

EE539: Analog Integrated Circuit Design

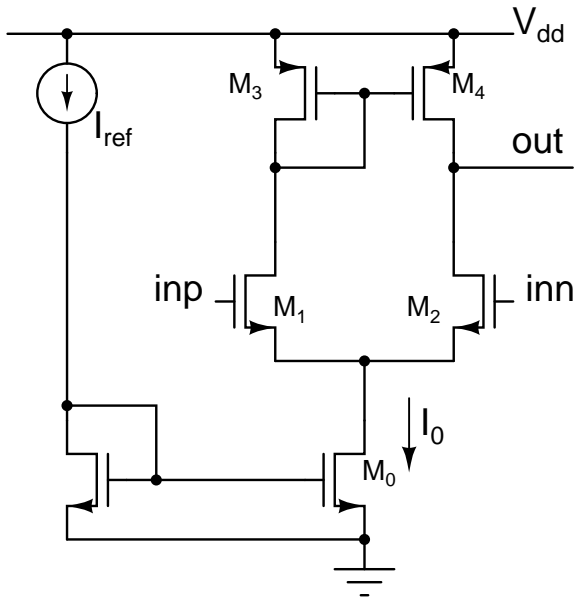
Opamp-summary

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Differential pair opamp

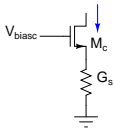


Differential pair opamp

G_m	g_{m1}
G_{out}	$g_{ds1} + g_{ds3}$
A_o	$g_{m1} / (g_{ds1} + g_{ds3})$
A_{cm}	g_{ds0} / g_{m3}
C_i	$C_{gs1} / 2$
ω_u	g_{m1} / C_L
p_k, z_k	$p_2 = -g_{m3} / (C_{db1} + C_{db3} + 2C_{gs3}); z_1 = 2p_2$
S_{vi}	$16kT / 3g_{m1} (1 + g_{m3} / g_{m1})$
σ_{Vos}^2	$\sigma_{VT1}^2 + (g_{m3} / g_{m1})^2 \sigma_{VT3}^2$
V_{cm}	$\geq V_{T1} + V_{DSAT1} + V_{DSAT0}$ $\leq V_{dd} - V_{DSAT3} - V_{T3} + V_{T1}$
V_{out}	$\geq V_{cm} - V_{T1}$ $\leq V_{dd} - V_{DSAT3}$
SR	$\pm I_0 / C_L$
I_{supply}	$I_0 + I_{ref}$

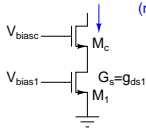
Cascode output resistance

$$R_{out} = g_{mc}/g_{dsc}G_s + 1/G_s + 1/g_{dsc}$$



$$R_{out} = g_{mc}/g_{dsc}g_{ds1} + 1/g_{dsc} + 1/g_{ds1}$$

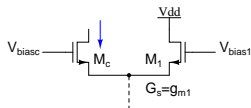
(negligible)



$$R_{out} = g_{mc}/g_{dsc}g_{m1} + 1/g_{dsc} + 1/g_{m1}$$

(negligible)

$$R_{out} = 1/g_{dsc}(1 + g_{mc}/g_{m1})$$



differential pair: M_c degenerated by M_1 's source impedance (g_{m1})

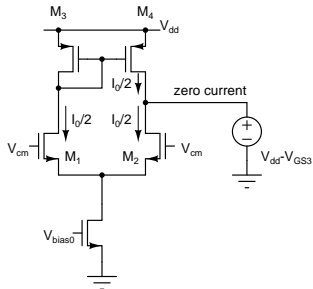
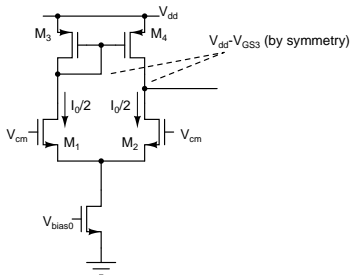
- Output resistance looking into one side of the differential pair is $2/g_{ds1}$ ($g_{m1} = g_{mc}$ in the figure)

Opamp: dc small signal analysis

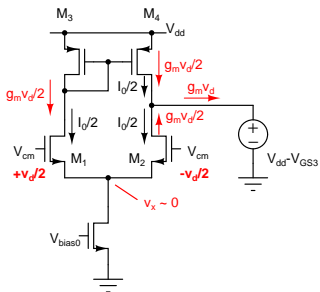
- Bias values in black
- Incremental values in red
- Impedances in blue

Total quantity = Bias + increment

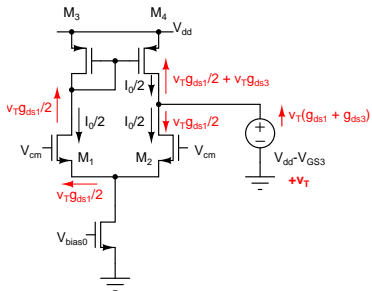
Differential pair: Quiescent condition



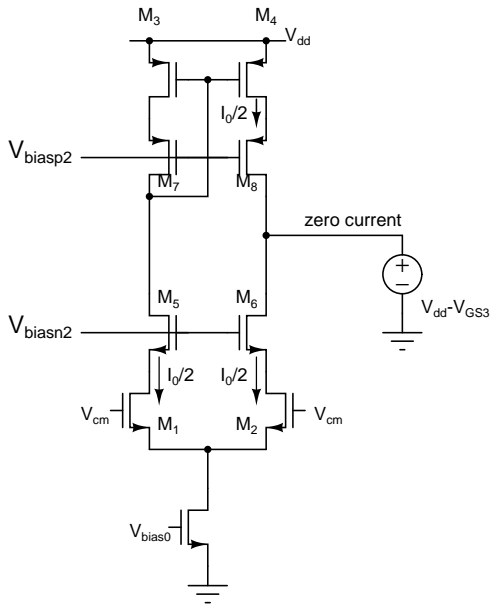
Differential pair: Transconductance



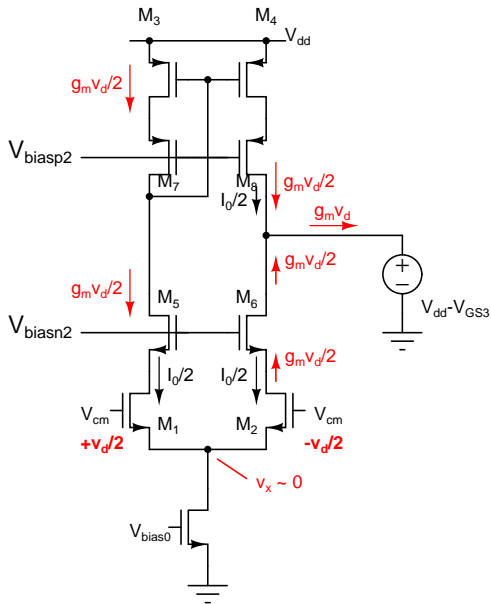
Differential pair: Output conductance



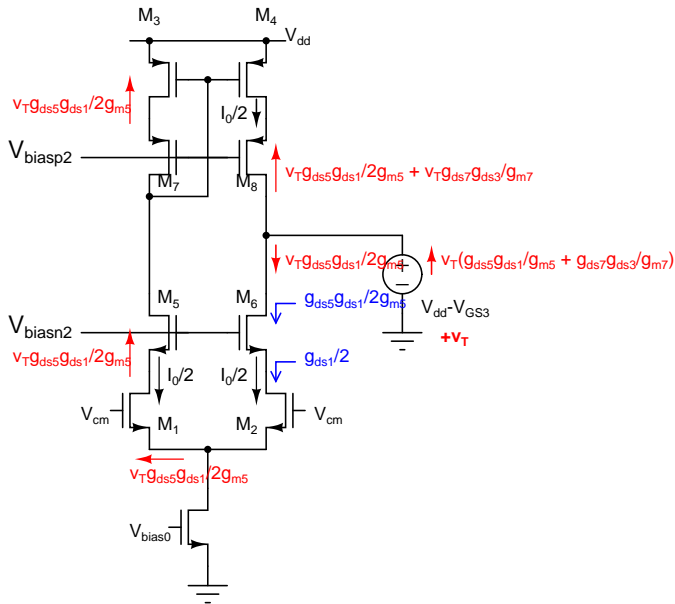
Telescopic cascode: Quiescent condition



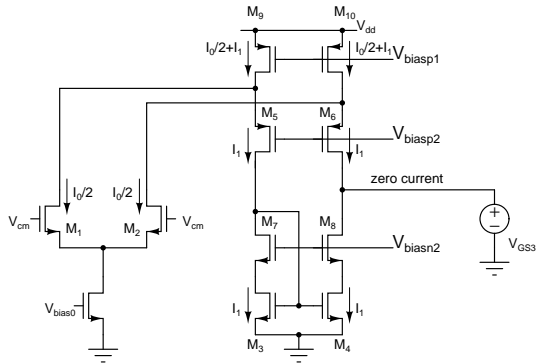
Telescopic cascode: Transconductance



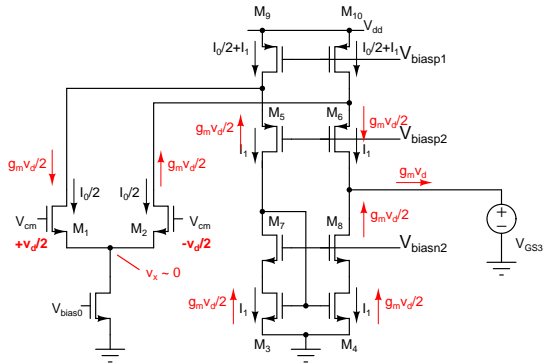
Telescopic cascode: Output conductance



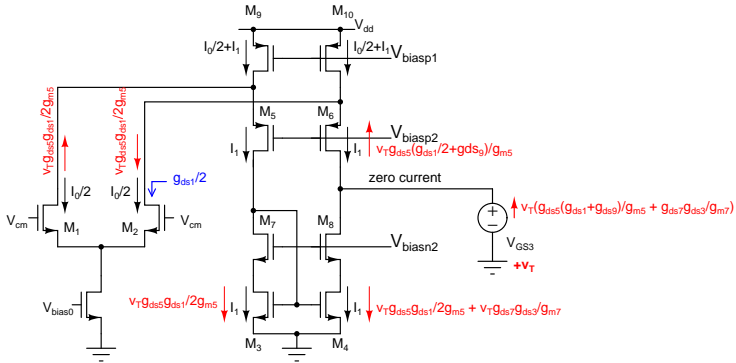
Folded cascode: Quiescent condition



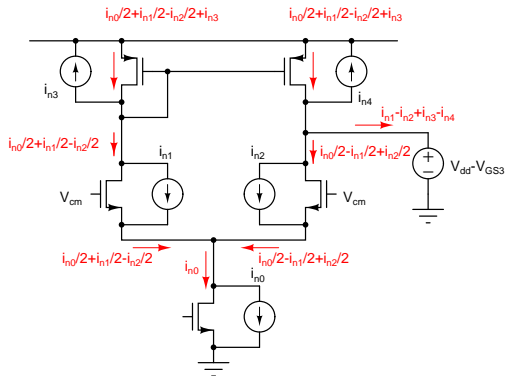
Folded cascode: Transconductance



Folded cascode: Output conductance

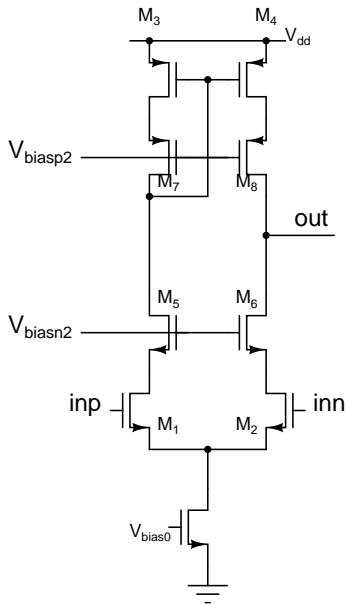


Differential pair: Noise



- Carry out small signal linear analysis with one noise source at a time
- Add up the results at the output (current in this case)
- Add up corresponding spectral densities
- Divide by gain squared to get input referred noise

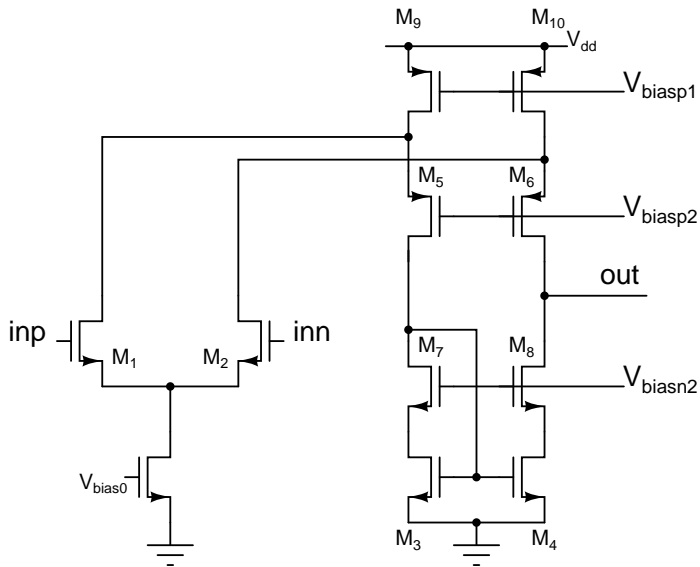
Telescopic cascode opamp



Telescopic cascode opamp

G_m	g_{m1}
G_{out}	$g_{ds1}g_{ds5}/g_{m5} + g_{ds3}g_{ds7}/g_{m7}$
A_o	$g_{m1}/(g_{ds1}g_{ds5}/g_{m5} + g_{ds3}g_{ds7}/g_{m7})$
A_{cm}	g_{ds0}/g_{m3}
C_i	$C_{gs1}/2$
ω_u	g_{m1}/C_L
p_k, z_k	$p_2 = -g_{m3}/(C_{db1} + C_{db3} + 2C_{gs3})$ $p_3 = -g_{m5}/C_{p5}$ $p_4 = -g_{m7}/C_{p7}$ $p_{2,4}$ appear for one half and cause mirror zeros
S_{vi}	$16kT/3g_{m1} (1 + g_{m3}/g_{m1})$
σ_{Vos}^2	$\sigma_{VT1}^2 + (g_{m3}/g_{m1})^2 \sigma_{VT3}^2$
V_{out}	$\geq V_{biasn1} - V_{T5}$ $\leq V_{biasp1} + V_{T7}$
SR	$\pm I_0/C_L$
I_{supply}	$I_0 + I_{ref}$

Folded cascode opamp

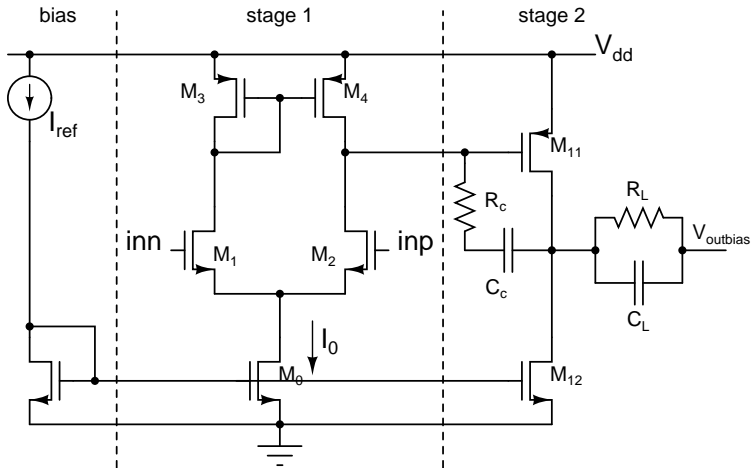


Folded cascode opamp

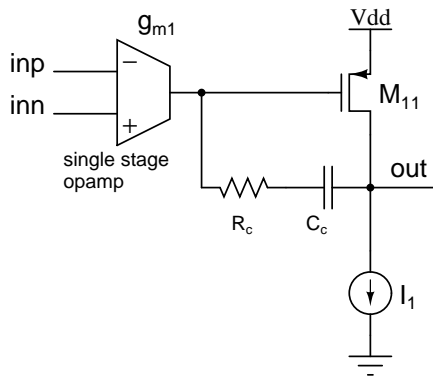
G_m	g_{m1}
G_{out}	$(g_{ds1} + g_{ds9})g_{ds5}/g_{m5} + g_{ds3}g_{ds7}/g_{m7}$
A_o	$g_{m1}/((g_{ds1} + g_{ds9})g_{ds5}/g_{m5} + g_{ds3}g_{ds7}/g_{m7})$
A_{cm}	g_{ds0}/g_{m3}
C_i	$C_{gs1}/2$
ω_u	g_{m1}/C_L
p_k, z_k	$p_2 = -g_{m3}/(C_{db1} + C_{db3} + 2C_{gs3})$ $p_3 = -g_{m5}/C_{p5}$ $p_4 = -g_{m7}/C_{p7}$ $p_{2,4}$ appear for one half and cause mirror zeros
S_{vi}	$16kT/3g_{m1} (1 + g_{m3}/g_{m1} + g_{m9}/g_{m1})$
σ_{Vos}^2	$\sigma_{VT1}^2 + (g_{m3}/g_{m1})^2 \sigma_{VT3}^2 + (g_{m9}/g_{m1})^2 \sigma_{VT9}^2$
V_{out}	$\geq V_{biasn1} - V_{T5}$ $\leq V_{biasp1} + V_{T7}$
SR	$\pm \min\{I_0, I_1\}/C_L$
I_{supply}	$I_0 + I_1 + I_{ref}$

- All nMOS bulk terminals to ground
- All pMOS bulk terminals to V_{dd}
- A_{cm} has an additional factor $g_{m1}/(g_{m1} + g_{mb1})$
- $g_{m5} + g_{mb5}$ instead of g_{m5} in cascode opamp results
- $g_{m7} + g_{mb7}$ instead of g_{m7} in cascode opamp results

Two stage opamp



Two stage opamp



- First stage can be Differential pair, Telescopic cascode, or Folded cascode; Ideal g_{m1} assumed in the analysis
- Second stage: Common source amplifier
- Frequency response is the product of frequency responses of the first stage g_m and a common source amplifier driven from a current source

Common source amplifier: Frequency response

$$\frac{V_o(s)}{V_d(s)} = \left(\frac{g_{m1} g_{m11}}{G_1 G_L} \right) \frac{s C_c (R_c - 1/g_{m11}) + 1}{a_3 s^3 + a_2 s^2 + a_1 s + 1}$$

$$a_3 = \frac{R_c C_1 C_L C_c}{G_1 G_L}$$

$$a_2 = \frac{C_1 C_c + C_c C_L + C_L C_1 + R_c C_c (G_1 C_L + C_1 G_L)}{G_1 G_L}$$

$$a_1 = \frac{C_c (g_{m11} + G_1 + G_L + G_1 G_L R_c) + C_1 G_L + G_1 C_L}{G_1 G_L}$$

- G_1 : Total conductive load at the input
- G_L : Total conductive load at the output
- C_1 : Total capacitive load at the input
- C_L : Total capacitive load at the output

Common source amplifier: Poles and zeros

$$p_1 \approx -\frac{G_1}{C_c \left(\frac{g_{m11}}{G_L} + 1 + \frac{G_1}{G_L} + G_1 R_c \right) + C_1 \left(1 + \frac{G_1}{G_L} \right)}$$
$$p_2 \approx -\frac{g_{m11} \frac{C_c}{C_1 + C_c} + G_L + G_1 \frac{C_c + C_L}{C_1 + C_c} + G_1 G_L R_c \frac{C_c}{C_1 + C_c}}{\frac{C_1 C_c}{C_1 + C_c} + C_L + \frac{R_c C_c (G_1 C_L + G_L C_1)}{C_c + C_L}}$$
$$p_3 \approx -\left(\frac{1}{R_c} \left(\frac{1}{C_L} + \frac{1}{C_c} + \frac{1}{C_1} \right) + \frac{G_1}{C_1} + \frac{G_L}{C_L} \right)$$
$$z_1 = \frac{1}{(1/g_{m11} - R_c) C_c}$$

Unity gain frequency

$$\omega_u \approx \frac{g_{m1}}{C_c \left(1 + \frac{G_L}{g_{m11}} + \frac{G_1}{g_{m11}} + \frac{G_1 G_L R_c}{g_{m11}} \right) + C_1 \left(\frac{G_L}{g_{m11}} + \frac{G_1}{g_{m11}} \right)}$$

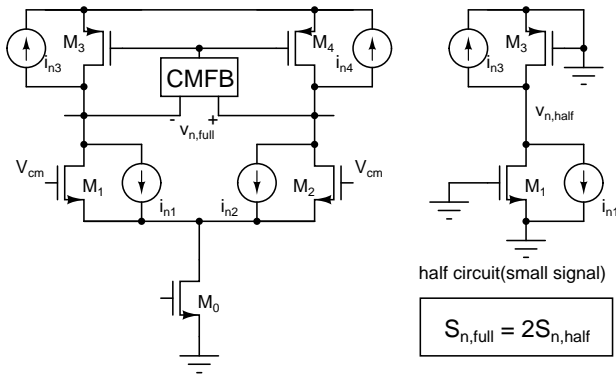
Common source amplifier: Frequency response

- Pole splitting using compensation capacitor C_C
 - p_1 moves to a lower frequency
 - p_2 moves to a higher frequency (For large C_C , $p_2 = g_{m11}/C_L$)
- Zero cancelling resistor R_C moves z_1 towards the left half s plane and results in a third pole p_3
 - z_1 can be moved to ∞ with $R_C = 1/g_{m11}$
 - z_1 can be moved to cancel p_2 with $R_C > 1/g_{m11}$ (needs to be verified against process variations)
 - Third pole p_3 at a high frequency
- Poles and zeros from the first stage will appear in the frequency response— $Y_{m1}(s)$ instead of g_{m1} in V_o/V_i above
 - Mirror pole and zero
 - Poles due to cascode amplifiers

Two stage opamp

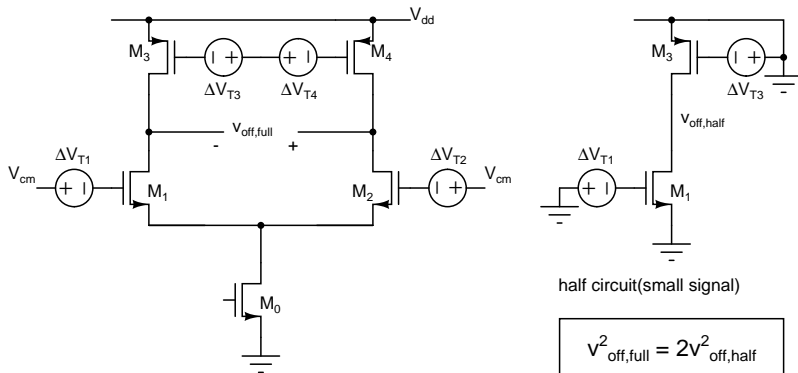
A_o	$g_{m1}g_{m11}/(g_{ds1} + g_{ds3})(g_{ds11} + g_{ds12})$
A_{cm}	$g_{ds0}g_{m11}/g_{m3}(g_{ds11} + g_{ds12})$
C_i	$C_{gs1}/2$
ω_u	g_{m1}/C_c
p_k, z_k	See previous pages
S_{vi}	$\approx 16kT/3g_{m1} (1 + g_{m3}/g_{m1})$
σ_{Vos}^2	$\approx \sigma_{VT1}^2 + (g_{m3}/g_{m1})^2 \sigma_{VT3}^2$
V_{cm}	$\geq V_{T1} + V_{DSAT1} + V_{DSAT0}$ $\leq V_{dd} - V_{DSAT3} - V_{T3} + V_{T1}$
V_{out}	$\geq V_{DSAT12}$ $\leq V_{dd} - V_{DSAT11}$
SR+	I_0/C_c
SR-	$\min\{I_0/C_c, I_1/(C_L + C_c)\}$
I_{supply}	$I_0 + I_1 + I_{ref}$

Fully differential circuits: Noise



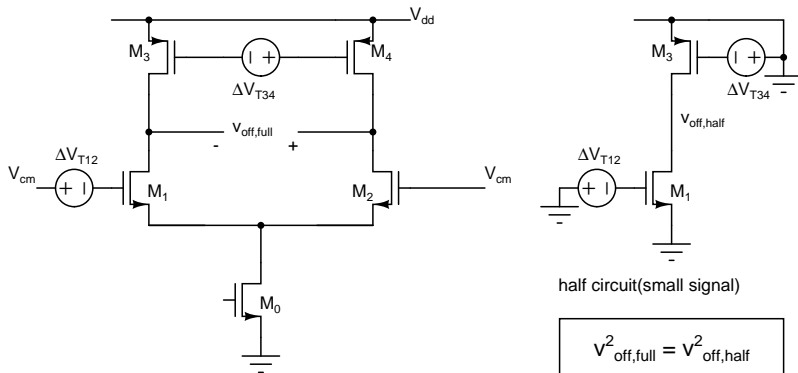
- Calculate noise spectral density of the half circuit
- Multiply by $2\times$

Fully differential circuits: Offset



- Calculate mean squared offset of the half circuit
- Multiply by $2\times$ if mismatch (e.g. ΔV_T) wrt ideal device is used

Fully differential circuits: Offset

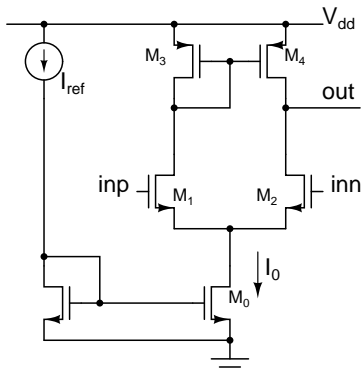


- Calculate mean squared offset of the half circuit
- Multiply by $1 \times$ if mismatch between two real devices is used

Opamp comparison

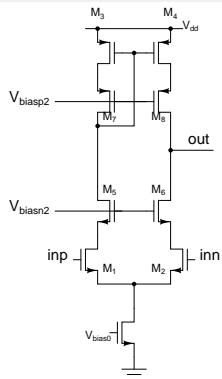
	Differential pair	Telescopic cascode	Folded cascode	Two stage
Gain	–	++	+	++
Noise	=	=	high	=
Offset	=	=	high	=
Swing	–	–	+	++
Speed	++	+	–	+

Differential pair



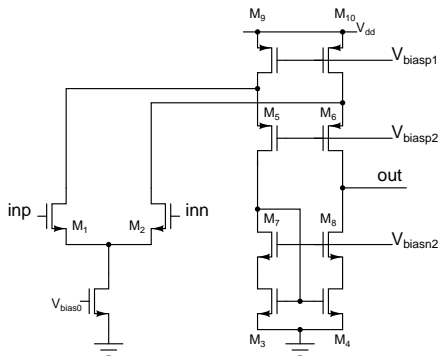
- Low accuracy (low gain) applications
- Voltage follower (capacitive load)
- Voltage follower with source follower (resistive load)
- In bias stabilization loops (effectively two stages in feedback)

Telescopic cascode



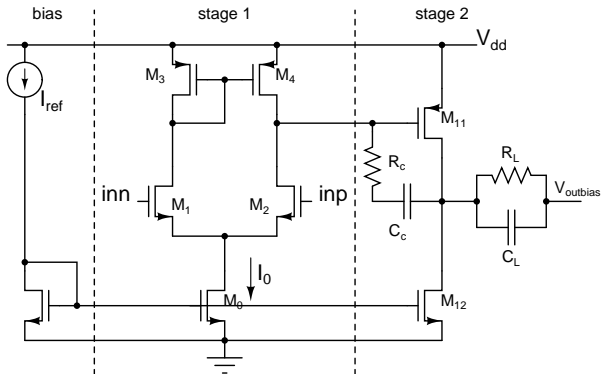
- Low swing circuits
- Switched capacitor circuits
 - Capacitive load
 - Different input and output common mode voltages
- First stage of a two stage opamp
 - Only way to get high gain in fine line processes

Folded cascode



- Higher swing circuits
- Higher noise and offset
- Lower speed than telescopic cascode
 - Low frequency pole at the drain of the input pair
- Switched capacitor circuits (Capacitive load)
- First stage of a two stage class AB opamp

Two stage opamp



- Highest possible swing
- Resistive loads
- Capacitive loads at high speed
- “Standard” opamp: Miller compensated two stage opamp
- Class AB opamp: Always two (or more) stages

Opamps: pMOS versus nMOS input stage

- nMOS input stage
 - Higher g_m for the same current
 - Suitable for large bandwidths
 - Higher flicker noise (usually)
- pMOS input stage
 - Lower g_m for the same current
 - Lower flicker noise (usually)
 - Suitable for low noise low frequency applications