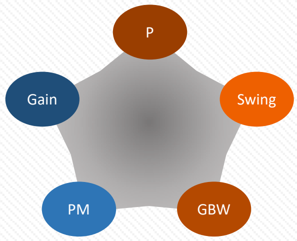
Advanced Amplifier Topologies

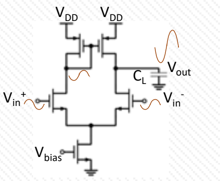
Trade-off



There is no perfect amplifier.

➡ Analog Design is all about finding the **perfect trade-off**.

Simple amplifier



$$A = g_m \frac{r_{ds}}{2} \approx 30\ dB$$

$$PM = 90°$$

$$GBW = \frac{g_m}{2\pi C_L}$$

$$V_{swing} = V_{DD} - 3V_{ov}$$

Gain | PM | GBW | Swing | P

CM input range: $V_{gs} + V_{ov} < V_{in\ CM} < V_{DD} - V_{gs} + V_{th}$

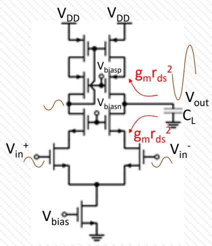
➡ $CMIR = V_{DD} - V_{gs} - 2V_{ov}$

Good power efficiency but **poor gain**.

We need to sacrifice something to get more gain.

Telescopic Cascode Amplifier

Trading swing for gain.



$$A = gm^2 \frac{{r_{ds}}^2}{2} \approx \mathbf{60\ dB}$$

$$PM = 90°$$

$$GBW = \frac{g_m}{2\pi C_L}$$

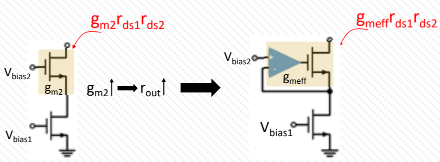
$$V_{swing} = V_{DD} - 5V_{ov}$$

Gain | PM | GBW | Swing | P

CM input range: $V_{gs} + V_{ov} < V_{in\ CM} < V_{DD} - V_{gs} - V_{ov} + V_{th}$

➡ $CMIR = V_{DD} - V_{gs} - 3V_{ov}$

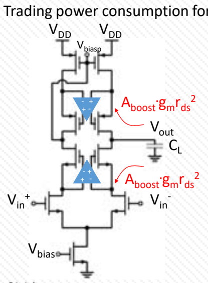
Gain Boosting



$$g_{meff} = A_{boost} \cdot g_m$$

Gain Boosted Cascode Amplifier

Trading power consumption for gain.



$$A = gm^2 A_{boost} \frac{{r_{ds}}^2}{2} > \mathbf{90\ dB}$$

$$PM = 90°$$

$$GBW = \frac{g_m}{2\pi C_L}$$

$$V_{swing} = V_{DD} - 5V_{ov}$$

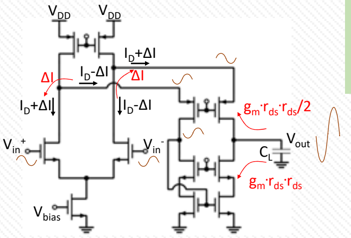
Gain | PM | GBW | Swing | P

CM input range: $V_{gs} + V_{ov} < V_{in\ CM} < V_{DD} - V_{gs} - V_{ov} + V_{th}$

➡ $CMIR = V_{DD} - V_{gs} - 3V_{ov}$

Folded Cascode Amplifier

Trading power consumption for swing.



$$A = gm^2 \frac{{r_{ds}}^2}{3} \approx \mathbf{60\ dB}$$

$$PM = 90°$$

$$GBW = \frac{g_m}{2\pi C_L}$$

$$V_{swing} = V_{DD} - 4V_{ov}$$

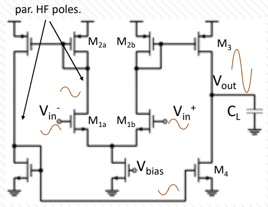
Gain
PM
GBW
Swing
P

CM input range: $V_{gs} + V_{ov} < V_{in\,CM} < V_{DD} - V_{gs} + V_{th}$

➡ CM input range includes supply rail at the expense of larger supply current due to folding.

Single Stage OTA

Trading power consumption for swing.



$$A = \frac{g_{m1}}{g_{m2}} \cdot \frac{g_{m3} + g_{m4}}{2} \cdot \frac{r_{ds}}{2}$$

$$PM < 90°$$

$$GBW = \frac{g_{m1}}{g_{m2}} \cdot \frac{g_{m3} + g_{m4}}{2} \frac{1}{2\pi C_L}$$

$$V_{swing} = V_{DD} - 2V_{ov}$$

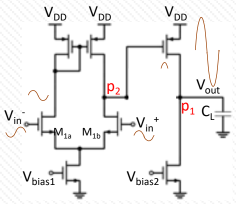
Gain
PM
GBW
Swing
P

Highest output swing so far but poor gain.

Can we get the same swing with more gain?

Two Stage Miller OTA

Trading PM & GBW for swing & gain.



$$A = g_{m1} \cdot \frac{r_{ds1}}{2} \cdot g_{m2} \cdot \frac{r_{ds2}}{2}$$

$$45° < PM < 70°$$

$$GBW = \frac{g_{m1}}{2\pi C_c}$$

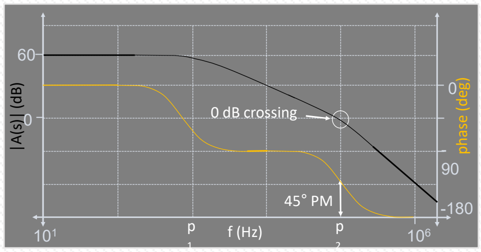
$$V_{swing} = V_{DD} - 2V_{ov}$$

Gain
PM
GBW
Swing
P

two gain stages ➡ two poles

➡ Miller compensation required which reduces GBW.

Two Stage Miller OTA



Recall

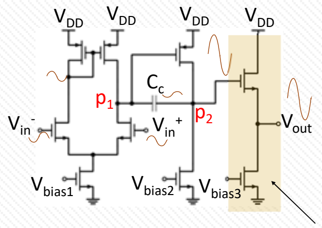
All amplifiers discussed so far are operational transconductance amplifiers (OTA).
Due to their high output impedance they behave like voltage controlled curent sources.

Tradeoff between Gain and GBW, PM, Swing and P.

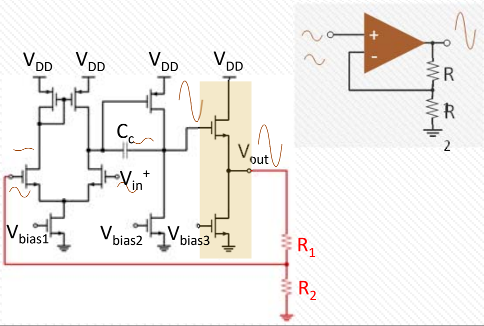
Opamp

Sometimes we need to drive a resistive load.

➡ Add output buffer.

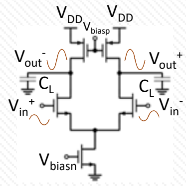


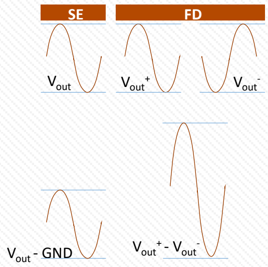
Opamp in Feedback



Fully Differential

Differential in, Differential out.

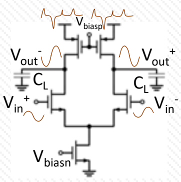


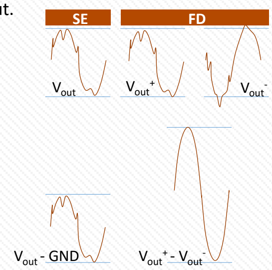


We get double the swing.

Fully Differential

Differential in, Differential out.



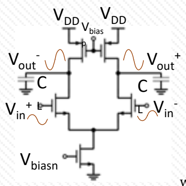


Supply Disturbances are CM.

➡ Cancellation.

Fully Differential

Differential in, Differential out.



Assume each differential branch as a nonlinear function:

$$V_{out} = \alpha_1 V_{in} + \alpha_2 V_{in}{}^2 + \alpha_3 V_{in}{}^3 + \alpha_3 V_{in}{}^4 + \cdots$$

$$\Rightarrow V_{out}{}^+ = \alpha_1 V_{in}{}^- + \alpha_2 V_{in}{}^{-2} + \alpha_3 V_{in}{}^{-3} + \alpha_4 V_{in}{}^{-4} + \cdots$$

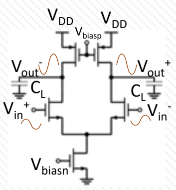
$$V_{out}{}^- = \alpha_1 V_{in}{}^+ + \alpha_2 V_{in}{}^{+2} + \alpha_3 V_{in}{}^{+3} + \alpha_4 V_{in}{}^{+4} + \cdots$$

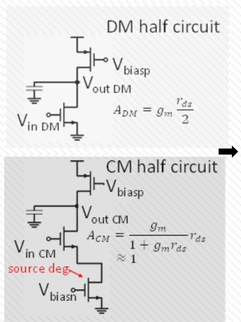
with $V_{in}{}^+ = -V_{in}{}^- = (V_{in}{}^+ - V_{in}{}^-)/2$:

$$V_{out}{}^+ - V_{out}{}^- = \alpha_1 \left(V_{in}{}^+ - V_{in}{}^-\right) + \alpha_3 \left(V_{in}{}^+ - V_{in}{}^-\right)^3 + \cdots$$

Even order harmonics are cancelled.

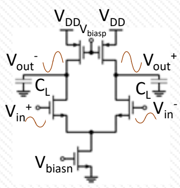
CMFB





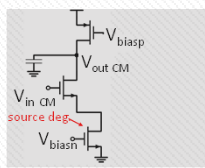
$$\Rightarrow \frac{A_{CM}}{A_{DM}} = \frac{1}{g_m \frac{r_{ds}}{2}}$$

CMFB



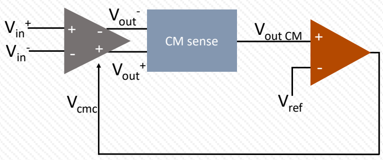
$$\frac{V_{out\ CM}}{V_{biasp}} = g_{mp}(r_{ds} || g_{mn} r_{ds}{}^2) \approx g_{mp} r_{ds}$$

➡ Very high gain from V_{biasp} to $V_{out\ CM}$.
How can we stabilize the output CM?

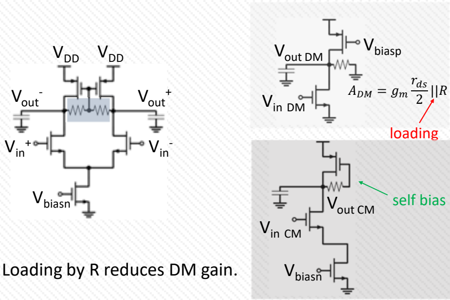


CMFB

Use CM feedback loop to define the output CM.

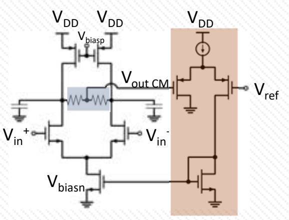


CMFB



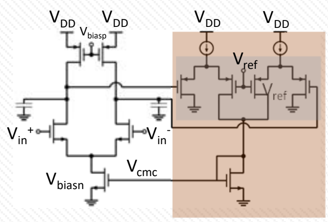
Loading by R reduces DM gain.

CMFB



Output CM can be set to an arbitraral level V_{ref}.

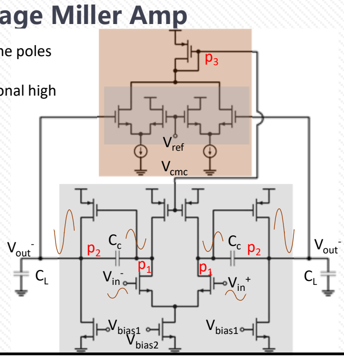
CMFB

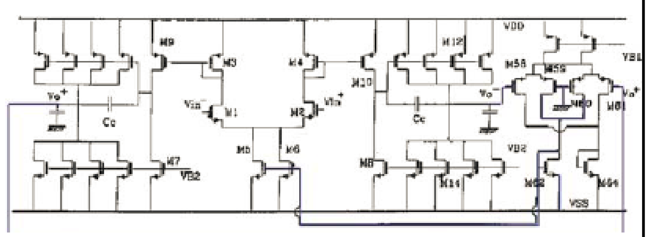


No loading of differential amplifier output.
but: CM sense is nonlinear
➡Restriction on DM output swing to prevent DM to CM conversion.

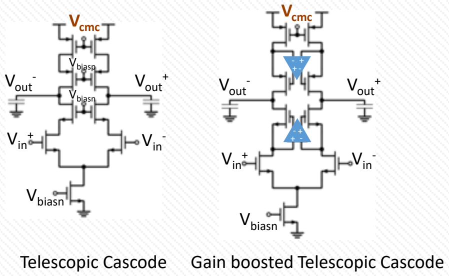
FD Two Stage Miller Amp

CMFB sees the same poles as main amplifier but has one additional high frequency pole p_3.

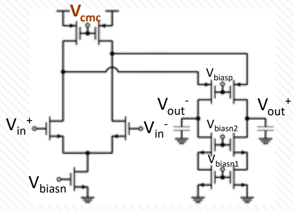




Single Stage FD Amplifiers

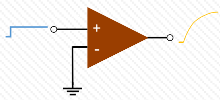


Single Stage FD Amplifiers

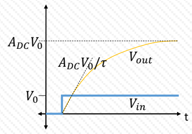


Folded Cascode

Slew Rate



$A(s) = \frac{A_{DC}}{1 + s/p}$



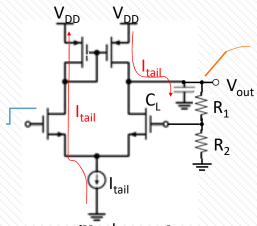
$V_{out} = A_{DC}V_0 \cdot \left(1 - e^{-\frac{t}{\tau}}\right)$ with $\tau = \frac{1}{p}$

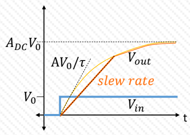
$\frac{dV_{out}}{dt} = \frac{A_{DC}V_0}{\tau} \cdot e^{-\frac{t}{\tau}}$

max. slope A_{DC} V_0/τ at t = 0.

Is there a limit on the max. slope the amplifier can handle?

Slew Rate



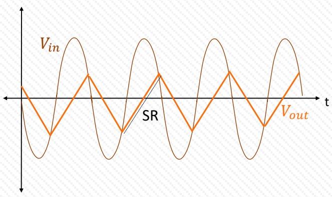


$SR = \left.\frac{dV_{out}}{dt}\right|_{max} = \frac{I_{tail}}{C_L}$ I_{tail} = 1mA, C_L = 1 μF ➡ SR = 1000 V/s

If V_0/τ > slew rate then settling is slew rate limited. ➡ nonlinear

Slew Rate

An extreme example of slewing:



Recall

Topology	Gain	PM	GBW	Swing	P
Basic Diff Pair	-	+	+	o	+
Telescopic Cascode	o	+	+	-	+
Gain Boosted Tel. Cascode	+	+	+	-	-
Folded Cascode	o	+	+	o	-
Single Stage OTA	-	+	+	+	-
2 stage Miller	o	o	-	+	-

Recall

Fully differential benefits from
- twice the output swing
- supply noise supression
- even order nonlinearity cancellation

Fully differential requires CM feedback to stabilize the output CM.

Bias current and C_L define the slew rate (dV_{out}/dt).