

# Third SPICE Exercise

Fundamentals Of Electronics - a.a. 2018-2019 - University of Padua (Italy)

Pietro Prandini (mat. 1097752)

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# Chapter 1

## Differential amplifier with MOS current source

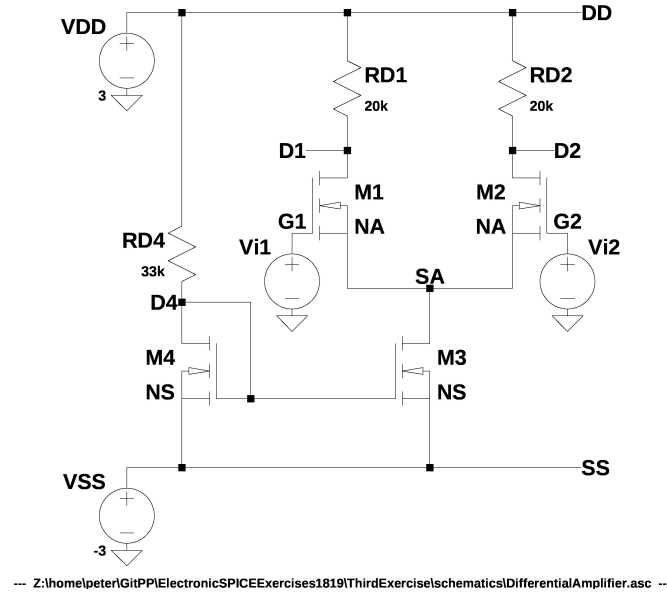


Figure 1.1: Differential amplifier with MOS current source

Initial data:

$$V_t = 0.5V \quad (1.1)$$

$$K'_n = \mu_n C_{ox} = 200 \frac{\mu A}{V^2} \quad (1.2)$$

$$\lambda = 0 \quad (1.3)$$

$$\left(\frac{W}{L}\right)_1 = \left(\frac{W}{L}\right)_2 = 20 \quad (1.4)$$

$$\left(\frac{W}{L}\right)_3 = \left(\frac{W}{L}\right)_4 = 5 \quad (1.5)$$

$$R_{D1} = R_{D2} = R_D = 20k\Omega \quad (1.6)$$

$$R_{D4} = \frac{30}{1000} \cdot 1097752\Omega = 32.93k\Omega \simeq 33k\Omega \quad (1.7)$$

$$V_{DD} = 3V \quad (1.8)$$

$$V_{SS} = -3V \quad (1.9)$$

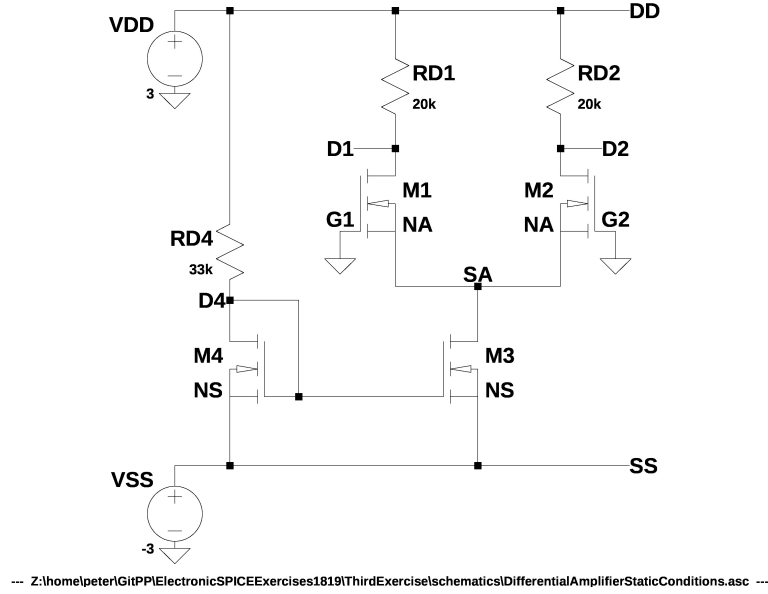


Figure 1.2: Differential amplifier with MOS current source - Static conditions

## 1.1 Static conditions - Analytic solution

On static conditions it's considered the input signals  $V_{i1}$  and  $V_{i2}$  turned off. The equivalent circuit is on figure 1.2.

### 1.1.1 MOSFET $M_4$

#### Saturation mode checks

The transistor  $M_4$  has a short circuit between its drain and its gate, so the transistor works in saturation mode and the voltage between the drain and the gate are the same of the voltage between the gate and the source:

$$V_{D_4SS} > V_{G_4SS} - V_t \xrightarrow{V_{G_4SS}=V_{D_4SS}} V_{D_4SS} > V_{D_4SS} - V_t \quad (1.10)$$

$$0 > -V_t \quad (\text{Always true: } V_t > 0) \quad (1.11)$$

It's requested to pay attention to the another check to confirm the work on saturation mode:

$$V_{G_4SS} > V_t \xrightarrow{V_{G_4SS}=V_{D_4SS}} V_{D_4SS} > V_t \quad (1.12)$$

$$V_{D_4SS} \quad (= V_{G_4SS})$$

Supposing that the transistor  $M_4$  works on the saturation mode (see the section 1.1.1 for details), the current  $I_{D_4}$  could be calculated as:

$$I_{D_4} = \frac{1}{2} K'_n \left( \frac{W}{L} \right)_4 (V_{D_4SS} - V_t)^2 \quad (1.13)$$

Other expression of the current  $I_{D_4}$  could be calculated using the LKT:

$$V_{DD} - R_{D_4} I_{D_4} - V_{D_4SS} - V_{SS} = 0 \implies I_{D_4} = \frac{V_{DD} - V_{D_4SS} - V_{SS}}{R_{D_4}} \quad (1.14)$$

Using the equations 1.13 and 1.14 it's possible calculating  $V_{D_4SS}$ :

$$\frac{1}{2} K'_n \left( \frac{W}{L} \right)_4 (V_{D_4SS} - V_t)^2 = \frac{V_{DD} - V_{D_4SS} - V_{SS}}{R_{D_4}} \quad (1.15)$$

$$\frac{1}{2} \cdot 200 \frac{\mu A}{V^2} \cdot 5 \frac{\mu m}{\mu m} (V_{D_4SS} - 0.5V)^2 = \frac{3V - V_{D_4SS} - (-3V)}{33k\Omega} \quad (1.16)$$

$$500 \frac{\mu A}{V^2} (V_{D_4SS} - 0.5V)^2 = \frac{6}{33} mA - \frac{1}{33k\Omega} V_{D_4SS} \quad (1.17)$$

$$500 \frac{\mu A}{V^2} (V_{D_4SS}^2 - V_{D_4SS} \cdot V + 0.25V^2) = \frac{6}{33} mA - \frac{1}{33k\Omega} V_{D_4SS} \quad (1.18)$$

$$500 \frac{\mu A}{V^2} \cdot V_{D_4SS}^2 + \left( -500 \frac{\mu A}{V^2} V + \frac{1}{33k\Omega} \right) V_{D_4SS} + 500 \frac{\mu A}{V^2} \cdot 0.25V^2 - \frac{6}{33} mA = 0 \quad (1.19)$$

$$0.5 \frac{mA}{V^2} \cdot V_{D_4SS}^2 + \left( -0.5 \frac{mA}{V^2} V + \frac{1}{33k\Omega} \right) V_{D_4SS} + 0.5 \frac{mA}{V^2} \cdot 0.25V^2 - \frac{6}{33} mA = 0 \quad (1.20)$$

$$\left( 0.5 \frac{mA}{V^2} \right) V_{D_4SS}^2 + \left( -\frac{31}{66} \frac{mA}{V} \right) V_{D_4SS} + \left( -\frac{5}{88} mA \right) = 0 \quad (1.21)$$

$$V_{D_4SS_{1,2}} = \frac{-\left(-\frac{31}{66} \frac{mA}{V}\right) \pm \sqrt{\left(-\frac{31}{66} \frac{mA}{V}\right)^2 - 4 \cdot \left(0.5 \frac{mA}{V^2}\right) \cdot \left(-\frac{5}{88} mA\right)}}{2 \cdot 0.5 \frac{mA}{V^2}} = \begin{cases} 1.04784V \\ -0.10845V \end{cases} \quad \text{Not possible: } < \text{ of } V_t \quad (1.22)$$

Now it's possible to check the last equation that can confirm the work on saturation mode of the MOSFET  $M_4$  (equation 1.12):

$$1.04784V > 0.5V \quad M_4 \text{ works on saturation mode.} \quad (1.23)$$

$I_{D_4}$

Using the equation 1.13 and the result of the equation 1.22:

$$I_{D_4} = \frac{1}{2} \cdot 200 \mu A / V^2 \cdot 5 \frac{\mu m}{\mu m} \cdot (1.04784V - 0.5V)^2 = 150.06433 \mu A \quad (1.24)$$

### 1.1.2 MOSFET $M_3$

$V_{G_3SS}$

Observing the circuit represented on the figure 1.2 it's clear that the voltage  $V_{G_3SS}$  is equal to the voltage  $V_{D_4SS}$  calculated in the equation 1.22.

$$V_{G_3SS} = V_{D_4SS} \quad (1.25)$$

$I_{S_A}$

As agree with the consideration of the section 1.1.2 and supposing the work of the MOSFET  $M_3$  on the saturation mode, it's possible calculating the drain current of the MOSFET  $M_3$ :

$$I_{S_A} = \frac{1}{2} K'_n \left( \frac{W}{L} \right)_3 (V_{D_4SS} - V_t)^2 \quad (1.26)$$

$$I_{S_A} = \frac{1}{2} \cdot 200 \mu A / V^2 \cdot 5 \frac{\mu m}{\mu m} \cdot (1.04784V - 0.5V)^2 = 150.06433 \mu A \quad (1.27)$$

### Saturation mode checks

For obtaining the confirm of the work of the MOSFET  $M_3$  on saturation mode the next two equations have to be satisfied:

$$V_{D_3SS} > V_{G_3SS} - V_t \xrightarrow{V_{D_3SS}=V_{S_ASS}, V_{G_3SS}=V_{D_4SS}} V_{S_ASS} > V_{D_4SS} - V_t \quad (1.28)$$

$$V_{G_3SS} > V_t \xrightarrow{V_{G_3SS}=V_{D_4SS}} V_{D_4SS} > V_t \quad (1.29)$$

The equation 1.28 hasn't to be checked,  $V_{S_ASS}$  isn't calculated yet.

The equation 1.29 is satisfied (see the equation 1.23).

### 1.1.3 MOSFET $M_1$ and MOSFET $M_2$

The MOSFET  $M_1$  and the MOSFET  $M_2$  have the same dimension and the same constructive parameters (see initial data at the start of this chapter 1).

They also have the same voltage applied to every their pins (see figure 1.2).

So, additionally supposing the work on the saturation mode of  $M_1$  and  $M_2$ , it's possible to confirm the next equations:

$$I_{D_1} = I_{D_2} \quad (1.30)$$

$$V_{G_1 S_A} = V_{G_2 S_A} \quad (1.31)$$

$$V_{D_1 S_A} = V_{D_2 S_A} \quad (1.32)$$

$$I_{D_1} (= I_{D_2})$$

$$\text{LKC node } S_A: I_{D_1} + I_{D_2} - I_{S_A} = 0 \xrightarrow{\text{eq.1.30}} 2I_{D_1} - I_{S_A} = 0 \implies I_{D_1} = \frac{I_{S_A}}{2} \quad (1.33)$$

$$I_{D_1} = \frac{150.06433\mu A}{2} = 75.03217\mu A \quad (1.34)$$

$$V_{G_1 S_A} (= V_{G_2 S_A})$$

Supposing the work of the MOSFET  $M_1$  (equally  $M_2$ ) on the saturation mode, the drain current could be calculated as:

$$I_{D_1} = \frac{1}{2} K'_n \left( \frac{W}{L} \right)_1 (V_{G_1 S_A} - V_t)^2 \quad (1.35)$$

It's possible using the equation 1.35 to calculate  $V_{G_1 S_A}$ :

$$I_{D_1} = \frac{1}{2} K'_n \left( \frac{W}{L} \right)_1 (V_{G_1 S_A} - V_t)^2 \quad (1.36)$$

$$\sqrt{I_{D_1}} = \sqrt{\frac{1}{2} K'_n \left( \frac{W}{L} \right)_1} (V_{G_1 S_A} - V_t) \quad (1.37)$$

$$\sqrt{\frac{I_{D_1}}{\frac{1}{2} K'_n \left( \frac{W}{L} \right)_1}} = V_{G_1 S_A} - V_t \quad (1.38)$$

$$V_{G_1 S_A} = \sqrt{\frac{2I_{D_1}}{K'_n \left( \frac{W}{L} \right)_1}} + V_t \quad (1.39)$$

$$V_{G_1 S_A} = \sqrt{\frac{2 \cdot 75.03217\mu A}{200\mu A \cdot 20 \frac{\mu A}{\mu A}}} + 0.5V \quad (1.40)$$

$$V_{G_1 S_A} = 0.69369V \quad (1.41)$$

$V_{S_A}$  Now it's possible calculating the voltage on the node  $S_A$ :

$$V_{G_1 S_A} = V_{G_1} - V_{S_A} \implies V_{S_A} = V_{G_1} - V_{G_1 S_A} \xrightarrow{V_{G_1}=0, \text{eq.1.41}} V_{S_A} = -0.69369V \quad (1.42)$$

#### Saturation mode checks

In order to check the mode of the  $M_1$  (and  $M_2$ ) the equations to respect are 1.43 and 1.48.

$$V_{D_1 S_A} > V_{G_1 S_A} - V_t \quad (1.43)$$

$$V_{D_1} - V_{S_A} > V_{G_1 S_A} - V_t \quad (1.44)$$

$$I_{D_1} R_{D_1} - V_{S_A} > V_{G_1 S_A} - V_t \quad (1.45)$$

$$75.03217\mu A \cdot 20k\Omega - (-0.69369V) > 0.69369V - 0.5V \quad (1.46)$$

$$2.19433V > 0.19369V \quad \text{True.} \quad (1.47)$$



$$V_{G_1 S_A} > V_t \quad (1.48)$$

$$0.69369V > 0.5V \quad \text{True.} \quad (1.49)$$

Checking the mode of the  $M3$ 's work (see equation 1.28):

$$V_{S_A SS} > V_{D_4 SS} - V_t \quad (1.50)$$

$$V_{S_A} - V_{SS} > V_{D_4 SS} - V_t \quad (1.51)$$

$$-0.69369V - (-3V) > 1.04784V - 0.5V \quad (1.52)$$

$$2.30631V > 0.54784V \quad M_3 \text{ works on the saturation mode.} \quad (1.53)$$

### 1.1.4 MOSFET $V_{DSQ}$ , $V_{GSQ}$ , $I_{DQ}$ - Resuming

MOSFET	$V_{DSQ}$	$V_{GSQ}$	$I_{DQ}$
$M1$	$V_{D_1 S_A} = 2.19433V$	$V_{G_1 S_A} = 0.69369V$	$I_{D_1} = 75.03217\mu A$
$M2$	$V_{D_2 S_A} = 2.19433V$	$V_{G_2 S_A} = 0.69369V$	$I_{D_2} = 75.03217\mu A$
$M3$	$V_{S_A SS} = 2.30631V$	$V_{D_4 SS} = 1.04784V$	$I_{S_A} = 150.06433\mu A$
$M4$	$V_{D_4 SS} = 1.04784V$	$V_{D_4 SS} = 1.04784V$	$I_{D_4} = 150.06433\mu A$

### 1.1.5 $g_m$

$$g_{m_1} = g_{m_2} = K'_n \left( \frac{W}{L} \right)_1 (V_{G_1 S_A} - V_t) \quad (1.54)$$

$$= 200 \frac{\mu A}{V^2} \cdot 20 \frac{\mu A}{\mu A} \cdot (0.69369V - 0.5V) \quad (1.55)$$

$$= 774.76\mu A/V \quad (1.56)$$

### 1.1.6 MOSFET $M_3$ with $\lambda = 0.02$

From now the MOSFET  $M_3$  is considered with  $\lambda = 0.02$ .

On this way there are some changes of the voltages and the currents of the circuit but they could be considered negligible, so it's considered true the past result from now too.

With  $\lambda = 0.02$ , the  $r_0$  has a finite value:

$$r_0 = \frac{1}{\lambda I_{S_A}} = \frac{1}{0.02 \cdot 150.06433\mu A} \simeq 333.2k\Omega \quad (1.57)$$

It's possible see the  $r_0$  resitances in the small signal circuit by using the PI model of the transistor MOSFET (figure 1.3).

In the small signal circuit are considered only the alternate sources, so the  $V_{DD}$  and the  $V_{SS}$  voltage sources are substituted by a short circuit.

In this way the mirror current source composed by the MOSFET  $M_4$  and the MOSFET  $M_5$  are off because the drain, the source and the gate of these MOSFETs have no voltage applied. So we can simplify the small signal circuit of the figure 1.3 to the small signal circuit of the figure 1.4.

Now it could be clear the effect of the  $\lambda = 0.02$  of the MOSFET  $M_3$  because its resistance  $r_0$  has an effect to the gain of the circuit if the voltage of the node  $S_A$  is different than null.

### 1.1.7 Gain single ended

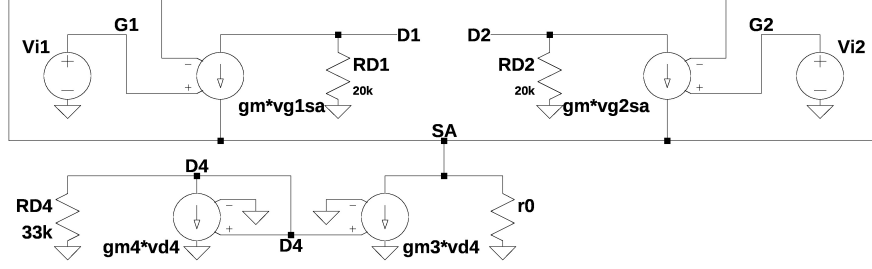
#### Differential pure signal

Now it's applied small alternate voltage signal to the circuit of the figure 1.4:

$$V_{i_1} = +\frac{V_{id}}{2} \quad (1.58)$$

$$V_{i_2} = -\frac{V_{id}}{2} \quad (1.59)$$

Applying a small alternate voltage signal to the circuit of the figure 1.4 there aren't current on the resistance  $r_0$  so it could be treated as a short circuit.



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Figure 1.3: Small signal circuit by using the PI model of the Transistor MOSFET

Given that the circuit of the figure 1.4 is symmetrical it's possible analyse the single ended behaviour of the circuit on figure 1.5.

It's possible finding the single ended gain  $A_d$  for a small differential signal by calculate first the single ended gain (eq. 1.60, 1.61 and 1.67).

$$V_{D1} = -g_m V_{G1} R_{D1} \xrightarrow{(eq.1.58)} V_{D2} = -g_m \frac{V_{id}}{2} R_{D2} \implies \frac{V_{D1}}{V_{id}} = -\frac{g_m R_{D1}}{2} = A_{d_{single-ended.1}} \quad (1.60)$$

$$V_{D2} = -g_m V_{G2} R_{D2} \xrightarrow{(eq.1.59)} V_{D2} = -g_m \left( -\frac{V_{id}}{2} \right) R_{D2} \implies \frac{V_{D2}}{V_{id}} = \frac{g_m R_{D2}}{2} = A_{d_{single-ended.2}} \quad (1.61)$$

$$A_d = \frac{V_{D2} - V_{D1}}{V_{id}} \quad (1.62)$$

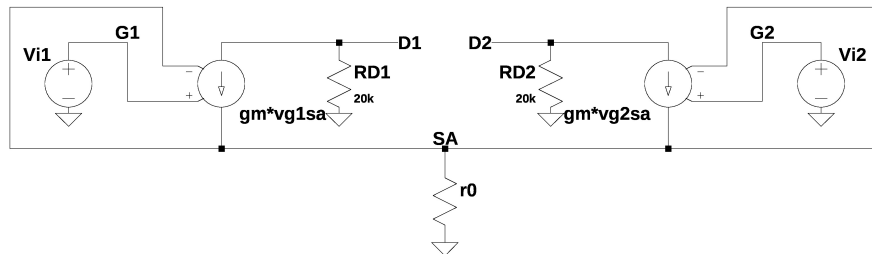
$$= A_{d_{single-ended.2}} - A_{d_{single-ended.1}} \quad (1.63)$$

$$= \frac{g_m R_{D2}}{2} - \left( -\frac{g_m R_{D1}}{2} \right) \quad (1.64)$$

$$= \frac{g_m R_{D2}}{2} + \frac{g_m R_{D1}}{2} \quad (1.65)$$

$$= \frac{g_m R_D}{2} + \frac{g_m R_D}{2} \quad (\text{see eq. 1.6}) \quad (1.66)$$

$$= g_m R_D \quad (1.67)$$



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Figure 1.4: Small signal circuit by using the PI model of the Transistor MOSFET - simplifications



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Figure 1.5: Small signal circuit single ended for a differential pure signal

## 1.2 SPICE analysis

### 1.2.1 Operating Point on static conditions

```

* Differential Amplifier – Static conditions
*****
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*****

* Parameters
.param RD = 20k

* NMOS models
.model NA NMOS VT0=0.5 KP=200u LAMBDA=0 W=4.00u L=0.20u
.model NS NMOS VT0=0.5 KP=200u LAMBDA=0 W=1.25u L=0.25u

* Resistances
RD1 DD D1 {RD}
RD2 DD D2 {RD}
RD4 DD D4 33k

* Transistors
M1 D1 G1 SA SA NA
M2 D2 G2 SA SA NA
M3 SA D4 SS SS NS
M4 D4 D4 SS SS NS

* Voltage sources
VDD DD 0 3
VSS SS 0 -3
Vi1 G1 0 0
Vi2 G2 0 0

* Analysis
.op

.END

```

#### — Operating Point —

V(dd):	3	voltage
V(d1):	1.49935	voltage
V(d2):	1.49935	voltage
V(d4):	-1.95216	voltage
V(g1):	0	voltage
V(sa):	-0.693691	voltage
V(g2):	0	voltage
V(ss):	-3	voltage
Id(M4):	0.000150065	device_current
Ig(M4):	0	device_current
Ib(M4):	-1.05784e-012	device_current
Is(M4):	-0.000150065	device_current
Id(M3):	0.000150065	device_current
Ig(M3):	0	device_current
Ib(M3):	-2.31631e-012	device_current

Is(M3):	-0.000150065	device_current
Id(M2):	7.50327e-005	device_current
Ig(M2):	0	device_current
Ib(M2):	-2.20304e-012	device_current
Is(M2):	-7.50327e-005	device_current
Id(M1):	7.50327e-005	device_current
Ig(M1):	0	device_current
Ib(M1):	-2.20304e-012	device_current
Is(M1):	-7.50327e-005	device_current
I(Rd4):	0.000150065	device_current
I(Rd2):	7.50327e-005	device_current
I(Rd1):	7.50327e-005	device_current
I(Vi2):	0	device_current
I(Vi1):	0	device_current
I(Vss):	0.000300131	device_current
I(Vdd):	-0.000300131	device_current

### 1.2.2 Operating Point - common mode signal

```

* Differential Amplifier – Common Mode signals
*****
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*****

* Parameters
.param RD = 20k

* NMOS models
.model NA NMOS VT0=0.5 KP=200u LAMBDA=0 W=4.00u L=0.20u
.model NS NMOS VT0=0.5 KP=200u LAMBDA=0 W=1.25u L=0.25u

* Resistances
RD1 DD D1 {RD}
RD2 DD D2 {RD}
RD4 DD D4 33k

* Transistors
M1 D1 G1 SA SA NA
M2 D2 G2 SA SA NA
M3 SA D4 SS SS NS
M4 D4 D4 SS SS NS

* Voltage sources
VDD DD 0 3
VSS SS 0 -3
Vi1 G1 0 sine(0 10m 10k 0 0 0)
Vi2 G2 0 sine(0 10m 10k 0 0 0)

* Analysis
.op

.END

```

—— Operating Point ——

```

V(dd):      3          voltage
V(d1):      1.49935    voltage
V(d2):      1.49935    voltage
V(d4):      -1.95216   voltage
V(g1):      0          voltage
V(sa):      -0.693691  voltage
V(g2):      0          voltage
V(ss):      -3         voltage
Id(M4):     0.000150065 device_current
Ig(M4):     0          device_current
Ib(M4):     -1.05784e-012 device_current
Is(M4):     -0.000150065 device_current
Id(M3):     0.000150065 device_current
Ig(M3):     0          device_current
Ib(M3):     -2.31631e-012 device_current
Is(M3):     -0.000150065 device_current
Id(M2):     7.50327e-005 device_current
Ig(M2):     0          device_current
Ib(M2):     -2.20304e-012 device_current
Is(M2):     -7.50327e-005 device_current
Id(M1):     7.50327e-005 device_current
Ig(M1):     0          device_current
Ib(M1):     -2.20304e-012 device_current
Is(M1):     -7.50327e-005 device_current
I(Rd4):     0.000150065 device_current
I(Rd2):     7.50327e-005 device_current
I(Rd1):     7.50327e-005 device_current
I(Vi2):     0          device_current
I(Vi1):     0          device_current
I(Vss):     0.000300131 device_current
I(Vdd):     -0.000300131 device_current

```

### 1.2.3 Operating Point - differential signals

```

* Differential Amplifier – Differential signals
*****
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*****

* Parameters
.param RD = 20k

* NMOS models
.model NA NMOS VT0=0.5 KP=200u LAMBDA=0 W=4.00u L=0.20u
.model NS NMOS VT0=0.5 KP=200u LAMBDA=0 W=1.25u L=0.25u
.model NS3 NMOS VT0=0.5 KP=200u LAMBDA=0.02 W=1.25u L=0.25u

* Resistances
RD1 DD D1 {RD}
RD2 DD D2 {RD}
RD4 DD D4 33k

```

```

* Transistors
M1 D1 G1 SA SA NA
M2 D2 G2 SA SA NA
M3 SA D4 SS SS NS3
M4 D4 D4 SS SS NS

* Voltage sources
VDD DD 0 3
VSS SS 0 -3
Vi1 G1 0 sine(0 10m 10k 0 0 0)
Vi2 0 G2 sine(0 10m 10k 0 0 0)

* Analysis
.TRAN 0u 250u 0 1u

.END

```

—— Operating Point ——

V(dd):	3	voltage
V(d1):	1.49935	voltage
V(d2):	1.49935	voltage
V(d4):	-1.95216	voltage
V(g1):	0	voltage
V(sa):	-0.693691	voltage
V(g2):	0	voltage
V(ss):	-3	voltage
Id(M4):	0.000150065	device_current
Ig(M4):	0	device_current
Ib(M4):	-1.05784e-012	device_current
Is(M4):	-0.000150065	device_current
Id(M3):	0.000150065	device_current
Ig(M3):	0	device_current
Ib(M3):	-2.31631e-012	device_current
Is(M3):	-0.000150065	device_current
Id(M2):	7.50327e-005	device_current
Ig(M2):	0	device_current
Ib(M2):	-2.20304e-012	device_current
Is(M2):	-7.50327e-005	device_current
Id(M1):	7.50327e-005	device_current
Ig(M1):	0	device_current
Ib(M1):	-2.20304e-012	device_current
Is(M1):	-7.50327e-005	device_current
I(Rd4):	0.000150065	device_current
I(Rd2):	7.50327e-005	device_current
I(Rd1):	7.50327e-005	device_current
I(Vi2):	0	device_current
I(Vi1):	0	device_current
I(Vss):	0.000300131	device_current
I(Vdd):	-0.000300131	device_current