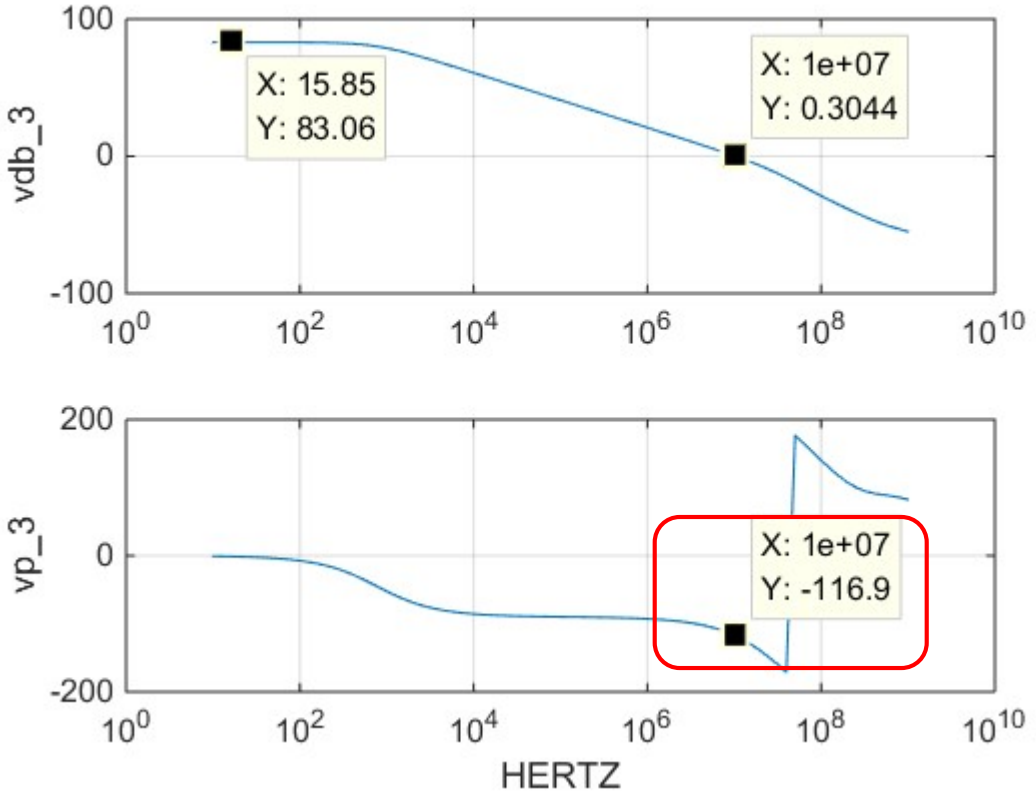
输入失调电压

- 输出失调电压
  - 150mV
- 输入失调电压
  - 10uV
- 没有考虑加工精度可能导致的电路非对称性
  - 偏乐观的估计



开环增益

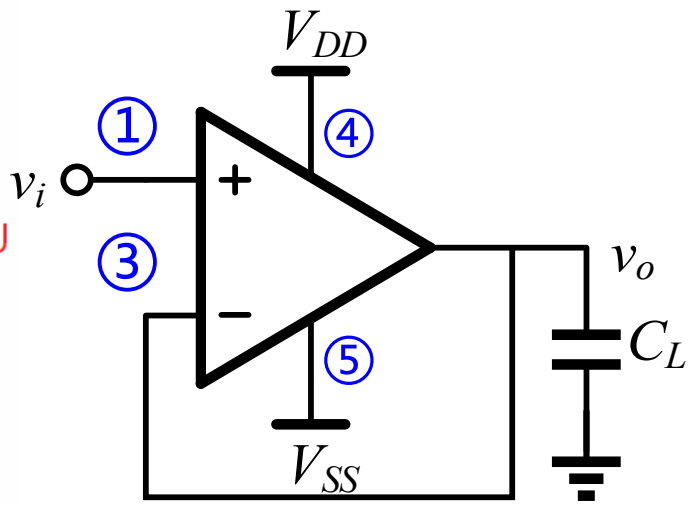
- 直流增益
  - 83dB
- 单位增益带宽
  - 10MHz
- 相位裕度
  - 180-117=63°



单位增益测试电路

```
.title OPAMP_unity_gain

.include 'OPA.cdl'

X1 1 3 3 4 5 OPAMP
* 1 vip  * 2 vin  * 3 vout  * 4 VDD  * 5 VSS
VDD 4 0 DC  2.5
VSS 0 5 DC  2.5
vvip 1 0 PWL(0 -2 10N -2 20N 2 2U 2 2.01U -2 4U -2 4.01U
+ -0.1 6U -0.1 6.01U 0.1 8U 0.1 8.01U -0.1 10U -0.1)
CL 3 0 10P

.DC vvip -2.5 2.5 0.1          * 直流扫描仿真
.probe dc v(3)  id5=id(X1.M5)

.TRAN 0.05U 10U 0 10n          * 瞬态仿真
.probe tran v(3) v(1)

.option post probe

.end
```

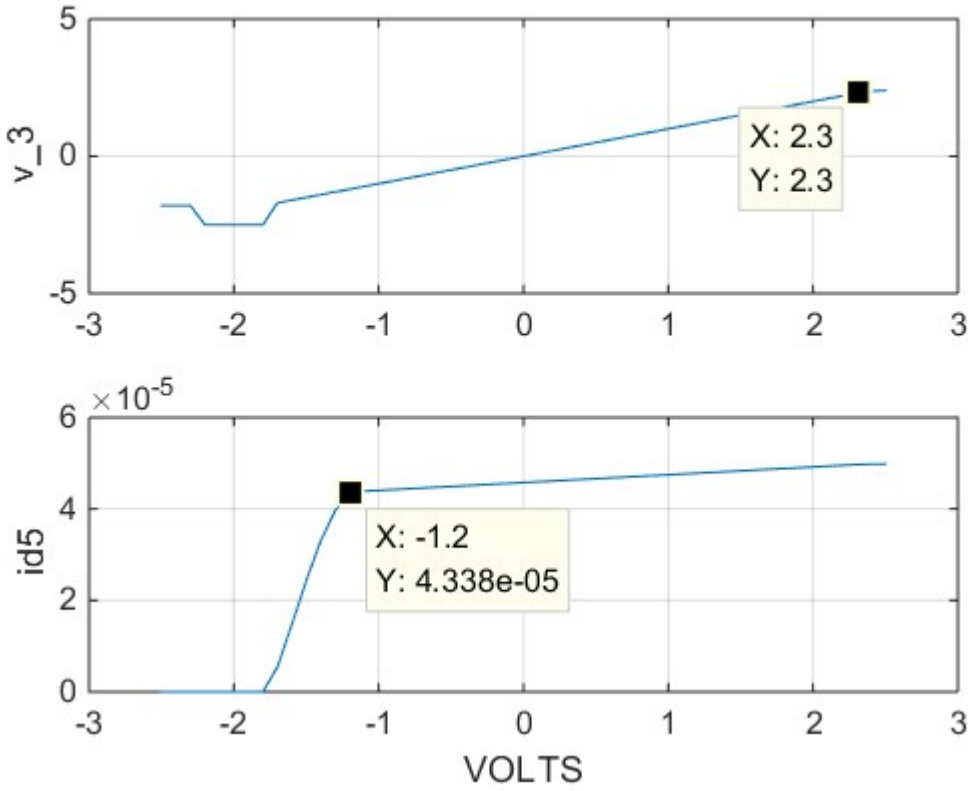
- 运放接成电压跟随器
  - v_o必须跟随v_i变化



共模输入范围

- 最大值
  - 2.3V
- 最小值
  - -1.2V

大于2.3V时，输出饱和

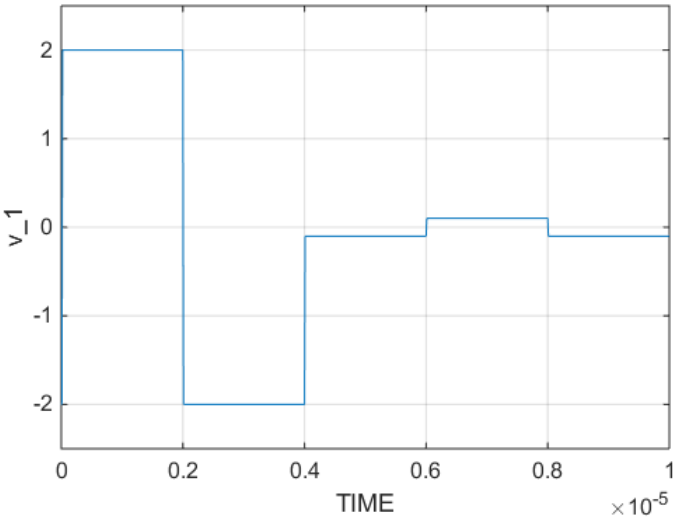


小于-1.2V，M5进入线性区

压摆率

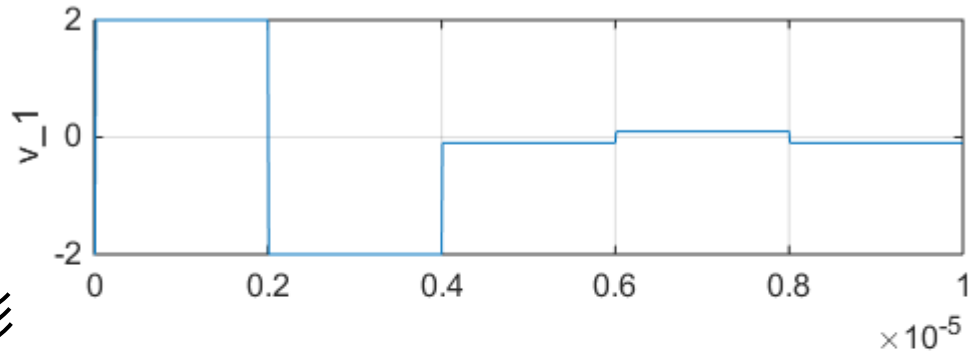
```
.title OPAMP_unity_gain

.include 'OPA.cdl'

X1 1 3 3 4 5 OPAMP
* 1 vip  * 2 vin  * 3 vout  * 4 VDD  * 5 VSS
VDD 4 0 DC  2.5
VSS 0 5 DC  2.5
vvip 1 0 PWL(0 -2 10N -2 20N 2 2U 2 2.01U -2 4U -2 4.01U
+ -0.1 6U -0.1 6.01U 0.1 8U 0.1 8.01U -0.1 10U -0.1)
CL 3 0 10P

.DC vvip -2.5 2.5 0.1          * 直流扫描仿真
.probe dc v(3)  id5=id(X1.M5)

.TRAN 0.05U 10U 0 10n          * 瞬态仿真
.probe tran v(3) v(1)

.option post probe

.end
```

- 输入电压波形
  - 上升/下降时间：10ns
  - 大信号上升/下降幅度：4V
  - 小信号上升/下降幅度：0.2V

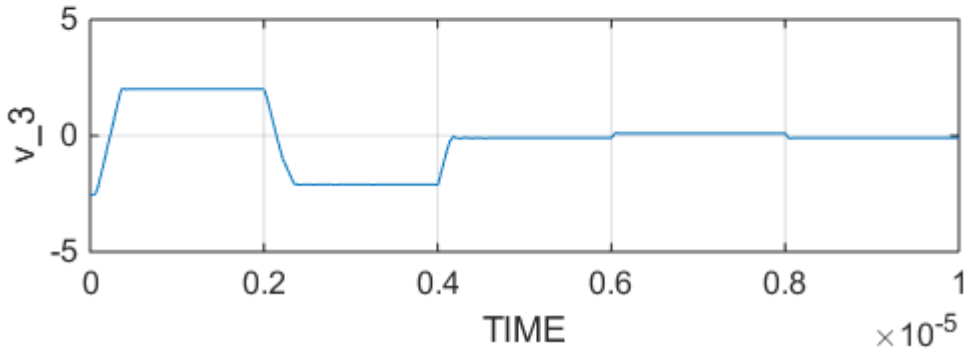


压摆率

- 输入电压波形

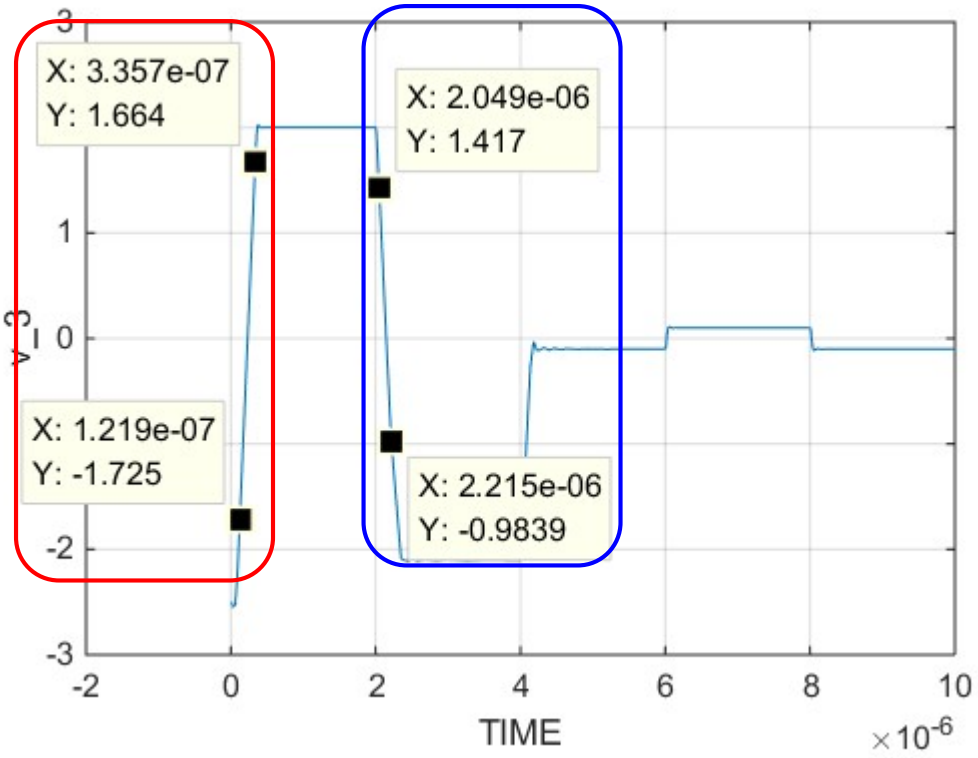


- 输出电压波形



大信号压摆率

- 上行压摆率
  - 15.9V/us
- 下行压摆率
  - -14.5V/us
  - 没有达到指标要求

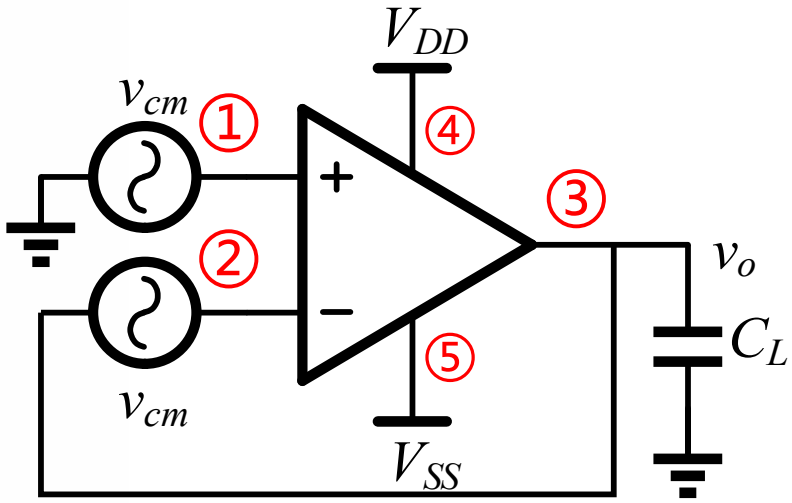


$$\frac{1.664-(-1.725)}{(0.3357-0.1219)\times10^{-6}}=15.9\,V/\mu s$$

$$\frac{-0.9839-(1.417)}{(2.215-2.049)\times10^{-6}}=-14.5\,V/\mu s$$

CMRR测试电路

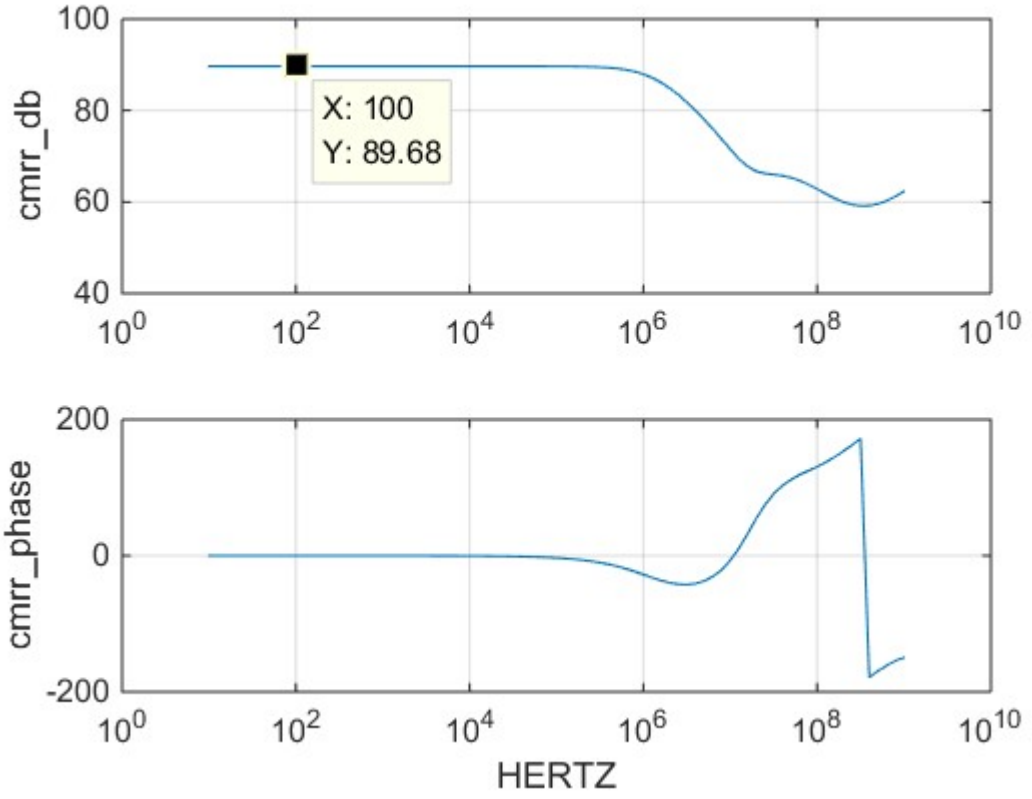
```
.title OPAMP_CMRR

.include 'OPA.cdl'

X1 1 2 3 4 5 OPAMP
* 1 vip  * 2 vin  * 3 vout  * 4 VDD  * 5 VSS
VDD 4 0 DC  2.5
VSS 0 5 DC  2.5
CL 3 0 10P

.PARAM VCM=1
Vcm1 1 0 DC 0 AC VCM
Vcm2 2 3 DC 0 AC VCM

.AC dec 10 10 1g
.probe ac vdb(3) vp(3)
.probe ac cmrr_db=par('- vdb(3)') cmrr_phase=par('- vp(3)')
* Vout / Vcm = 1 / CMRR
* cmrr_db = - (vdb(3))   即，仅正负号区别
* cmrr_phase = - (vp(3))  即，仅正负号区别

.option post probe

.end
```



$$\frac{v_o}{v_{cm}} \cong \frac{1}{CMRR}$$

共模抑制比

- CMRR
  - 90dB



CMOS二级运放指标

设计指标	设计要求	仿真结果
静态功耗	≤2mW	1.5mW
开环直流增益	≥80dB	83dB
单位增益带宽	10MHz	10MHz
相位裕量	≥60°	63°
转换速率	≥15V/us	+15.9, -14.5 (V/us)
共模抑制比	≥80dB	90dB
输出电压摆幅	±2V	+2.3, -2.2 (V)
输入共模范围	-1~2V	+2.3, -1.2 (V)