Analog Lab (EE2401)
Experiment 1 : Inverter characteristics

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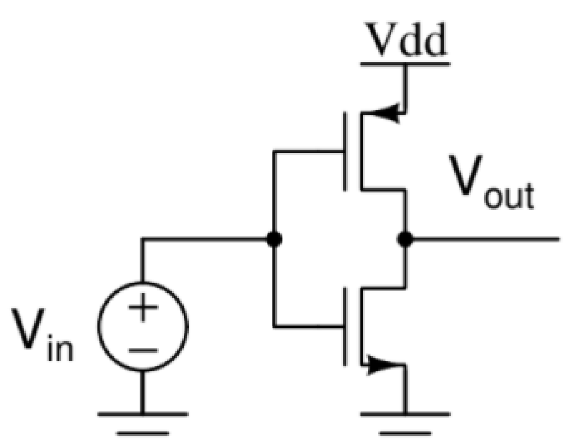
1 Aim

our aim here is to understand how an inverter works and understand it's characteristics.

Inverter

An inverter does the functions of Not gate i.e. it negates the input.

CMOS inverter



Inverter using NMOS and PMOS

2 Problem statement)

1. Determine large-signal I_{out} vs V_{in} of a CMOS inverter using the circuit below:

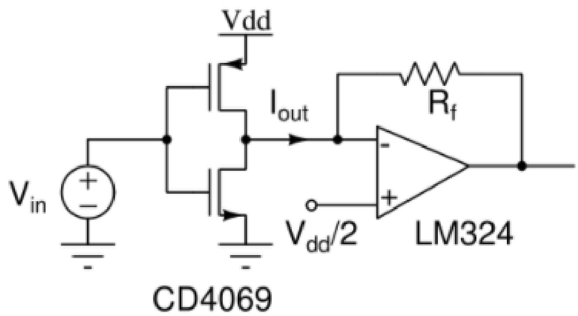
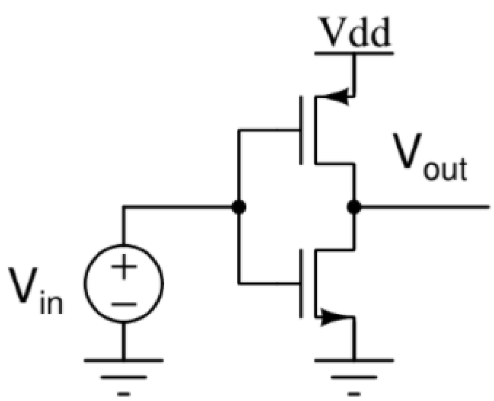


Figure 1: Setup to find I_{out} without using an ammeter.

- Sweep V_{in} from 0V to V_{DD} (6V).
- What is the self-bias voltage (V_B) of the inverter?
- Find the transconductance at V_B.
- Choose appropriate supply voltages for the opamp.

2. Determine large-signal V_{out} vs V_{in} of a CMOS inverter using the circuit below:



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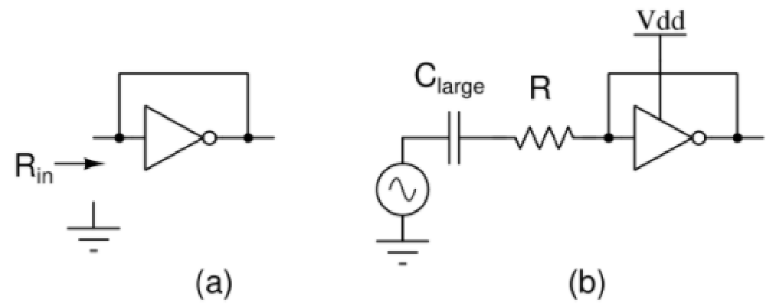
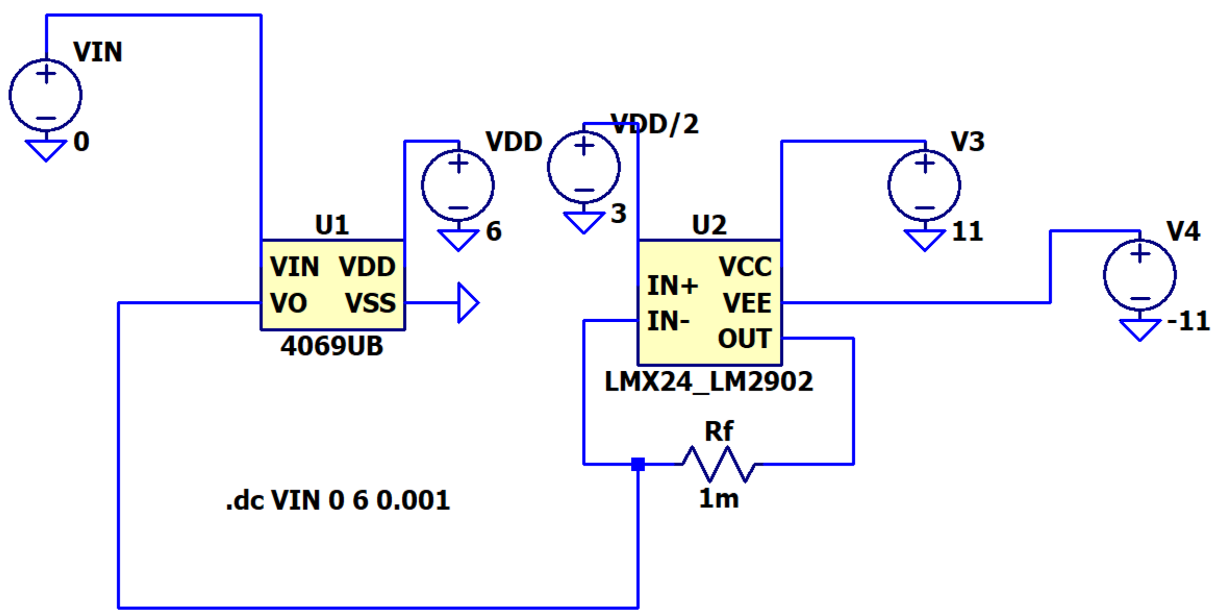
Find small-signal resistance of the self-biased inverter using the circuit shown below for V_{DD} = 5V, 6V and 9V:



3. Using the data from above two experiments, estimate small-signal g_m and r_o of the transconductor. Also find out V_T and β of the NMOS and PMOS of inverter.

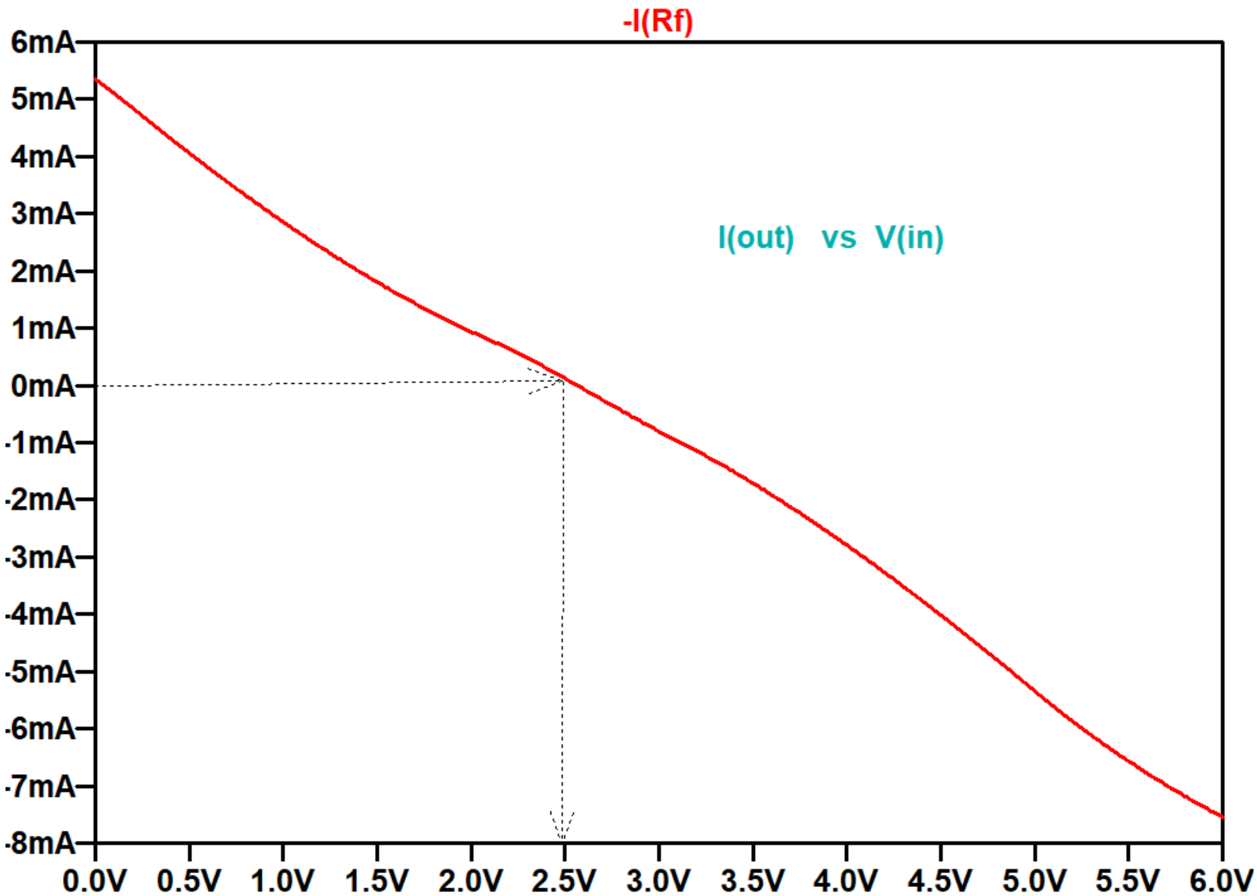
3 Results and observations

Question 1



CMOS Inverter circuit with Opamp to find Iout

Output plot



Plot: I(out) Vs V(in)

Self-Bias Voltage :

• Now as we can see $I_{out} = 0$ A at $V_{in} = 2.56$ V i.e. let's say it's point A and let's say that the self-bias voltage is V_B.

• Since we already know that at self-bias the only self-biased inverter circuit has pmos and nmos in saturation region.

$$I_{out} = \beta_p(6 - V_B - |V_{Tp}|)^2 - \beta_n(V_B - |V_{Tn}|)^2 = 0 \tag{1}$$

• Now let's see how the current equations are and what region pmos and nmos are in at point A.

NMOS

$$V_{gs} = 2.56, V_{ds} = 3 \tag{2}$$

$$V_{ds} \geq V_{gs} - V_{T_n} \tag{3}$$

NMOS is in saturation region.

PMOS

$$V_{sg} = 3.44, V_{ds} = 3 \tag{4}$$

. $V_{sd} \geq$ V$_{sg}$ - $|V_{T_p}|$ if $|V_{T_p}| > 0.44$V (saturation region).
. $V_{sd} \leq$ V$_{sg}$ - $|V_{T_p}|$ if $|V_{T_p}| < 0.44$V (linear region)

• Therefore if $|V_{T_p}|$ is greater than 0.44 V, then both PMOS and NMOS are in saturated region at point A and by comparing current equations we can say $V_B = 2.56$ V.(self-bias voltage)

• We will verify whether $|V_{T_p}|$ is greater than 0.44 V at last while doing calculations, if it is not then we will correct the self bias voltage accordingly.

• For now let's assume $|V_{T_p}|$ is greater than 0.44 V and proceed with $V_B = 2.56$ V.

Transconductance at V_B

$$Transconductance = \left.\frac{\partial I_{out}}{\partial V_{in}}\right|_{V_{in}=V_B} \tag{5}$$

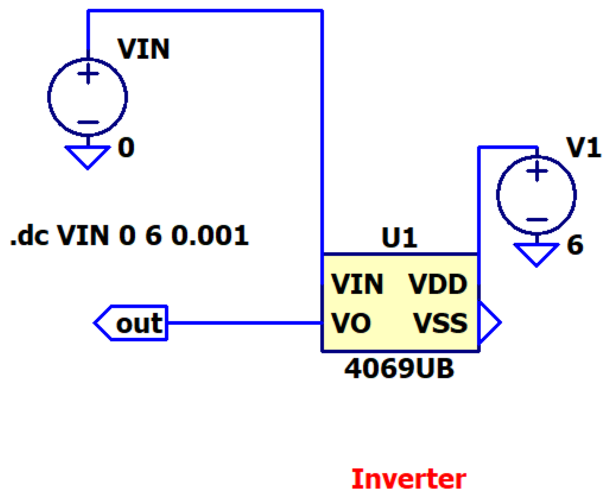
• From the above equation we can clearly say that Transconductance is the slope of I_{out} Vs V_{in} at self bias voltage.

$$Transconductance = \left.\frac{\partial I_{out}}{\partial V_{in}}\right|_{V_{in}=2.56V} \tag{6}$$

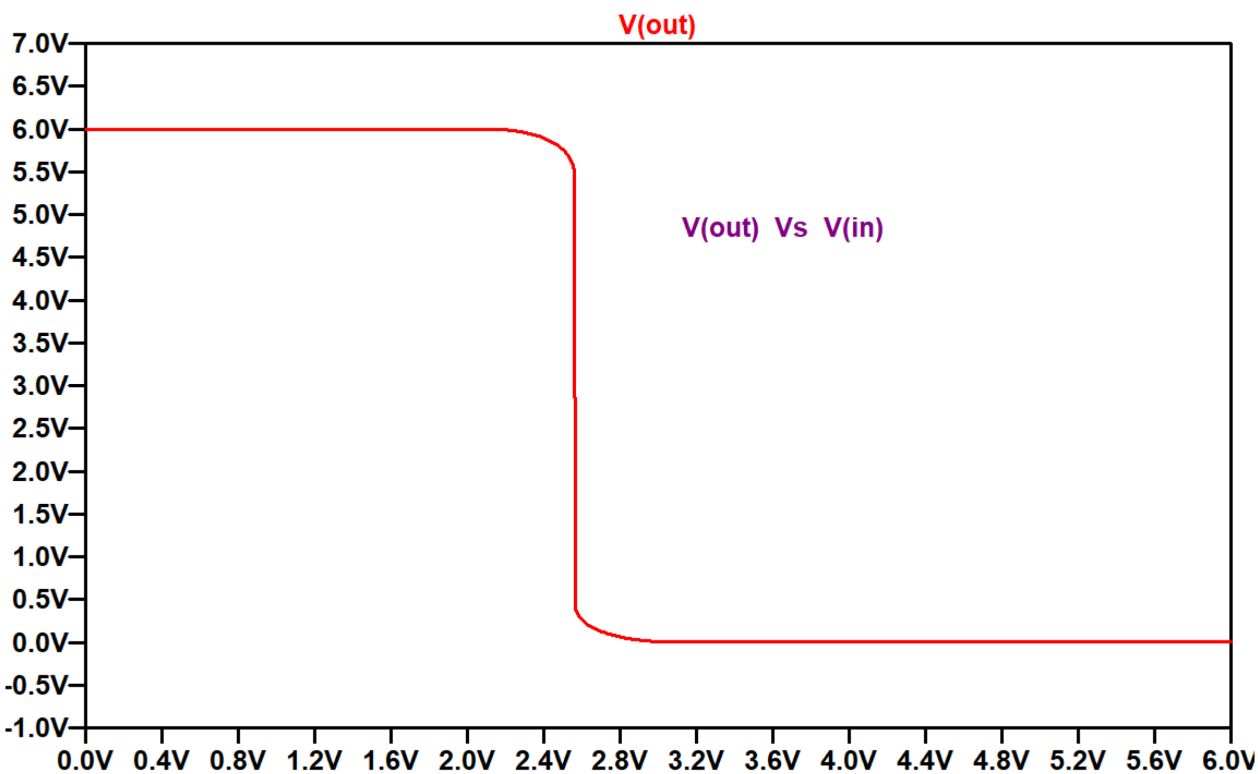
• Transconductance at V_B is 0.00187 Ω^{-1}.

P.T.O

Question 2



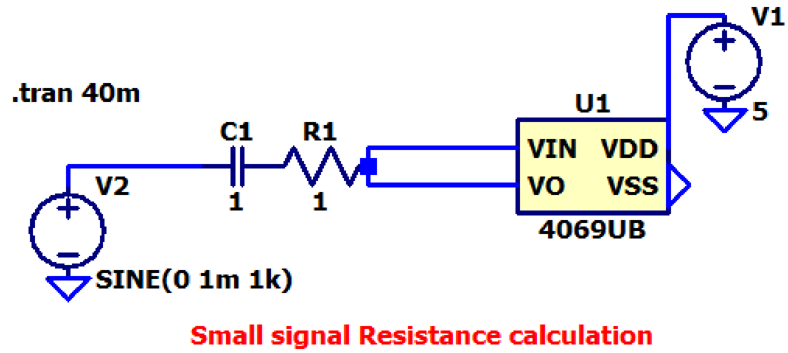
Output plot



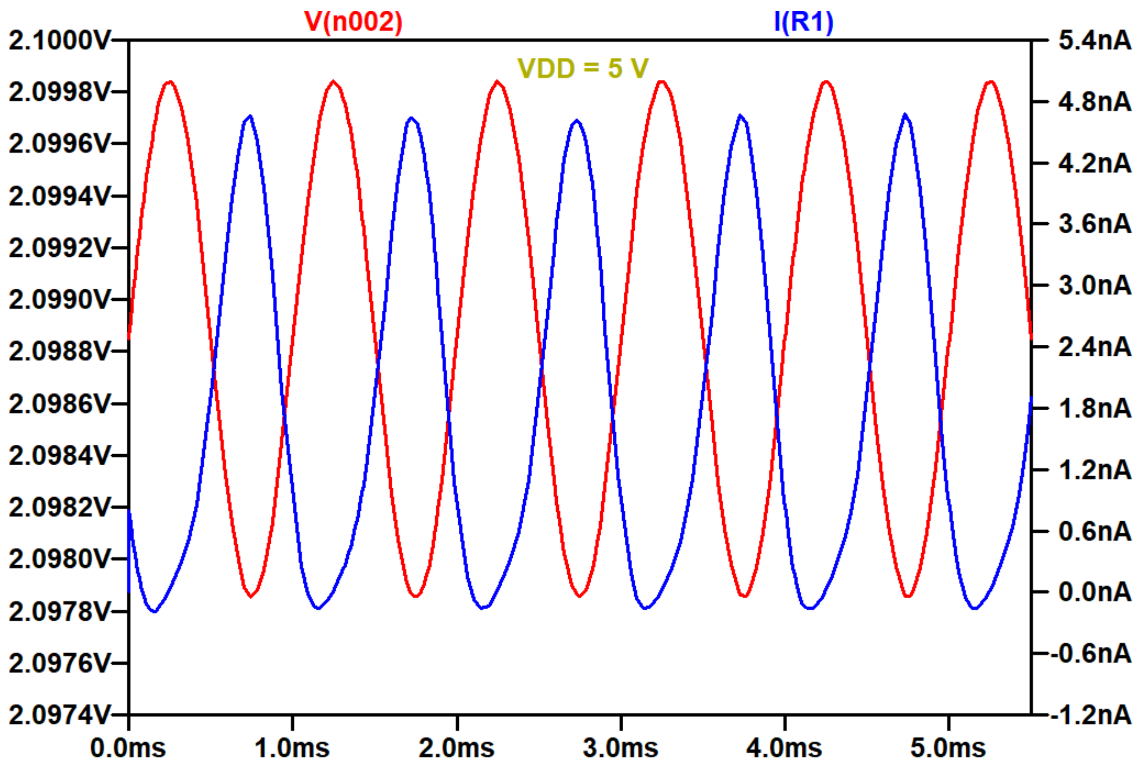
Plot: V(out) Vs V(in)

• As we can clearly see that the output stays at 6V until V_{in} is 2.1 V and then starts to decrease slowly in parabolic way until around V_{in} is 2.56 V and then decreases suddenly with almost ∞ slope around same V_B and starts to slow down and then becomes 0 V after V_{in} is 3.1 V.

Question 2(a)



Output plot at VDD = 5V



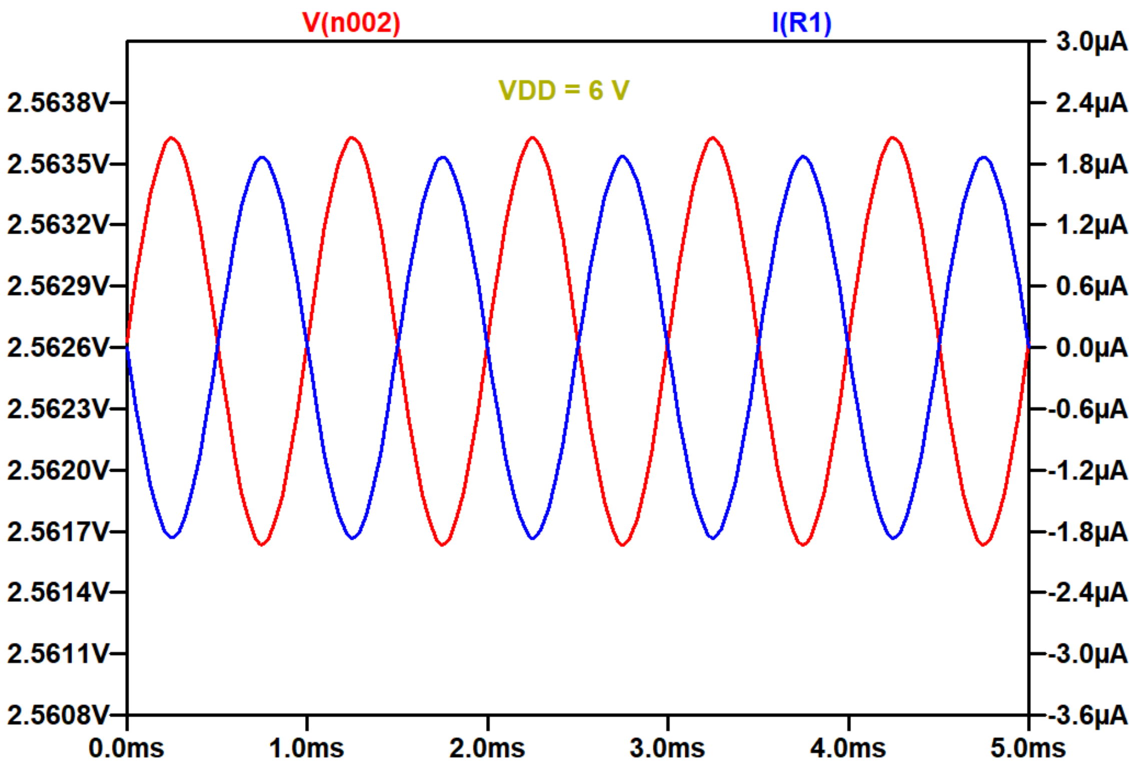
Plot: V(o), I(R1) Vs time(ms)

Calculating small signal resistance at VDD = 5V

$$\Delta I = 4.5585862\ nA, \Delta V = 1.9616359\ mV. \tag{7}$$

$$Small\ signal\ resistance(R_{in}) = \frac{\Delta V}{\Delta I} = 430316.72\ \Omega \approx 430.3K\Omega \tag{8}$$

Output plot at VDD = 6V



Plot: V(o), I(R1) Vs time(ms)

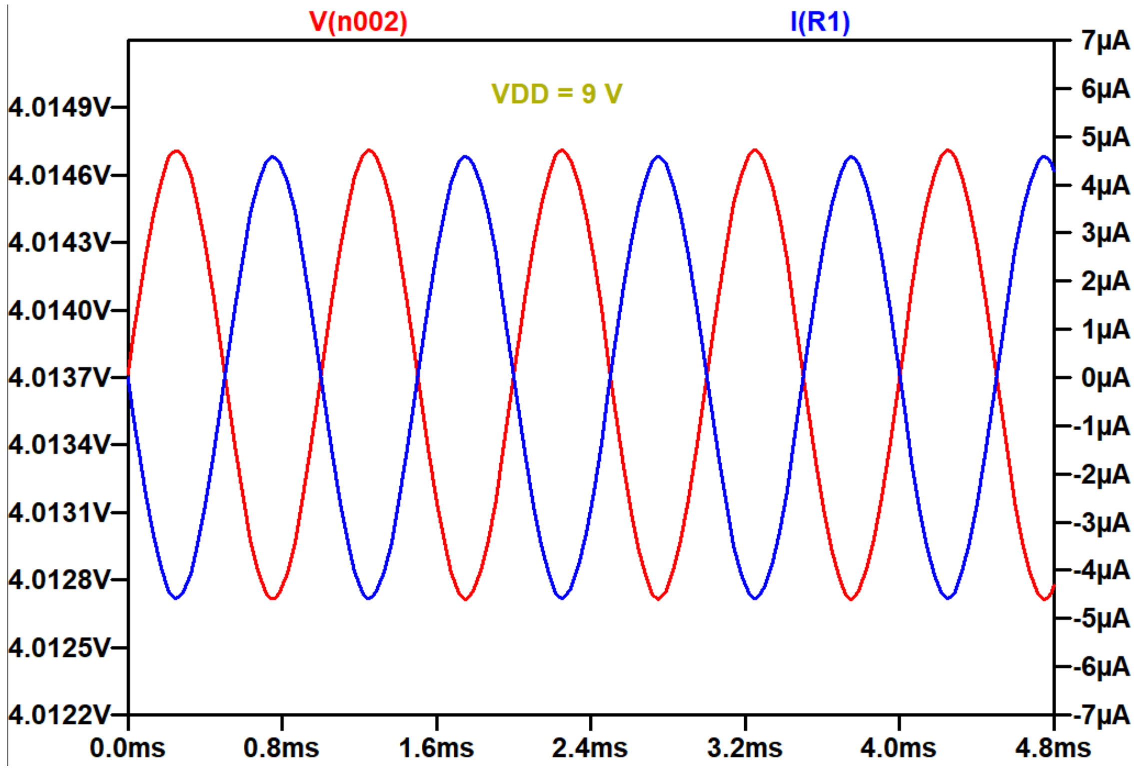
Calculating small signal resistance at VDD = 6V

- Similar from the above case but now we have used R1 = 1m.

$$\Delta I = 3.7244534\ \mu A, \Delta V = 1.9905448\ mV \tag{9}$$

$$Small\ signal\ resistance(R_{in}) = \frac{\Delta V}{\Delta I} = 534.45\ \Omega \tag{10}$$

Output plot at VDD = 9V



Plot: V(o), I(R1) Vs time(ms)

Calculating small signal resistance at VDD = 9V

- Similar from the above case.

$$\Delta I = 9.1278399\ \mu A, \Delta V = 1.9863906\ mV \tag{11}$$

$$Small\ signal\ resistance(R_{in}) = \frac{\Delta V}{\Delta I} = 217.61\ \Omega \tag{12}$$

- The large differences in small signal resistance when VDD=5V and VDD=6,9V can be accounted to the fact that Self bias at VDD=5V is less than V_{Tn} i.e. the NMOS and PMOS are not in saturation.

P.T.O

Question 3

Finding g_m, r_o and V_T , β of NMOS and PMOS

• From V_{out} Vs V_{in} plot, we can say that V_{Tn} = 2.1 V, Since V_{out} is 6V until 2.1V, i.e. Nmos is in cutoff region when $0 < V_{in} < V_{Tn}$.

• Similarly 6 - $|V_{TP}|$ = 3.1 ,i.e. V_{Tp} = -2.9V because V_{out} is 0V when V_{in} is from 3.1V to 6V, i.e. Pmos is in cutoff region when 6-$|V_{Tp}| < V_{in} < 6$ and therefore our assumption from earlier for finding self-bias is correct and $V_B = 2.562$ V

• Now to find β_p , β_n ,λ_p and λ_n, we need to 4 equations which we can extract from 4 data points of the I_{out} Vs V_{in} and V_{out} Vs V_{in} plots.

• Let's do two cases and compare first when we assume no early effect in mosfets.

No early effect

• Assume $\lambda_p, \lambda_n \approx 0$.

Data point A (V_{in} = 0V)

ﬃ$From$ I_{out} Vs V_{in} ,we get I_{out} = 5.3520189 mA, Since NMOS is in cutoff region and PMOS is in linear region.

$$I_{out} = \beta_p\left(V_{SG} - |V_{Tp}| - \frac{V_{SD}}{2}\right)V_{SD} = 5.3520189mA. \tag{13}$$

• By substituting all values we obtain β_p = 0.001115 A/V^2.

Data point B (V_{in} = 6V)

• From I_{out} Vs V_{in} , I_{out} = -7.5530359mA, Since NMOS is in linear region and PMOS is in cutoff region.

$$I_{out} = -\beta_n\left(V_{GS} - |V_{Tn}| - \frac{V_{DS}}{2}\right)V_{DS} = -7.5530359mA. \tag{14}$$

• By substituting all values we obtain β_n = 0.00104903276 A/V^2.

• Now we take into account the early effect and see how it affects our parameters.

With early effect

Data point A (V_{in} = 0V)

- From I_{out} Vs V_{in} ,we get I_{out} = 5.3520189 mA,

$$I_{out} = \beta_p \left(V_{SG} - |V_{Tp}| - \frac{V_{SD}}{2} \right) V_{SD}(1 + \lambda_p V_{SD}) = 5.3520189mA. \tag{15}$$

- By substituting all the values we get.

$$I_{out} = 4.8\beta_p(1 + 3\lambda_p) = 5.3520189 \; mA. \tag{16}$$

Data point B (V_{in} = 6V)

- From I_{out} Vs V_{in} ,we get I_{out} = -7.5530359 mA,

$$I_{out} = -\beta_n \left(V_{GS} - |V_{Tn}| - \frac{V_{DS}}{2} \right) V_{DS}(1 + \lambda_n V_{DS}) = -7.5530359 \; mA. \tag{17}$$

- By substituting all the values we get.

$$I_{out} = 7.2\beta_n(1 + 3\lambda_n) = 7.5530359 \; mA. \tag{18}$$

Data point C (V_{in} = 2.42V)

- From V_{out} Vs V_{in} ,we get V_{out} = 5.8718 V. and NMOS is in Saturation region and PMOS is in linear region.Using $I_p = I_n$.

$$\beta_p \left(V_{SG} - |V_{Tp}| - \frac{V_{SD}}{2} \right) V_{SD}(1 + \lambda_p V_{SD}) = \frac{\beta_n}{2} \left(V_{GS} - |V_{Tn}| \right)^2 (1 + \lambda_n V_{DS}). \tag{19}$$

- By substituting all the values we get,

$$0.07896\beta_p(1 + 0.1282\lambda_p) = 0.0512\beta_n(1 + 5.8718\lambda_n). \tag{20}$$

Data point D (V_{in} = 2.70V)

• From V_{out} Vs V_{in} ,we get V_{out} = 124.74 mV. and NMOS is in linear region and PMOS is in saturation region.Using $I_p = I_n$.

$$\beta_n\left(V_{GS}-|V_{Tn}|-\frac{V_{DS}}{2}\right)V_{DS}(1+\lambda_n V_{DS})=\frac{\beta_p}{2}\left(V_{SG}-|V_{Tp}|\right)^2(1+\lambda_p V_{SD}). \tag{21}$$

• By substituting all the values we get,

$$0.0007476\beta_n(1+0.0012474\lambda_n)=0.08\beta_p(1+5.9987526\lambda_p). \tag{22}$$

• Now solving all the 4 equations (16),(18),(20),(22) we get
β_p = 0.00224347,
β_n = - 0.00139172,
λ_p = - 0.167667,
λ_n = - 0.584588.

• As we can see the results obtained doesn't match with expectations and from the netlist data sheet we can see that λ_n and λ_p is given as 1.87m.

• Therefore let's use β_p and β_n obtained from case 1 without early effect and λ_n and λ_p from datasheet to find g_m ,r_o.

g_m and r_o at self-bias

$$g_m=g_{mn}+g_{mp}=\beta_n(V_{GS}-V_{Tn})+\beta_p(V_{SG}-|V_{Tp}|)=0.0010845A/V. \tag{23}$$

$$r_o=(r_{no}//r_{po})=\frac{1}{(\lambda_p+\lambda_n)I_{DS}}=2409168.86\Omega\approx 2.409M\Omega \tag{24}$$

4 Unusual behaviour comments

• The small signal resistance of the self-biased inverter at VDD = 5V is quite high which can be because V(self-bias) < $|V_{Tp}|$.

• We have seen the unusual values of parameters obtained when early effect is taken into consideration.

• We can also see that r_o value is quite high.


thank you