EE517 : VLSI LAB-II

Experiment No. - 09

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Objective :

- Design Analysis of a Telescopic and Folded Cascode single-ended Operational Transconductance Amplifier for high Gain as shown below.
- All Transistors should be biased using current mirror approach.

Provided:

Supply voltage of 1.8V and load cap of 1pF, tsmc-180nm technology.

Specifications:

GBW of 15MHz, Reference golden current source of 40uA, slew rate=10v/us.

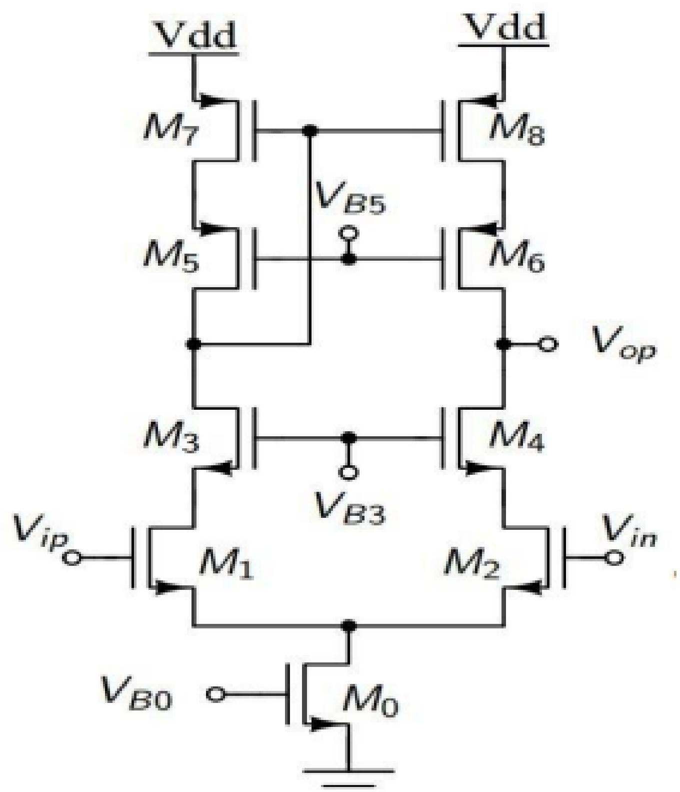
Tool used :

LTspice Simulator.

Theory :

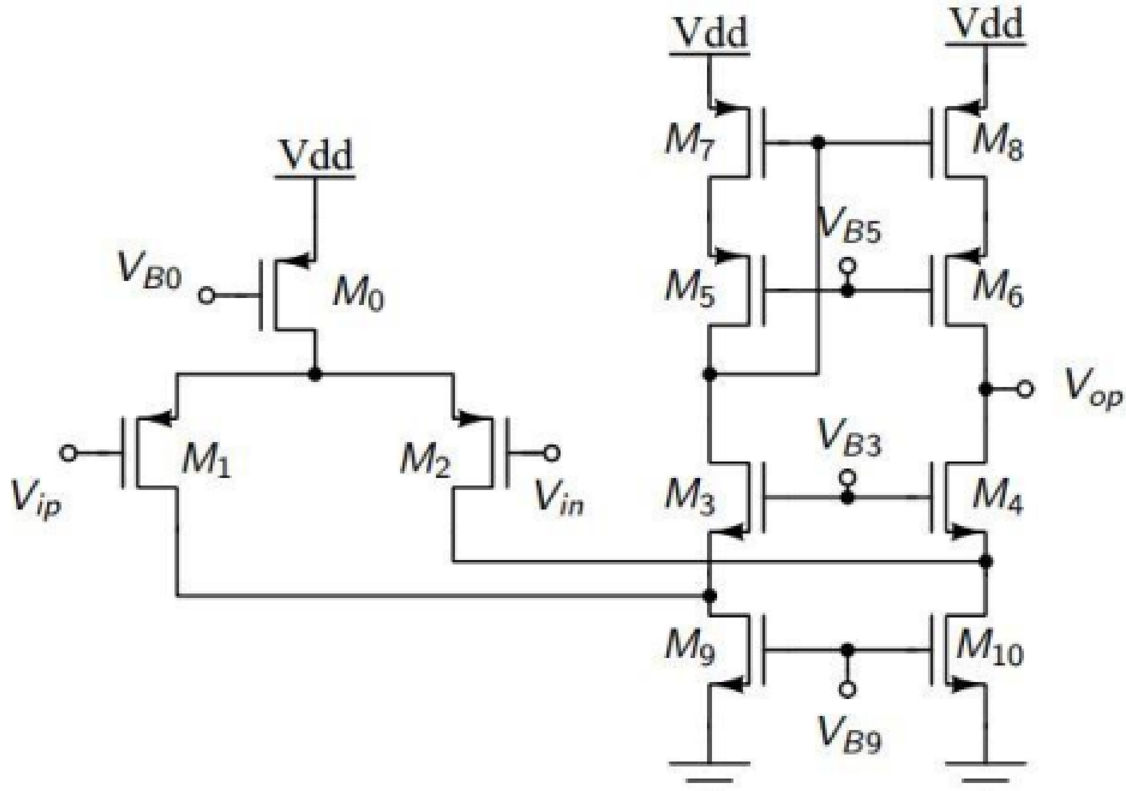
Telescopic cascode single-ended Operational Transconductance Amplifier :

Cascode configurations may be used to increase the voltage gain of CMOS transistor amplifier stages. This structure has been called a 'telescopic-cascode' op amp because the cascode are connected between the power supplies in series with the transistors in the differential pair, resulting in a structure in which the transistors in each branch are connected along a straight line. The main potential advantage of telescopic cascode op amps is that they can be designed so that the signal variations are entirely handled by the fastest-polarity transistors . In the first stage, we were simply looking for a configuration that allowed for high gain, low noise and minimal current since output swing is less critical. The folded cascode and the telescopic configurations were considered since we required at least one cascoded stage for a gain on the order of ${g_m}^2$. A high swing configuration still needs to be used to that all the devices in this stage are in saturation. In comparing the two topologies, the folded cascode has more current legs and more devices in the signal path.



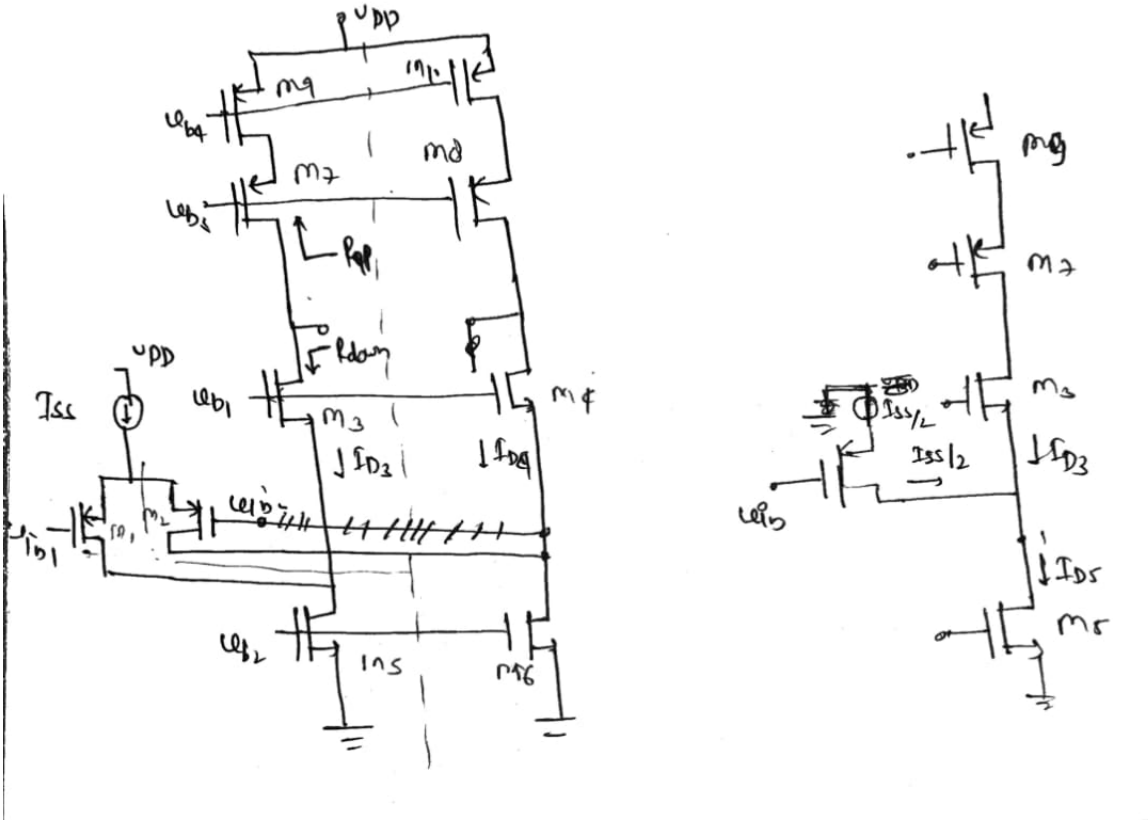
Flded cascode single-ended Operational Transconductance Amplifier

Figure shows typical structure of a folded cascode op-amp Folded cascade topology is called as 'folded cascode' because it comes from a folding down p-channel cascode active loads of a different-pair and changing the MOSFET to the n-channel. These topologies allow the input common-mode level of being close to the power supply voltage as well as providing a high output swing, wide input common-mode range and preferably steering in low voltage supply circuits. However, this topology has higher noise compare to the telescopic op-amp. Folded cascode amplifier is a single-pole operational amplifier with large output swing and has higher gain compared to the ordinary op-amp. It is very suitable for deep negative feedback because of its small signal gain that can be very large. Comparing to the ordinary telescopic amplifiers, folded cascode operational amplifiers have a larger output swing. Input and output can be short circuited to make it easier for the selection of input common-mode level due to its relatively large output swing. The input common-mode level can be close to the power supply voltage by using folded cascode op-amp.



Analysis of folded cascode :

Folded Cascode op-amp :- Design approach



① max. differential swing ⇒ $2\left(V_{DD} - \left(V_{OV_3} + V_{OV_5} + |V_{OV}|_7 + |V_{OV}|_9\right)\right)$

② We can take V_{OV} for ~~all~~ (M_3, M_7, M_9) transistor $= 0.2$ volt.

→ In this case M_7 & M_9 transistors has to be larger size than M_3 & M_5 [due to less k_p than k_n]

To manage same amount of current

③ $I_{D5} = I_{D3} + \frac{I_{ss}}{2}$

in that case M_5 ~~can~~ we can take larger V_{OV} as $(V_{OV})_5 = 0.3$ volt

& also can take larger $\left(\frac{W}{L}\right)$ ratio.

(4) let take power dessipation — up to 100 uwatts from there we can calculate how much current should be flow through the transistor →

$$\text{Total current} = I_{D5} + I_{D6}$$

$$= \frac{I_{SS}}{2} + I_{D3} + \frac{I_{SS}}{2} + I_{D4}$$

$$= \left[I_{SS} + I_{D3} + I_{D4}\right)$$

(5) Now we can calculate $\left(\frac{W}{L}\right)$ ratios

as we know, from I_D eqn.

$$I_D = \frac{1}{2}\mu_n C_{ox}\frac{W}{L}\left[V_{GS}-V_t\right]^2 \longrightarrow \text{nmos}$$

$$\Rightarrow \left(\frac{W}{L}\right)_n = \frac{2I_D}{\mu_n C_{ox}(V_{OV})^2} \longrightarrow \text{Nmos}$$

$$\Rightarrow \left(\frac{W}{L}\right)_p = \frac{2I_D}{\mu_p C_{ox}(V_{OV})^2} \longrightarrow \text{pmos}$$

(7) Calculate bias voltage.

$V_{b2} \rightarrow$ $V_{GS5} = V_{b2}$

$$V_{OV_5} = V_{GS} - V_t = 0.3 \text{ Volt} \quad \text{(assumption)}$$

$$\boxed{V_{GS} = 0.3 + V_{tn}} \leftarrow V_{b2}$$

$$\boxed{V_{b2} = (V_{OV})_5 + V_{tn}}$$

$V_{b1} \rightarrow$ $V_{GS_3} = V_{G3} - V_{S3} = V_{b1} - (V_{OV})_5$

$$V_{OV_3} = V_{GS_3} - V_{tn} = 0.2$$

$$\Rightarrow V_{b1} - (V_{OV})_5 - V_{th} = 0.2$$

$$\boxed{V_{b1} = 0.2 + (V_{OV})_5 + V_{tn}}$$

$$= V_{OV_5} + V_{th} + V_{OV_3}$$

$\underline{\underline{V_{b4}}} \rightarrow$

$$V_{SG9} = V_{S9} - V_{G9} = V_{DD} - V_{b4}$$

$$|V_{ov}|_9 = 0.2 = \left(V_{SG_9} - |V_{tp}|\right)$$

$$V_{SG} = 0.2 + |V_{tp}|$$

$$V_{DD} - V_{b4} = 0.2 + |V_{tp}|$$

$$\boxed{V_{b4} = V_{DD} - 0.2 - |V_{tp}|}$$

$$\boxed{V_{b4} = V_{DD} - |V_{ov}|_9 - |V_{tp}|}$$

$\underline{\underline{V_{b3}}} \rightarrow$

$$V_{SG7} = V_{S7} - V_{G7} =$$

$$V_{SG7} = V_{DD} - |V_{ov}|_9 - V_{G7}$$

$$|V_{ov}|_7 = V_{SG7} - |V_{thp}|$$

$$|V_{ov}|_7 = V_{DD} - |V_{ov}|_9 - V_{G7} - |V_{tp}|$$

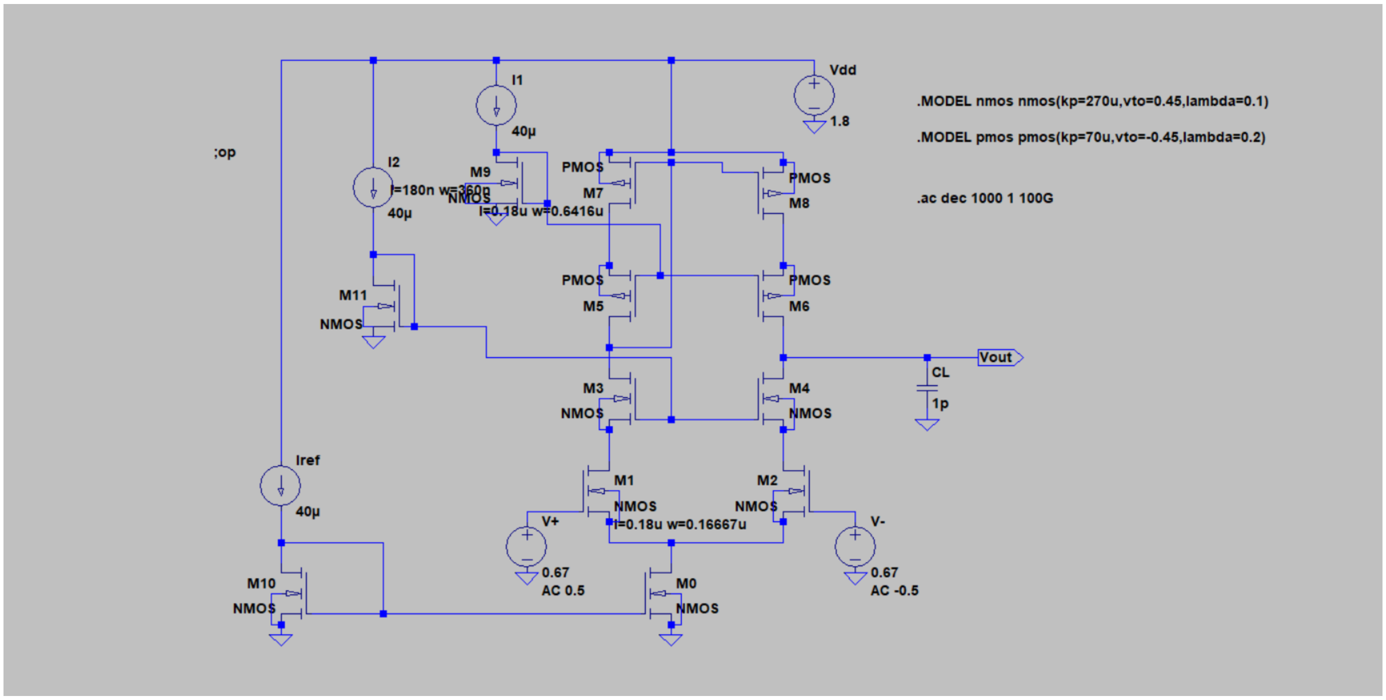
$$\Rightarrow \quad V_{G7} = V_{DD} - |V_{ov}|_9 - |V_{ov}|_7 - |V_{tp}|$$

$$\boxed{V_{b3} = V_{DD} - |V_{ov}|_9 - |V_{ov}|_7 - |V_{tp}|}$$

Observation and calculation :

Telescopic cascode single-ended Operational Transconductance Amplifier :

$K_n = 270\mu A/V$, $K_p = 70\mu A/V$,$\lambda_n = 0.1V^{-1}$, $\lambda_p = 0.2V^{-1}$,$V_{tn} = 0.45V$, $V_{tp} = -0.45V$



Schematic of telescopic cascode amplifier

Calculation :

Calculations & Design Procedure

① M_1 to M_4 : $\mu_n C_{ox} = k_p = 270\ \mu A/V^2$, $\lambda_n = 0.1$, $\lambda_p = 0.2$

Taking $I_D = 5\ \mu A$

$V_{ov} = 0.2$ volt

$$g_m = \frac{2 I_D}{V_{ov}} = 50\ \mu A/V$$

$$\left(\frac{W}{L}\right) = \frac{g_m^2}{2 I_D \mu_n C_{ox}} = 0.9259$$

② M_5 to M_8 similarly $I_D = 5\ \mu A$, $V_{ov} = 0.2$ volt

$$\left(\frac{W}{L}\right) = \frac{g_m^2}{2 I_D \mu_n C_{ox}} = 3.5647$$

③ Gain:

$$r_{on} = \frac{1}{0.1 \times 5\mu} = 2\,M\Omega$$

$$r_{op} = \frac{1}{0.2 \times 5\mu} = 1\,M\Omega$$

$$R_{out} = g_{m6}(r_{op})^2 \,||\, g_{m4} r_{on}^2$$

$$= (50 \times 10^6) \,||\, (50 \times 2 \times 10^6)$$

$$= \frac{50 \times 100}{50 + 100} \times 10^6$$

$$\boxed{R_{out} = 33.33\ M\Omega}$$

④ Gain → $A_v = g_{m1}(R_{out})$

$= 50 \times 33.33$

$$\boxed{A_v = 1667.66\ \frac{V}{V}} = 64.430\ dB$$

$$GBW = \frac{g_{m1}}{C_L} = \frac{50 \times 10^{-6}}{1 \times 10^{-12}}$$

$$2000 \, BW = 50 \times 10^{6}$$

$$\boxed{BW = 25 \, k\Omega}$$

(6) Input common mode →

$$V_{GS} - V_t > V_{ov}$$

$$V_G > V_{ov} + V_t + V_s$$

$$V_G > 0.2 + 0.45 + 0.1$$

$$\boxed{V_G > 0.75}$$

(7) Current should be maintain using the current mirror ckt. as shown in the schematic.

(8) $\left(\frac{W}{L}\right)_0 = 1.22$

$$\left(\frac{W}{L}\right)_{10,11,12} = 2$$

Ideal golden current source. = 90uA

* C:\VLASI LAB II\lab 09\telescopic6.asc

```
       --- Operating Point ---

V(n009):        0.214764        voltage
V(n012):        0.67            voltage
V(n011):        0.0584916       voltage
V(n010):        0.214764        voltage
V(n013):        0.67            voltage
V(n003):        1.19288         voltage
V(n005):        0.820027        voltage
V(vout):        1.19288         voltage
V(n002):        0.820027        voltage
V(n006):        1.42915         voltage
V(n007):        1.42915         voltage
V(n001):        1.8             voltage
V(n014):        0.820027        voltage
V(n004):        0.102774        voltage
V(n008):        0.102774        voltage
Id(M8):         -3.30816e-006   device_current
Ig(M8):         0               device_current
Ib(M8):         3.80848e-013    device_current
Is(M8):         3.30816e-006    device_current
Id(M7):         -3.30816e-006   device_current
Ig(M7):         0               device_current
Ib(M7):         3.80848e-013    device_current
Is(M7):         3.30816e-006    device_current
Id(M6):         -3.30816e-006   device_current
Ig(M6):         0               device_current
Ib(M6):         2.46269e-013    device_current
Is(M6):         3.30816e-006    device_current
Id(M5):         -3.30816e-006   device_current
Ig(M5):         0               device_current
Ib(M5):         2.46269e-013    device_current
Is(M5):         3.30816e-006    device_current
Id(M11):        4e-005          device_current
Ig(M11):        0               device_current
Ib(M11):        -1.02774e-013   device_current
Is(M11):        -4e-005         device_current
Id(M9):         4e-005          device_current
Ig(M9):         0               device_current
Ib(M9):         -1.02774e-013   device_current
Is(M9):         -4e-005         device_current
Id(M10):        4e-005          device_current
Ig(M10):        0               device_current
Ib(M10):        -8.30027e-013   device_current
Is(M10):        -4e-005         device_current
Id(M0):         6.61632e-006    device_current
```

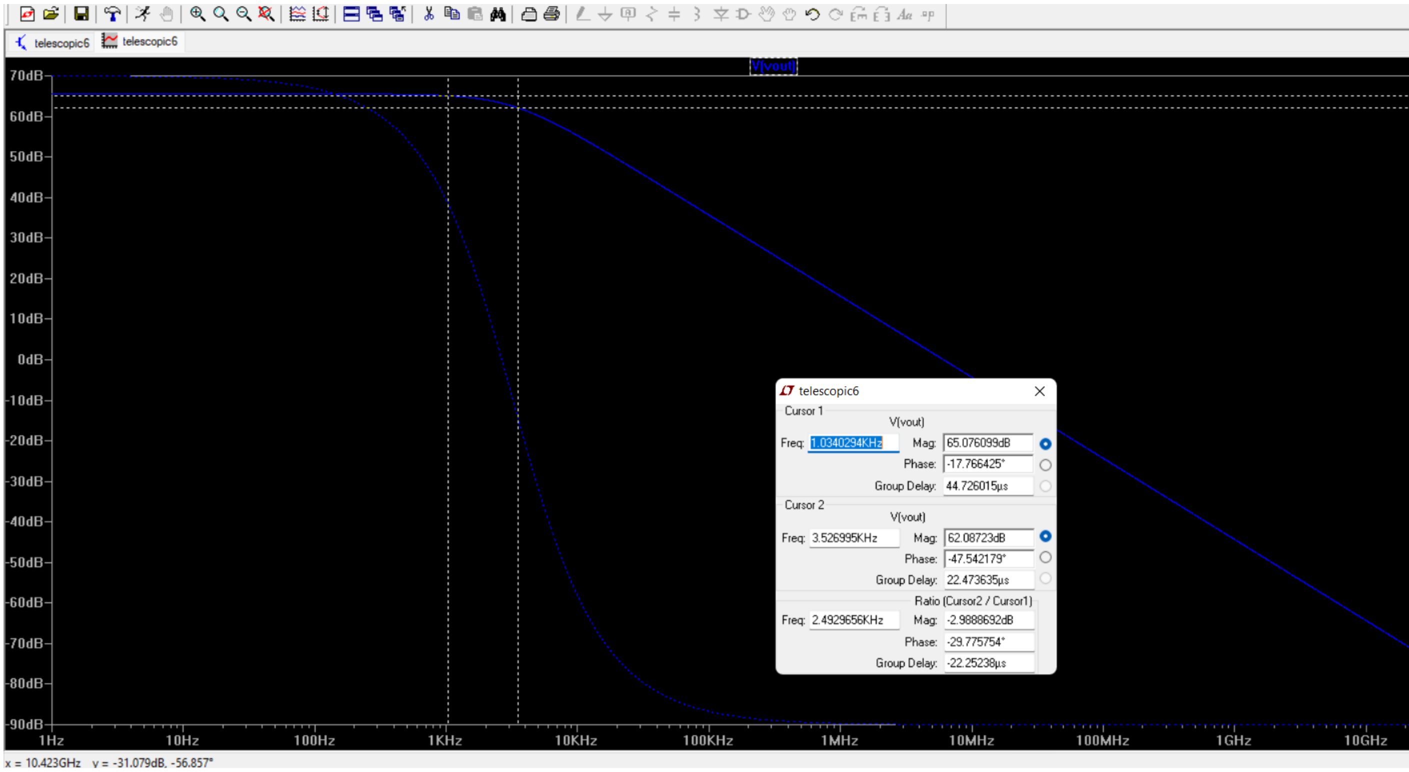
DC analysis of telescopic cascode

SPICE Error Log: C:\VLASI LAB II\lab 09\telescopic6.log

Cgb:	0.00e+00	0.00e+00	0.00e+00	0.00e+00	0.00e+00
Name:	m9	m10	m0	m4	m3
Model:	nmos	nmos	nmos	nmos	nmos
Id:	4.00e-05	4.00e-05	6.62e-06	3.31e-06	3.31e-06
Vgs:	8.20e-01	8.20e-01	8.20e-01	6.05e-01	6.05e-01
Vds:	8.20e-01	8.20e-01	5.85e-02	9.78e-01	9.78e-01
Vbs:	1.03e-01	0.00e+00	0.00e+00	0.00e+00	0.00e+00
Vth:	4.50e-01	4.50e-01	4.50e-01	4.50e-01	4.50e-01
Vdsat:	3.70e-01	3.70e-01	3.70e-01	1.55e-01	1.55e-01
Gm:	2.16e-04	2.16e-04	1.94e-05	4.26e-05	4.26e-05
Gds:	3.70e-06	3.70e-06	1.04e-04	3.01e-07	3.01e-07
Gmb:	0.00e+00	0.00e+00	0.00e+00	0.00e+00	0.00e+00
Cbd:	0.00e+00	0.00e+00	0.00e+00	0.00e+00	0.00e+00
Cbs:	0.00e+00	0.00e+00	0.00e+00	0.00e+00	0.00e+00
Cgsov:	0.00e+00	0.00e+00	0.00e+00	0.00e+00	0.00e+00
Cgdov:	0.00e+00	0.00e+00	0.00e+00	0.00e+00	0.00e+00
Cgbov:	0.00e+00	0.00e+00	0.00e+00	0.00e+00	0.00e+00
Cgs:	0.00e+00	0.00e+00	0.00e+00	0.00e+00	0.00e+00
Cgd:	0.00e+00	0.00e+00	0.00e+00	0.00e+00	0.00e+00
Cgb:	0.00e+00	0.00e+00	0.00e+00	0.00e+00	0.00e+00

Name:	m2	m1
Model:	nmos	nmos
Id:	3.31e-06	3.31e-06
Vgs:	6.12e-01	6.12e-01
Vds:	1.56e-01	1.56e-01
Vbs:	0.00e+00	0.00e+00
Vth:	4.50e-01	4.50e-01
Vdsat:	1.62e-01	1.62e-01
Gm:	3.97e-05	3.97e-05
Gds:	1.66e-06	1.66e-06
Gmb:	0.00e+00	0.00e+00
Cbd:	0.00e+00	0.00e+00
Cbs:	0.00e+00	0.00e+00
Cgsov:	0.00e+00	0.00e+00
Cgdov:	0.00e+00	0.00e+00
Cgbov:	0.00e+00	0.00e+00
Cgs:	0.00e+00	0.00e+00
Cgd:	0.00e+00	0.00e+00
Cgb:	0.00e+00	0.00e+00

Gm of telescopic cascode

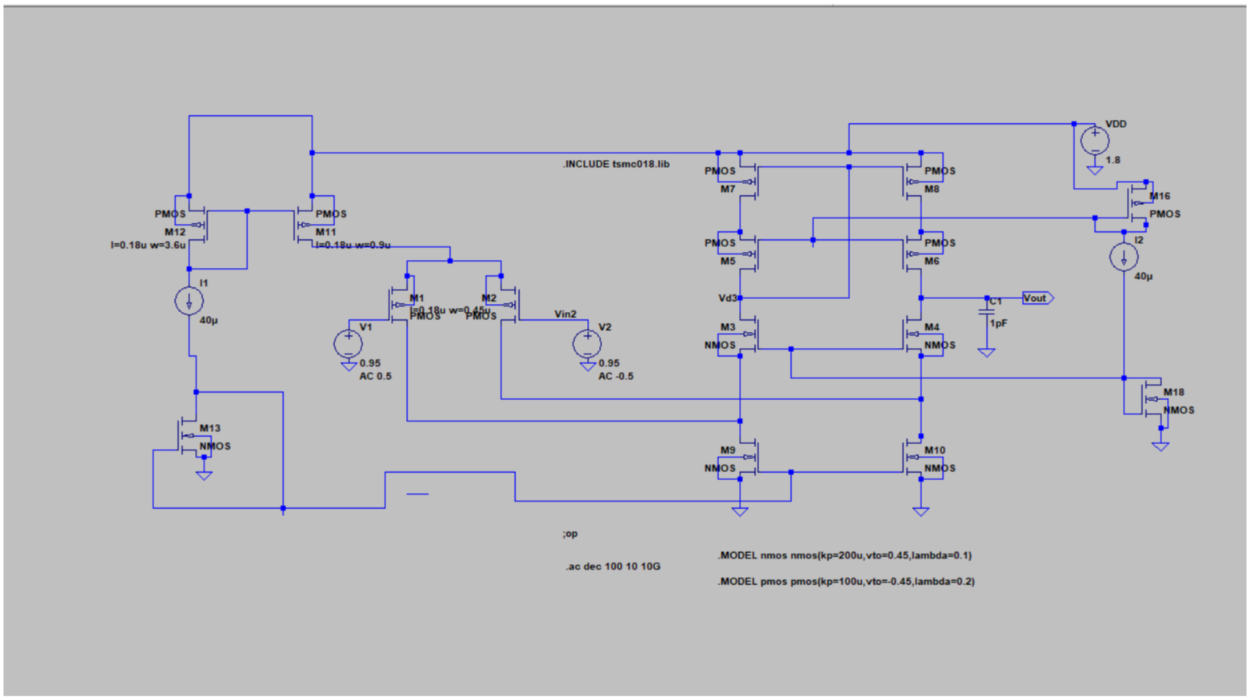


AC analysis of telescopic cascode

Gain = 65.07dB
B.W.=3.52KHz

Folded cascode single-ended Operational Transconductance Amplifier :

$K_n = 200\mu A/V$, $K_p = 100\mu A/V$,$\lambda_n = 0.1V^{-1}$, $\lambda_p = 0.2V^{-1}$,$V_{tn} = 0.45V$, $V_{tp} = -0.45V$



Schematic of Folded cascode amplifier

Calculation :

Calculation of folded cascode:

$C_L = 1pF$, $GBW = 15 MHz$, $I_{ref} = 40\mu A$, $K_n = 200\mu$, $K_p = 100\mu$, $\lambda_n = 0.1$, $\lambda_p = 0.2$, $V_{tn} = 0.4$, $V_{tp} = -0.4$

from schematic

$SR = 10$, $I_{D11} = 10\mu A$ $[\because I_D = SR\,C_L]$

Taking $|V_{ov}| = 0.2$ volt for both nmos & pmos

① $I_3 = I_5 = I_7 = I_4 = I_6 = I_8 = 5\mu A$,

$I_1 = I_2 = 5\mu A$

$g_{m1} = \frac{2I_1}{V_{ov}} = 50\mu A/V$ for $[M_1, M_2, M_5, M_6, M_7, M_8]$

$$\left(\frac{W}{L}\right) = \frac{g_{m1}^2}{2 I_D K_p} = \frac{(50\times10^{-6})^2}{2\times5\times10^{-6}\times100\mu}$$

$\boxed{\left(\frac{W}{L}\right) = 2.5}$ for $[M_1, M_2, M_5, M_6, M_7 \,\&\, M_8]$

for $\underline{M_3 \,\&\, M_4}$.

$I_D = 5\mu A$, $V_{ov} = 0.2V$

$$\left(\frac{W}{L}\right) = \frac{2I_D}{K_n (V_{ov})^2} = \frac{2}{0.8} = \underline{1.25}$$

$\underline{M_9 \,\&\, M_{10}}$

$I_D = 10\mu A$, $V_{ov} = 0.2$

$\boxed{\frac{W}{L} = 2.5}$

$$R_{out} = \left[g_{m6} (r_{op})^2 \right] \| \left[g_{m4}\, r_{o4} \left(r_{o1} \| r_{o10} \right) \right]$$

$$\cancel{r_{on} = \frac{1}{\lambda I_D} = \frac{1}{0.1 \times 1}}$$

$$r_{o4} = \frac{1}{\lambda_n I_D} = \frac{1}{0.1 \times 5\mu A} = 2\,M\Omega$$

$$r_{o6} = r_{o8} = \frac{1}{\lambda_p I_D} = \frac{1}{0.2 \times 5\mu} = 1\,M\Omega$$

$$r_{o10} = \frac{1}{\lambda_n I_D} = \frac{1}{0.1 \times 10\mu} = 1\,M\Omega$$

$$r_{o1} = \frac{1}{\lambda_p I_D} = \frac{1}{0.2 \times 5\mu} = 1\,M\Omega$$

$$g_{m6} = g_{m4} = \frac{2 I_D}{V_{ov}} = \frac{2 \times 5\mu}{0.2V} = 50\,\mu A/V$$

$$R_{out} = \left[50\mu \left[10^6 \times 10^6 \right] \right] \| \left(50\mu \times 2 \times 10^6 \left[\tfrac{1}{2} \times 10^6 \right] \right)$$

$$= 50M \| 50M$$

$$= 25\,M\Omega$$

$$A_v = g_{m1} R_{out} = 50\mu \times 25\,M\Omega$$

$$\boxed{A_v = 1250} \quad \text{or} \quad = 61.93\,dB$$

```
* C:\Users\pawan\Desktop\FOLDED CASCODE1.asc
       --- Operating Point ---

V(n001):        1.8             voltage
V(vout):        1.30451         voltage
V(n007):        0.95            voltage
V(vin2):        0.95            voltage
V(n006):        1.56927         voltage
V(n008):        0.0938619       voltage
V(n009):        0.0938619       voltage
V(n002):        1.16166         voltage
V(n011):        0.600468        voltage
V(n003):        1.16166         voltage
V(n010):        0.587442        voltage
V(n005):        1.65626         voltage
V(vd3):         1.30451         voltage
V(n004):        1.65626         voltage
Id(M10):        4.90468e-006    device_current
Ig(M10):        0               device_current
Ib(M10):        -1.03596e-013   device_current
Is(M10):        -4.90468e-006   device_current
Id(M9):         4.90468e-006    device_current
Ig(M9):         0               device_current
Ib(M9):         -1.03596e-013   device_current
Is(M9):         -4.90468e-006   device_current
Id(M3):         2.66147e-007    device_current
Ig(M3):         0               device_current
Ib(M3):         -1.22064e-012   device_current
Is(M3):         -2.66146e-007   device_current
Id(M4):         2.66147e-007    device_current
Ig(M4):         0               device_current
Ib(M4):         -1.22064e-012   device_current
Is(M4):         -2.66146e-007   device_current
Id(M18):        4e-005          device_current
Ig(M18):        0               device_current
Ib(M18):        -5.97442e-013   device_current
Is(M18):        -4e-005         device_current
Id(M13):        4e-005          device_current
Ig(M13):        0               device_current
Ib(M13):        -6.10468e-013   device_current
Is(M13):        -4e-005         device_current
Id(M7):         -2.66147e-007   device_current
Ig(M7):         0               device_current
Ib(M7):         1.53699e-013    device_current
Is(M7):         2.66147e-007    device_current
Id(M8):         -2.66147e-007   device_current
Ig(M8):         0               device_current
```

DC analysis of Folded cascode

```
SPICE Error Log: C:\Users\pawan\Desktop\FOLDED CASCODE1.log
Cgb:         0.00e+00    0.00e+00    0.00e+00    0.00e+00    0.00e+00

Name:          m13          m7          m8          m5          m6
Model:        nmos        pmos        pmos        pmos        pmos
Id:          4.00e-05   -2.66e-07   -2.66e-07   -2.66e-07   -2.66e-07
Vgs:         6.00e-01   -4.95e-01   -4.95e-01   -4.95e-01   -4.95e-01
Vds:         6.00e-01   -1.44e-01   -1.44e-01   -3.52e-01   -3.52e-01
Vbs:         0.00e+00    0.00e+00    0.00e+00    0.00e+00    0.00e+00
Vth:         4.50e-01   -4.50e-01   -4.50e-01   -4.50e-01   -4.50e-01
Vdsat:       1.50e-01   -4.55e-02   -4.55e-02   -4.46e-02   -4.46e-02
Gm:          5.32e-04    1.17e-05    1.17e-05    1.19e-05    1.19e-05
Gds:         3.77e-06    5.17e-08    5.17e-08    4.97e-08    4.97e-08
Gmb:         0.00e+00    0.00e+00    0.00e+00    0.00e+00    0.00e+00
Cbd:         0.00e+00    0.00e+00    0.00e+00    0.00e+00    0.00e+00
Cbs:         0.00e+00    0.00e+00    0.00e+00    0.00e+00    0.00e+00
Cgsov:       0.00e+00    0.00e+00    0.00e+00    0.00e+00    0.00e+00
Cgdov:       0.00e+00    0.00e+00    0.00e+00    0.00e+00    0.00e+00
Cgbov:       0.00e+00    0.00e+00    0.00e+00    0.00e+00    0.00e+00
Cgs:         0.00e+00    0.00e+00    0.00e+00    0.00e+00    0.00e+00
Cgd:         0.00e+00    0.00e+00    0.00e+00    0.00e+00    0.00e+00
Cgb:         0.00e+00    0.00e+00    0.00e+00    0.00e+00    0.00e+00

Name:          m16         m12         m11          m2          m1
Model:        pmos        pmos        pmos        pmos        pmos
Id:          4.00e-05   -4.00e-05   -9.28e-06    4.64e-06    4.64e-06
Vgs:         0.00e+00   -6.38e-01   -6.38e-01    8.56e-01    8.56e-01
Vds:         6.38e-01   -6.38e-01   -2.31e-01    1.48e+00    1.48e+00
Vbs:         6.38e-01    0.00e+00    0.00e+00    1.48e+00    1.48e+00
Vth:        -4.50e-01   -4.50e-01   -4.50e-01   -4.50e-01   -4.50e-01
Vdsat:      -1.88e-01   -1.88e-01   -1.88e-01   -1.69e-01   -1.69e-01
Gm:          4.25e-04    4.25e-04    9.85e-05    5.48e-05    5.48e-05
Gds:         7.09e-06    7.09e-06    1.77e-06    7.16e-07    7.16e-07
Gmb:         0.00e+00    0.00e+00    0.00e+00    0.00e+00    0.00e+00
Cbd:         0.00e+00    0.00e+00    0.00e+00    0.00e+00    0.00e+00
Cbs:         0.00e+00    0.00e+00    0.00e+00    0.00e+00    0.00e+00
Cgsov:       0.00e+00    0.00e+00    0.00e+00    0.00e+00    0.00e+00
Cgdov:       0.00e+00    0.00e+00    0.00e+00    0.00e+00    0.00e+00
Cgbov:       0.00e+00    0.00e+00    0.00e+00    0.00e+00    0.00e+00
Cgs:         0.00e+00    0.00e+00    0.00e+00    0.00e+00    0.00e+00
Cgd:         0.00e+00    0.00e+00    0.00e+00    0.00e+00    0.00e+00
Cgb:         0.00e+00    0.00e+00    0.00e+00    0.00e+00    0.00e+00


Date: Tue May 10 00:11:42 2022
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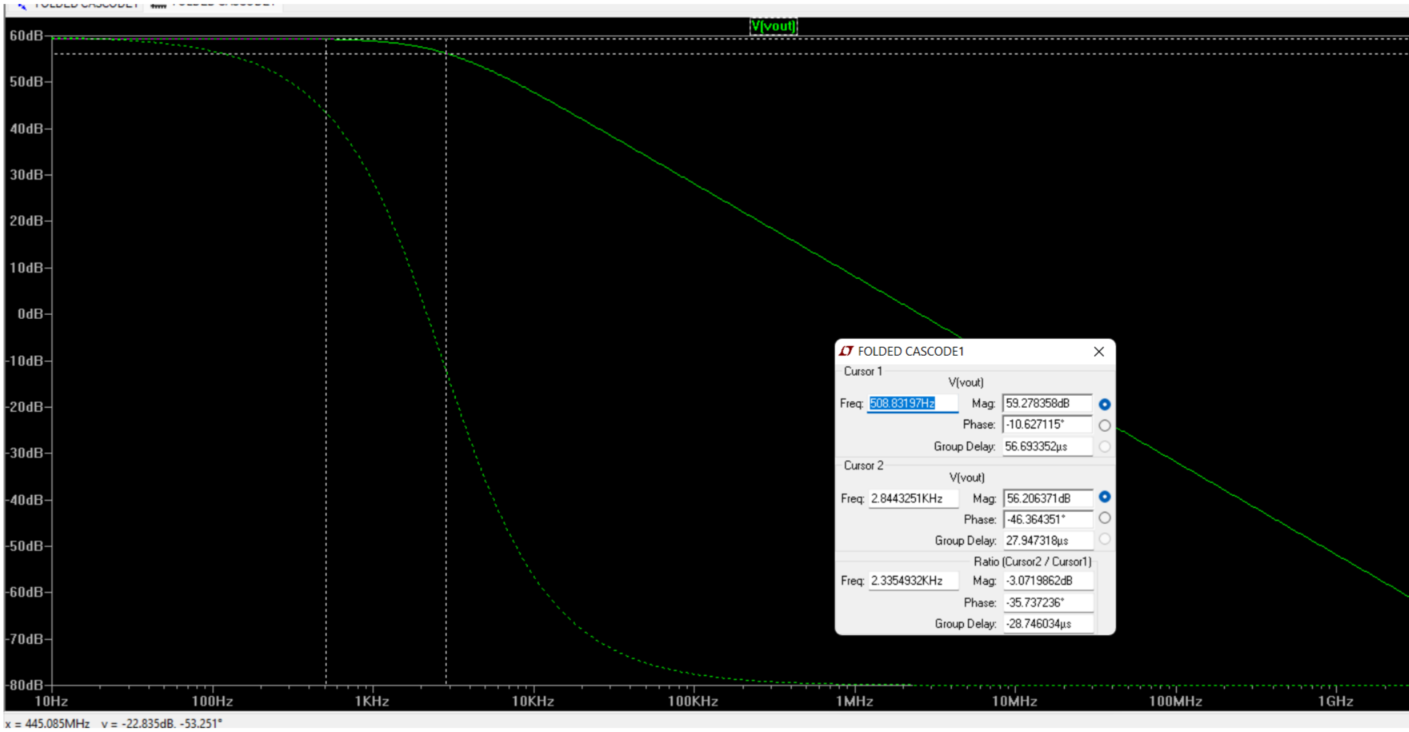
Gm of Folded cascode



AC analysis of Folded cascode

Gain = 59.27dB
B.W.=2.84KHz

Results :

Telescopic cascode single-ended Operational Transconductance Amplifier :

- W/L (of M1,M2,M3,M4) = 0.9259
- W/L (of M5,M6,M7,M8) = 3.5647
- W/L Of M0 = 1.22
- W/L (of M10,M11,M12) = 2
- $R_{out} = 33.33M\Omega$
- Gain = 65.07 dB
- Band Width 3.52KHz

Folded cascode single-ended Operational Transconductance Amplifier :

- W/L (of M1,M2,M5,M6,M7,M8) = 2.5
- W/L (of M3 , M4) = 1.25
- W/L Of M9 ,M10) = 2.5
- $R_{out} = 25M\Omega$
- Gain = 59.27 dB
- Band Width = 2.84KHz

Conclusion :

- Successfully implemented both of the design having high gain and high output impedence.
- Telescopic cascode has more gain and output impedence because of having a parallel small signal resistances in folded reduces the R_{out}.
- Experimental B.W. is very low than that of calculated b.w. because of transconductane of driving transistor is lower than the value which is taken in the calculation.
- Output swing is high in folded cascode in compare with telescopic.
- Folded topology has higher noise than telescopic.