A Two Stage Single Ended OPAMP DESIGN

&

Other OPAMP Structures (Cascode type)
Proof for \( \text{Vas3} = \text{Vas4} = \text{Vas6} \) in OPAMP

Current Mirror: If \( \text{Ids}_2 = \text{Ids}_1 \)

Then \( W_1 = W_2 \) & \( V_T \) is same for both.

\[ \text{Vas}_1 = \text{Vas}_2 \]
\[ \text{Vas}_1 = \text{Vds}_1 \]

\[ \therefore \text{Vas}_2 = \text{Vds}_1 \]

and \( \text{Vds}_1 = \text{Vds}_2 \)

Since \( \text{Vas}_1 = \text{Vas}_2 = \text{Vds}_2 \)

Hence if \( \text{Ids}_2 (\text{Vds}_2) \) is connected to \( C3 \), then

\[ \text{Vas}_3 = \text{Vds}_2 = \text{Vas}_1 = \text{Vas}_2 \]

\[ \therefore \frac{I_3}{I_2} = \frac{I_3}{I_1} = \frac{(W/L)_3}{(W/L)_1} \frac{(\text{Vas}_3 - V_T)^2}{(\text{Vas}_2 - V_T)^2} \]

\[ \frac{I_1}{I_2} = \frac{I_1}{I_3} = (W/L)_2 / (W/L)_1 \]
Other OPAMPS

1. Cascode OPAMP
2. High Performance OPAMP
3. High-Speed OPAMP
4. Differential Output OPAMP
5. Micropower OPAMP
6. Low Noise OPAMP
7. Chopper Stabilized OPAMP
8. Low-Voltage OPAMP
A Single Stage CASCODE OPAMP

To improve stability issues, one possibility that we have is single stage OPAMP (DIFFAMP) with larger gain. Since there is no second stage, 'second pole' will not exist. Thus increasing the stability. To improve the gain, we can have CASCODE DIFFAMP.

Cascaded stage improves \( R_{out} \) and hence we can get higher gain. \( G_{in} \cdot R_{out} = A_{V0} \). Then

\[
\text{Bandwidth} = \frac{GBW}{A_{V0}} = \text{Dominant Pole} = \frac{1}{R_{out} \cdot C_{out}}
\]
MCDD₁ to MCDD₄ gives cascode configuration.
R provides \( V_{ds} \) for MCDD₁ and allows mirror to MCDD₄.

\( V_{bias} \) provides bias for MCDD₁ and MCDD₂ and thus fixes \( V_{ds} \) for M₁ & M₂ close to
\( V_{dsat,1} = V_{dsat,2} \)

Drawback: Reduced ICNR & Voswing
Single stage cascode OPAMP with cascode in DiPamp stage can be improved by putting cascode at second stage (CS Amplifier) only.

However, the single cascode stage output is to be given to buffer stage which we shall see later.

MT1 & MT2 are called level translator.

Drawback without MT1 & MT2:

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CASCODE only at output stage (CS stage) in an OPAMP

\[ A_{o} = A_{o1} \cdot A_{o2} \]

\[ A_{o1} = -g_{m1} \left( R_{o2} \parallel R_{o4} \right) \]

\[ A_{o2} = -g_{m2} \left( R_{o6} \parallel R_{o9} \right) \]

\[ Rout = \left( g_{m_{C06}} \cdot R_{o6} \cdot R_{o9} \right) \parallel \left( g_{m_{C07}} \cdot R_{o7} \cdot R_{o9} \right) \]
An OPAMP always has a Buffer Stage as Output Amplifier.

The output Amplifier is necessary as output capacitive load may be large and often not exactly known. Hence Slew Rate at the output load can only be improved if Driving Current (Sinking Current) is large and not governed by Second Stage Amplifier requirements.

Typically an AB or B-type Amplifier can be used as an Output Amplifier.
A typical Class B or AB Amplifier basics could be understood by using circuit below.

$V_{ca1}$ and $V_{ca2}$ are so adjusted that the Amplifier can be Class-A, Class-B or Class-AB Type.

If $V_{in}$ (moderately large) increases, then $V_{gs2}$ increases $\Rightarrow$ Current in $M2$ increases.

And also $V_{sg1}$ decreases $\Rightarrow$ Current in $M1$ decreases.

When $V_{in}$ is large enough (active), $M1$ can turn-off, and then current in $M2$ charges $C_L$. Since current in $M2$ is not connected to currents in earlier CS stage, hence SR could be larger.
By same argument, M1 can be fully on with M2 off, for $V_{in}$ negative and large. Thus $C_L$ can discharge through M1.

For some value-band of $V_{in}$, both M1 & M2 will be ON. This is what we say, the Amplifier working in Class AB.

The output voltage swing will be then

$$V_{omax} = V_{DD} - V_{TN}$$

and

$$V_{omin} = V_{SS} + V_{TP}$$

The implementation of $V_{G1}$ & $V_{G2}$ can be realised by a simple Circuit embedded in this Class AB (or B) Amplifier.
Class AB output Amplifier

\[ I_{out_{max}} = \frac{B_m}{2} (V_{ovn})^2 \quad \Delta \quad I_{out_{min}} = \frac{B_p}{2} (V_{ovp})^2 \]

M1 & M2 Size decides \( I_{out_{max}} \& I_{out_{min}} \).
Basic CMOS OPAMP DESIGN can be extended to OPAMP with Output Amplifier.
OPERATIONAL Transconductance Amplifiers

OPAMP

OTA

Gain
Buffer stage

OTA

V_{DD}

V_{in+}

V_{in-}

V_{Bino}

V_{SS}

V_{SS}

CDEEP
IIT Bombay

EE 618 L 2.1 / Slide 13
OPAMP

1. OTA + Buffer
2. VCVS (Av)
3. Low Output Resistance
4. Drive possible for RC loads
5. Larger Power Dissipation A Complex Circuit
6. Useful in most General Purpose Applications

OTA

OTA

VCCS (Gm)

High Output Impedance

Drive Possible only Capacitive loads but not Resistive Loads

On chip Amplifiers are normally OTAs

Useful in realisation of Active Gm-C filters.
As said earlier, OTA is VCE, and hence can be represented as:

\[ I_0 = g_m (V_+ - V_-) = \frac{I_0}{V_{diff}} = G_m \]

Transconductance Amplifier.
Typical Circuit of OTA

We have initially

\[ \beta_{n1} = \beta_{n2} \]
\[ \beta_{p31} = \beta_{p41} \]
By small signal Analysis, we observe that

\[ i_{ds_{31}} = -\frac{g_{m1}}{2} (v_{in2} - v_{in1}) \quad - (i) \]

But \[ i_{ds_{31}} = - i_{ds_{41}} = -\frac{g_{m1}}{2} (v_{in2} - v_{in1}) \quad - (ii) \]

We also have the following relations

\[ \beta_4 = \beta_{P4} \left( \frac{W}{L} \right)_{41} = K \beta_{P} \left( \frac{W}{L} \right)_{41} \quad - (iii) \]

\[ \alpha \beta_4 = K \beta_{41} = K \beta_{31} = K \beta_{31} \quad - (iv) \]

\[ \beta_5 = K \beta_{51} \quad - (v) \]

clearly currents in M4 and M5 are out of phase

\[ \therefore \quad i_{ds4} = - i_{ds5} = K i_{ds_{41}} = -K i_{ds_{31}} \]
Output impedance at $V_{out}$,

$$R_{out} = \left( \pi_R || \pi_O \right) || \left( \frac{1}{j\omega C_L} \right)$$

If $\frac{1}{j\omega C_L}$ is quite high, then

$$R_{out} \approx \left( \pi_R || \pi_O \right)$$

we define $i_{ds} = -i_{ds_3} = i_{ds_4} = \frac{g_{m1}}{2} (V_{in2} - V_{in1})$

Then

$$i_{out} = i_{ds_4} - i_{ds_5} = (k' i_{ds_4}) - (k' i_{ds_3})$$

$$i_{out} = 2k' i_{ds} = 2k' \frac{g_{m1}}{2} (V_{in2} - V_{in1})$$

or

$$\frac{i_{out}}{V_{in2} - V_{in1}} = G_M = k' g_{m1} \left\{ \frac{\text{Transconductance}}{-\text{Gain}} \right\}$$
And then Voltage Gain \( A_{vo} \) is

\[
A_{vo} = \frac{U_{out}}{V_{in2} - V_{in1}} = \frac{2K \cdot i ds \cdot (r_{o4} + r_{o5})}{V_{in2} - V_{in1}}
\]

\[
= \frac{2K \cdot \frac{g_{m1}}{2} (V_{in2} - V_{in1}) (r_{o4} + r_{o5})}{(V_{in2} - V_{in1})}
\]

\[
A_{vo} = K \cdot g_{m1} (r_{o4} + r_{o5})
\]

If one chooses \( K = 1 \) (Equivalent of OPAMP case),

then \( g_m = g_{m1} \) & \( A_{vo} = g_{m1} (r_{o4} + r_{o5}) \)

Since \( g_{m1} = \sqrt{2 \beta_1 I_{ss}} = \sqrt{2 \beta_n (\frac{W}{L})_1 \cdot \frac{I_{ds}}{2}} \)

We choose \( I_{ds,2} = 2I_{bias} \)
Then \( g_{m1} = \sqrt{2\beta I_i} \)

\( \alpha \quad g_{m1} \propto \sqrt{I_{bias}} \)

\( \alpha \quad G_M \propto \sqrt{I_{bias}} \)

**OTA Symbol.**
Typically $I_{Bias}$ is created using some control voltage $V_{cont}$, which can have circuit as

$$I_{Bias} = \frac{V_{cont} - V_{as10}}{R}$$

$V_{as10} \equiv V_T$

If $(\frac{W}{L})_{10}$ is $V \cdot$ large (100-200)