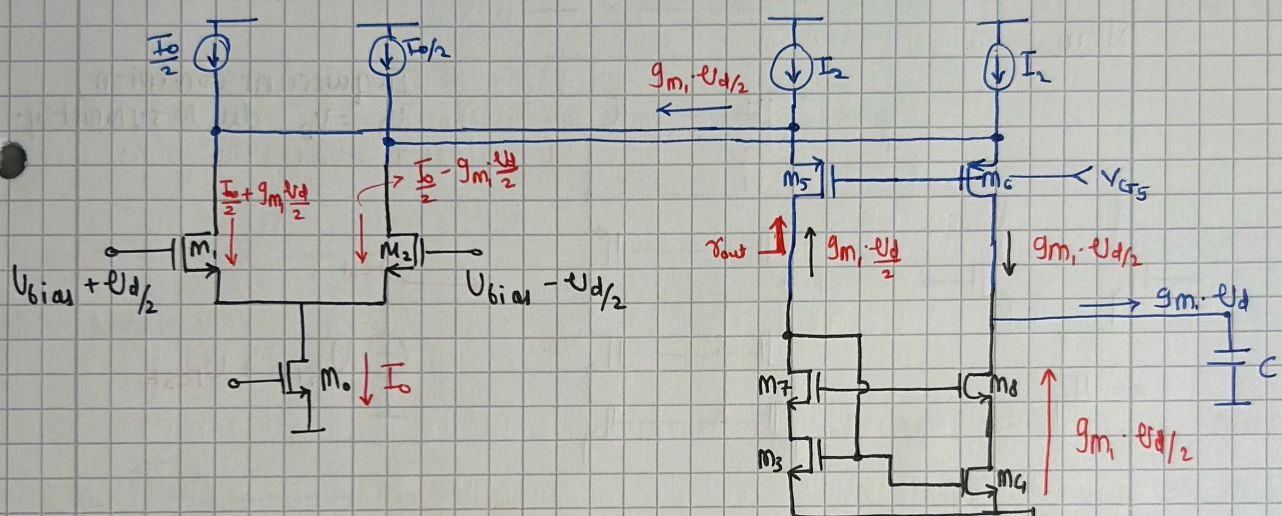
Telescopic Cascode	Differential pair.
higher gain	lesser swing limits

Now, the way we came up with the telescopic cascode was to take the current from the differential pair and put it through a common gate amplifier in order to achieve very high r_{out}.

where we chose n-mos-common gate with n-mos differential pair
↳ but we could equally use the p-mos common gate amp. with n-mos differential pair. we bias the pmos common gate amp. with some current source at the source node. (I_2)

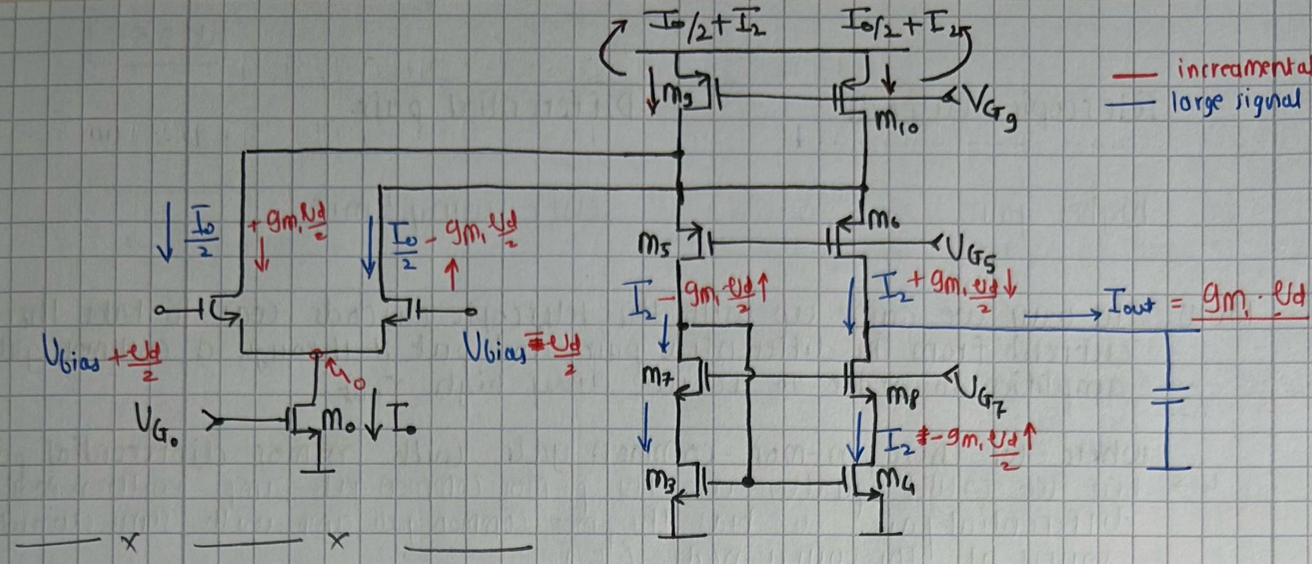


if we inject the current $g_{m_1} \cdot \frac{v_d}{2}$, the signal current in the drain of M_5 will be the same but with much higher r_{out} looking into drain of M_5

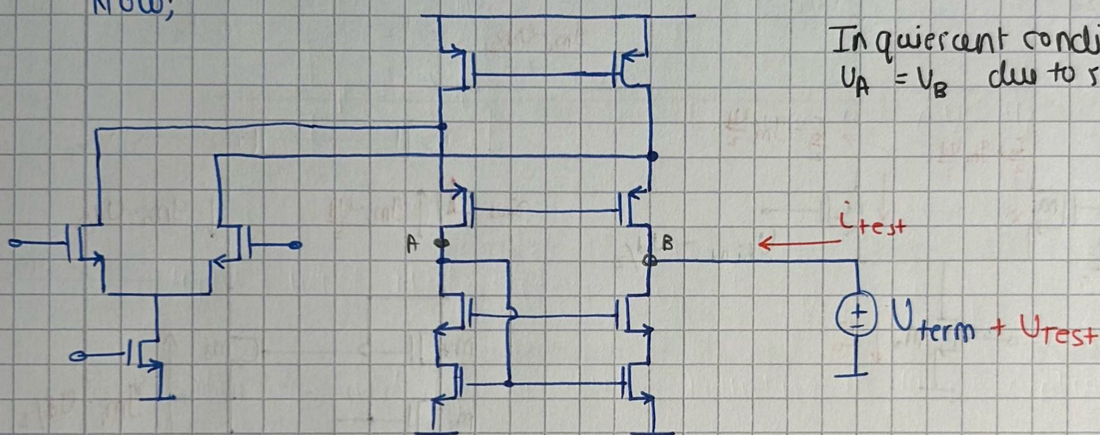
M_5 and M_6 are biased at const. gate voltage V_G.

This topology is called 'Folded Cascode op-amp'

The four current sources on top are in parallel so they will be combined into a single source.



Now;



In quiescent condition, $U_A = U_B$ due to symmetry.

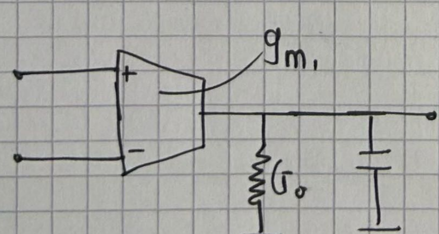
all mosfets are functionally identical to the telescopic one. we also have extra mosfets m_9 and m_{10}

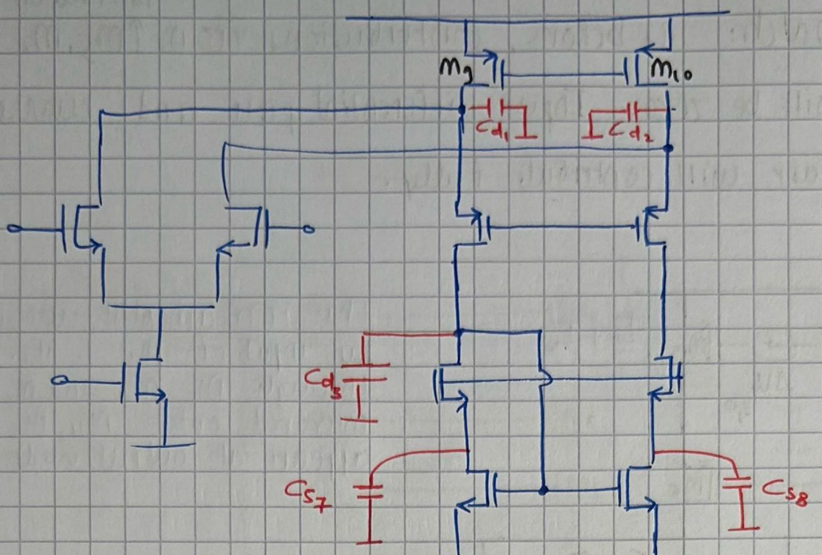
earlier we had : $G_o = \underbrace{\frac{g_{ds_3} \cdot g_{ds_7}}{g_{m_7}}}_{\text{contribut}^n\text{ from current mirror pair}} + \underbrace{\frac{g_{ds_5} \cdot g_{ds_1}}{g_{m_5}}}_{\text{contribut}^n\text{ from differential pair}}$

now, due to additional m_9 and m_{10}.

$$G_o = \frac{g_{ds_3} \cdot g_{ds_7}}{g_{m_7}} + \frac{g_{ds_5} \cdot (g_{ds_1} + g_{ds_9})}{g_{m_5}}$$

∴





The parasitics creating poles and zeros is similar to that of telescopic op-amp.

just the difference is;

due to M_9 and M_{10}

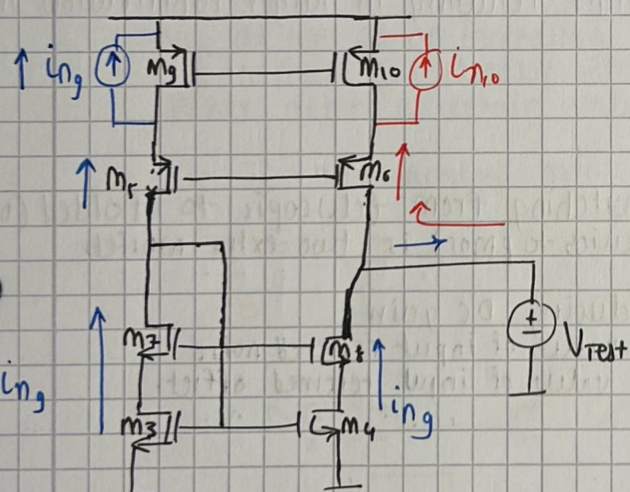
$$C_{d_1} = C_{db_1} + C_{sb_5} + C_{gs_5} + C_{db_9}$$

$\therefore$ M_9 contributes to C_{d_1} and makes it higher resulting in shifting pole to lower frequency.

$\therefore$ we might need to shift $\omega_{f.\omega}$ or ω_u to lower value in order to maintain the phase margin.

— x — x —

Noise:



i_{n_9} is seen by M_5 at its input

$\therefore$ its flown through M_5 M_7 and M_3 and reflected onto M_4 M_8

$\therefore$ it appears fully at output node

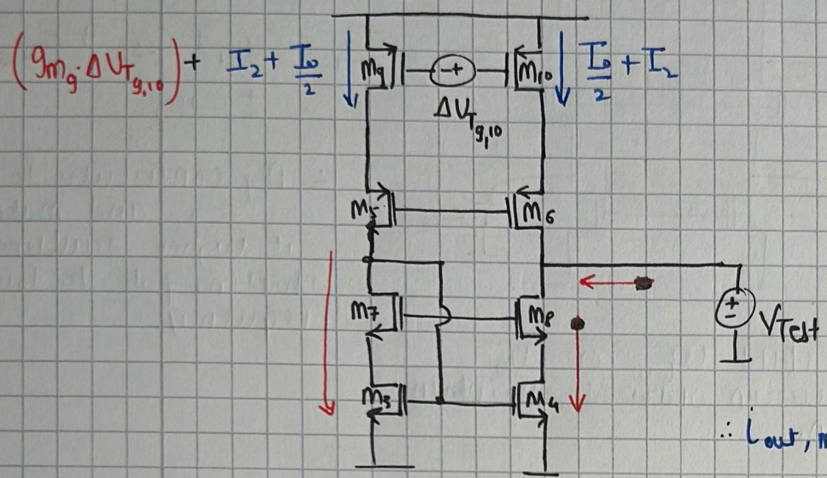
similarly $i_{n_{10}}$ also appears fully.

$$\therefore i_{n,out} = i_{n_1} - i_{n_2} + i_{n_3} - i_{n_4} + i_{n_9} - i_{n_{10}}$$

$$\therefore S_{U_i} = \frac{S_{i_{n,out}}}{g_{m_1}^2} = \frac{\frac{16}{3}kT\,(g_{m_1} + g_{m_3} + g_{m_9})}{g_{m_1}^2}$$

* also M_9 and M_{10} carry larger currents $\therefore$ having larger g_m $\therefore$ contributing larger noise.

* Offset or mismatch: as before, contributions from mismatch of M_5, M_6 and mismatch of $M_{7,8}$ will be zero. Input differential pair and current mirror pair will contribute fully.



This incremental current is seen by input of M_5 ∴ its flown through M_5 M_7 and M_3 and mirrored onto M_4, M_8 and thus appear at output node.

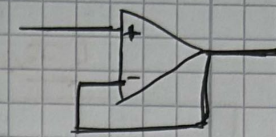
$$\therefore i_{out,\,mismatch} = \Delta V_{T_{12}} \cdot g_{m_1} + \Delta V_{T_{34}} \cdot g_{m_3} - \Delta V_{T_{9,10}} \cdot g_{m_9}$$

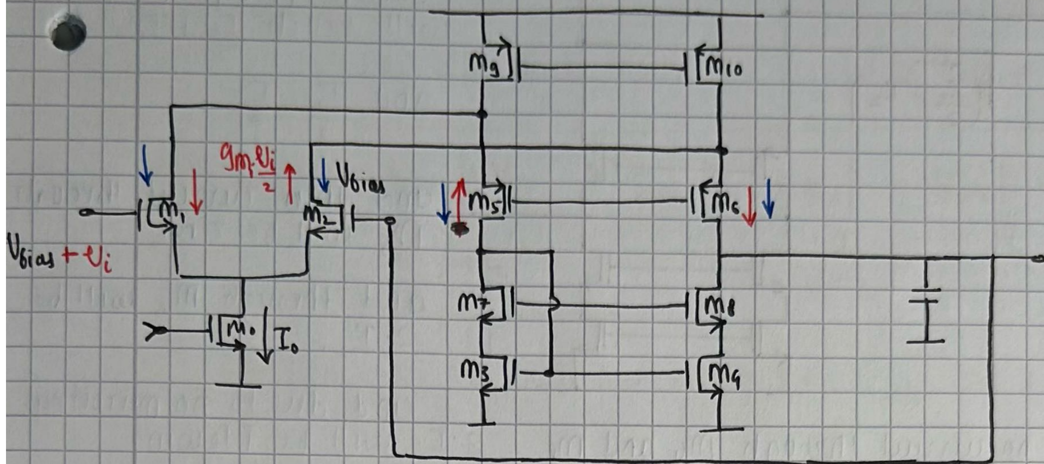
$$\therefore \text{Input reffered offset: } \sigma^2_{V_{os}} = \sigma^2_{V_{T_{12}}} + \sigma^2_{V_{T_{34}}} \left(\frac{g_{m_3}}{g_{m_1}}\right)^2 + \sigma^2_{V_{T_{9,10}}} \left(\frac{g_{m_9}}{g_{m_1}}\right)^2$$

* also g_{m_9} and $g_{m_{10}}$ are larger resulting in larger contribution in input referred offset.

* So, what we've got by switching from telescopic to folded (by changing nmos cascode devices to pmos) is two extra mosfets and, they contribute in reducing DC gain
↑ value of input reffered noise
↑ value of input referred offset.

* We'll take unity feedback:



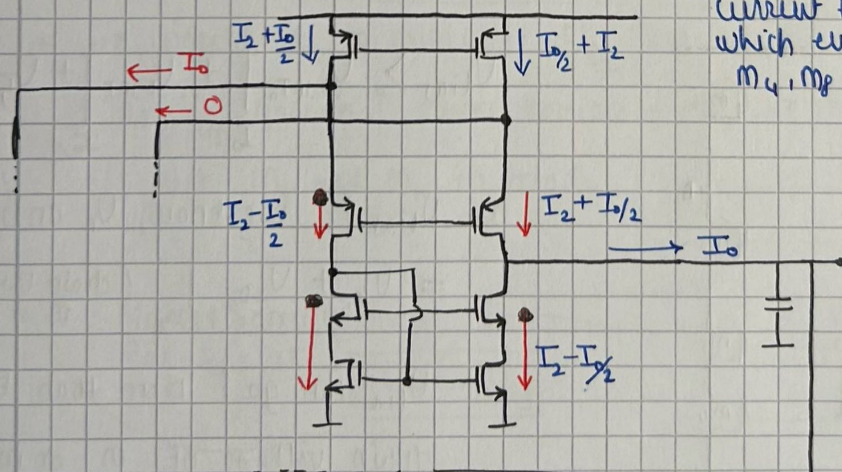


when v_i is applied, as usual this voltage doesn't change immediately. So, we have an incremental current $\left(g_{m_1}\cdot\frac{v_i}{2}\right)$

current in M_5 will be $I_2 - g_{m_1}\cdot v_i/2$

M_6 will be $I_2 + g_{m_1}\cdot v_i/2$

now, as we go on increasing v_i, current through m_1 $(g_{m_1}\cdot v_i)$ will increase but clearly not beyond I_0.
Hence, after a certain value of (v_i) current through m_1 will be I_0 and through m_2 it'll be just zero. So, under those conditions, current through M_5 will be $I_2 - \frac{I_0}{2}$ which eventually mirror on M_4, M_8 $\therefore$ at output we get I_0.

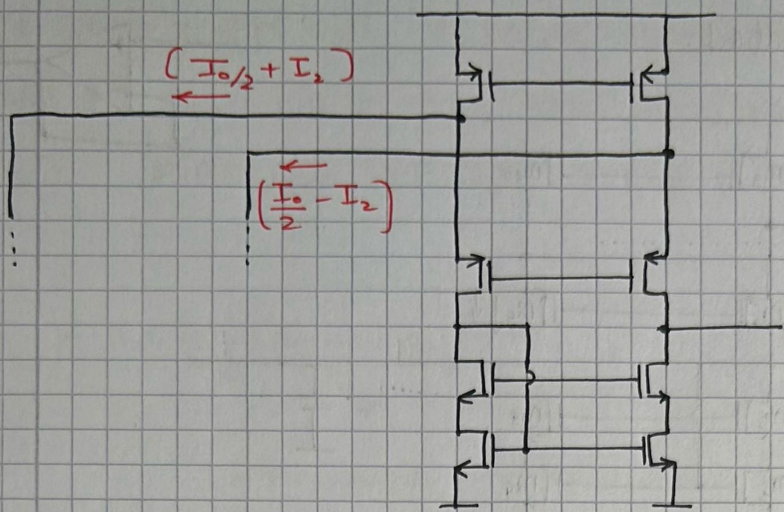


(imp) * we will get above result only if $I_2 > I_0/2$

Slew rate $= \frac{I_0}{C}$

what happens when $I_2 < I_0/2$

$\rightarrow$ P.T.O.



as we keep increasing v_i

current through m_1 and m_2 will reach $\frac{I_0}{2} + I_2$ and $\frac{I_0}{2} - I_2$

and then current through m_5 will be zero.

and through m_6 will be $2 \cdot I_2$.

and due to no mirroring. there's no current through m_4 and m_8 $\therefore$ $2 \cdot I_2$ will be flowing through capacitor.

$\therefore$ max. rate of change of o/p $= \frac{2 \cdot I_2}{C}$

$\therefore$ for $I_2 > \frac{I_0}{2}$: slew rate $= \frac{I_0}{C}$

$I_2 < \frac{I_0}{2}$: slew rate $= \frac{2 \cdot I_2}{C}$

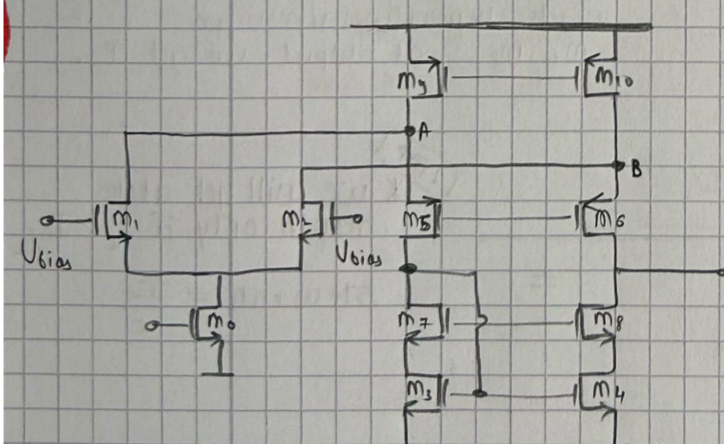
normally I_2 is choosen exactly equal to $\frac{I_0}{2}$

IMP

— x — x —

* Until this point, we saw no advantage of switching from telescopic to folded.

let's analyse swing limits now:



$$V_{bias} > V_{DSAT_0}\Big|_{I_0} + V_{DSAT_1}\Big|_{I_0/2} + V_{T_1}$$

as $V_{bias} \uparrow$ we know, V_A an V_B

$$= V_{G_5} + V_{SG_5}\Big|_{I_2}$$ (drain voltage of m_1 or m_2)

$\therefore$ V_{bias} can go $\uparrow$ more than ~~V_{G_5}~~ drain voltage of m_1 or m_2 but not more than $1 \cdot V_T$

$$\therefore V_{bias} < V_{G_5} + V_{SG_5} + V_{T_1}$$

~~$V_{DSAT_8} + V_{SG_5}$~~

→

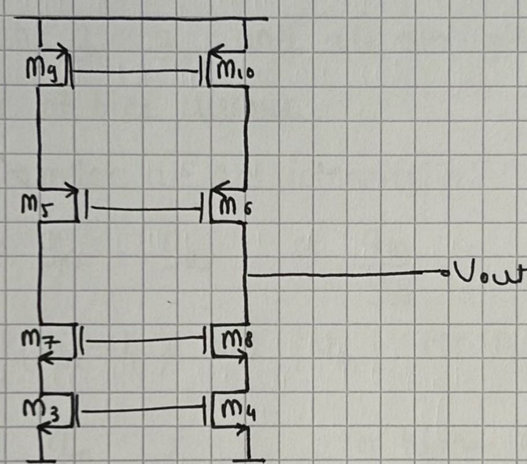
now, in order to maximize swing for V_{bias}; V_{SG_5} must be maximized.
but as $V_{SG} \uparrow$, $M_{9,10}$ squeezes

$\therefore$ node A and node B should be biased at $V_{DD} - V_{DSAT_9}\big|_{\frac{I_0}{2}+I_2}$

Hence; $\boxed{V_{DD} - V_{DSAT_9}\big|_{\frac{I_0}{2}+I_2} + V_{T_1} > V_{bias} > V_{DSAT_0}\big|_{I_0} + V_{DSAT}\big|_{\frac{I_0}{2}} + V_{T_1}}$

↳ This gives us very nice swing for $V_{i,cm}$ and it can actually go till V_{DD}

* limits on V_{out};



If V_{out} go on $\downarrow$ and goes $1 \cdot V_{T_7}$ below V_{G_7}, M_8 will enter triode region.

$\therefore V_{out} > V_{G_7} - V_{T_7}$

If V_{out} go on $\uparrow$ and goes $1 \cdot V_{T_5}$ above V_{G_5}, M_6 will enter triode region.

$\therefore V_{out} < V_{G_5} + V_{T_5}$

* we would like to minimize V_{G_7} and maximize V_{G_5} for maximum swing.
as V_{G_5} goes on $\uparrow$ source terminal of M_5 and M_6 will also follow V_{G_5} and push M_9 and M_{10} in triode. $\therefore V_{G_5} < V_{DSAT_9}\big|_{\frac{I_0}{2}+I_2} + V_{SG_5}$

$V_{G_5} < V_{DSAT_9}\big|_{\frac{I_0}{2}+I_2} + V_{T_5} + V_{DSAT_5}\big|_{I_2}$

$\therefore$ highest possible value for V_{out} is: $\boxed{\text{this} + V_{T_5}}$

↳* where highest value of $V_{G_5} = V_{DD} - V_{DSAT_9} - V_{DSAT_5} - V_{T_5}$

now, when V_{G_7} goes on $\downarrow$ source terminal of M_7 and M_8 fall down and pushes M_3 and M_4 into triode for value $V_{DSAT_3} + \underbrace{V_{GS_7}}_{V_{DSAT_7} + V_{T_7}}$

$$\therefore V_{G_7} > \underbrace{V_{DSAT_3} + V_{DSAT_7} + V_{T_7}}_{\text{lowest possible value for } V_{G_7}}$$

$$\therefore V_{out} > \underbrace{V_{DSAT_3} + V_{DSAT_8}}_{\text{lowest possible value for } V_{out}}$$

* Hence, the swing limits are much higher than telescopic and single stage op-amp.