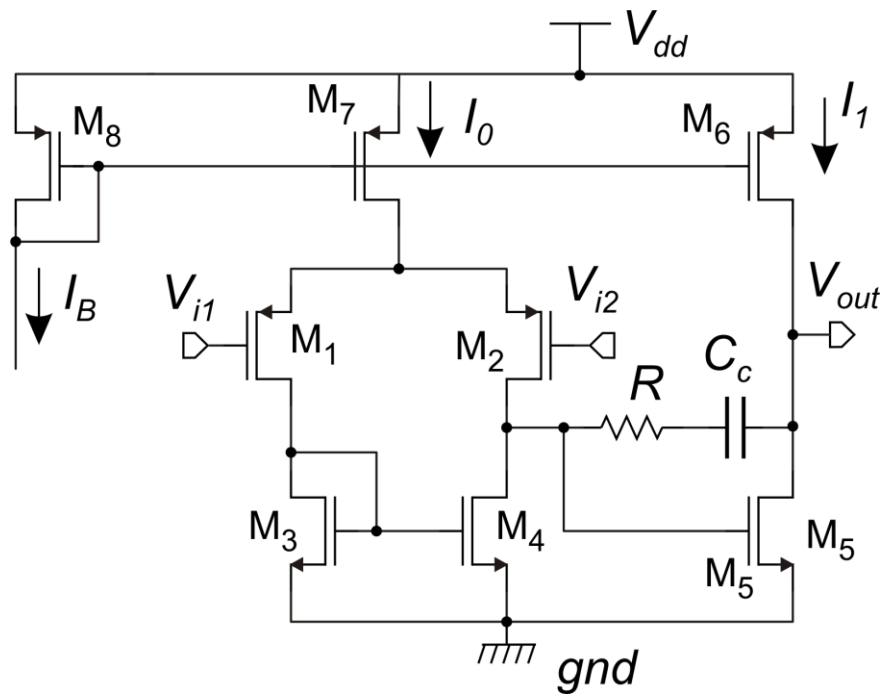


# 1 Design of a CMOS operational amplifier with Offset and GBW/stability specifications.

## 1.1 Amplifier topology



## 1.2 Process parameters

Parametro	n-MOS	p-MOS
$\mu_n C_{ox}, \mu_p C_{ox}$	$240 \times 10^{-6} \text{ A/V}^2$	$50 \times 10^{-6} \text{ A/V}^2$
$V_{in}, V_{tp}$	0.43 V	-0.56 V
$\gamma$ (effetto body)	$0.44 \text{ V}^{1/2}$	$0.59 \text{ V}^{1/2}$
$k_\lambda$	50 V/ $\mu\text{m}$	50 V/ $\mu\text{m}$
$\alpha$ (coeff. termico della $V_t$ )	-1 mV / °C	1 mV / °C
$N_{fn}, N_{fp}$ (fattore rumore flicker)	$6 \times 10^{-10} \text{ V}^2 \mu\text{m}^2$	$2 \times 10^{-10} \text{ V}^2 \mu\text{m}^2$
$C_{vt}$ (matching $V_t$ )	8.5 mV· $\mu\text{m}$	8.5 mV· $\mu\text{m}$
$C_\beta$ (matching beta)	0.03 $\mu\text{m}$	0.03 $\mu\text{m}$
$C_{ox}$	6.2 fF/ $\mu\text{m}^2$	6.2 fF/ $\mu\text{m}^2$
$L_c$ (lunghezza minima D/S)	1.2 $\mu\text{m}$	1.2 $\mu\text{m}$
$C_j$	1.8 fF/ $\mu\text{m}^2$	1.8 fF/ $\mu\text{m}^2$
$C_{gdo}$	0.6 fF/ $\mu\text{m}$	0.6 fF/ $\mu\text{m}$
$t_{ox}$	5.6 nm	5.6 nm

### 1.3 Design specifications

The goal is designing an operational amplifier with:

- An offset voltage (absolute value) smaller than 3 mV
- A GBW of 10 MHz for a load capacitance ( $C_L$ ) up to 10 pF.
- A phase margin around 70° in unity gain configuration

### 1.4 Solution

#### Offset condition

In order to have an offset voltage that is smaller than 3 mV for the most part of the fabricated devices (99.7 %) we need to impose that:

$$3\sigma_{vio} = 3 \text{ mV} \Rightarrow \sigma_{vio} = 1 \text{ mV} \quad (1.1)$$

We can express the standard deviation with the following relationship:

$$\sigma_{vio}^2 = \frac{A}{W_1 L_1} + \frac{B}{W_3 L_3} \quad (1.2)$$

where:

$$A = C_{Vtp}^2 + \left[ \frac{(V_{GS} - V_t)_1}{2} C_{\beta p} \right]^2 \quad B = F^2 C_{Vtn}^2 + \left[ \frac{(V_{GS} - V_t)_1}{2} C_{\beta n} \right]^2 \quad (1.3)$$

and

$$F = \frac{g_{m3}}{g_{m1}} = \frac{(V_{GS} - V_t)_1}{(V_{GS} - V_t)_3} \quad (1.4)$$

With the process parameters in paragraph 1.2,  $p$  and  $n$  devices have the same matching coefficients, then  $C_{\beta p} = C_{\beta n}$  and  $C_{Vtp} = C_{Vtn}$ . Inspection of the previous equations suggests that, the smaller coefficients  $A$  and  $B$ , the smaller will be the area ( $W_1 L_1$  and  $W_3 L_3$  gate areas) required to obtain the desired  $\sigma_{vio}$ . We can reduce  $A$  and  $B$  by choosing a small value for  $(V_{GS} - V_t)_1$ . In addition, we can choose a small value for  $F$ , in order to reduce coeff.  $B$ . We choose:

$$(V_{GS} - V_t)_1 = 100 \text{ mV}, (V_{GS} - V_t)_3 = 300 \text{ mV} \Rightarrow F = \frac{1}{3} \quad (1.5)$$

With these overdrive voltages, coefficients  $A$  and  $B$  are:

$$A = 74.5 \times 10^{-6} \text{ V}^2 \mu\text{m}^2$$

$$B = 10.3 \times 10^{-6} \text{ V}^2 \mu\text{m}^2$$

In spite of the coincidence of  $p$ -MOS and  $n$ -MOS matching parameters,  $A$  and  $B$  are very different. This is the effect of the coefficient  $F$ . Note that  $F$  affects only the threshold voltage mismatch term ( $C_{Vt}$ ), which, with small value of  $(V_{GS} - V_t)_1$ , is by far the dominant component of  $A$  and  $B$ .

At this point, we have one equation (1.2) and two unknowns ( $W_1L_1$  and  $W_3L_3$ ). We can chose the solution that minimizes the total gate area ( $W_1L_1 + W_3L_3$ ). This is obtained for:

$$\frac{W_3L_3}{W_1L_1} = \sqrt{\frac{B}{A}} = 0.37 \quad (1.6)$$

from which we find:

$$W_1L_1 = \frac{1}{\sigma_{vio}^2} (A + \sqrt{AB}) \cong 102 \mu\text{m}^2$$

$$W_3L_3 = W_1L_1 \sqrt{\frac{B}{A}} \cong 38 \mu\text{m}^2 \quad (1.7)$$

At this point, we have determined the gate areas of  $M_1$  and  $M_3$ , but we are still unable to find their  $W$  and  $L$ . If the offset specification is the only requirement, than this problem remains undetermined.

### GBW and phase margin

In our example, we have also a GBW specification and this allow determining the  $W/L$ . With the hypotheses:

$$C_1 \ll C_c, C_2 \quad \text{and} \quad C_2 \cong C_L \quad (1.8)$$

We have:

$$GBW = \frac{1}{2\pi\sigma} \frac{g_{m5}}{C_L} \Rightarrow g_{m5} = 2\pi\sigma C_L \cdot GBW \cong 1.88 \text{ mS} \quad (1.9)$$

where we choose  $\sigma=3$  to obtain a phase margin of nearly  $70^\circ$ .

With the value of  $g_{m5}$ , we can calculate the value of resistor  $R$  necessary to shift the RHP (Right Half-Plane) zero to infinity:

$$R = 1/g_{m5} = 532 \Omega$$

From  $g_{m5}$  we can find  $M_5$  aspect ratio:

$$g_{m5} = \mu_n C_{OX} \frac{W_5}{L_5} (V_{GS} - V_t)_5 \Rightarrow \frac{W_5}{L_5} = \frac{g_{m5}}{\mu_n C_{OX} (V_{GS} - V_t)_5} = 26.1 \quad (1.10)$$

where we have used the property:  $(V_{GS} - V_t)_5 = (V_{GS} - V_t)_3 = 300 \text{ mV}$

We can propagate the result found for  $g_{m5}$  back to the first stage:

$$g_{m1} = \frac{1}{\sigma} \frac{C_c}{C_L} g_{m5} \quad (1.11)$$

Using the practical rule  $C_c = C_L = 10 \text{ pF}$  and  $\sigma=3$ , we obtain:

$$g_{m1} = \frac{g_{m5}}{3} \cong 0.63 \text{ mS} \quad (1.12)$$

*Design completion*

From  $g_{m1}$ , we can determine  $g_{m3}$ , considering that, from the definition of parameter  $F$ :

$$g_{m3} = F \cdot g_{m1} = 0.21 \mu\text{S} \quad (1.13)$$

Again, since we have fixed  $M_1$  overdrive voltage to 100 mV, we can find  $W_1/L_1$ :

$$\frac{W_1}{L_1} = \frac{g_{m1}}{\mu_p C_{OX} (V_{GS} - V_t)_1} = 126 \quad (1.14)$$

and  $W_3/L_3$ :

$$\frac{W_3}{L_3} = \frac{g_{m3}}{\mu_n C_{OX} (V_{GS} - V_t)_3} = 2.92 \quad (1.15)$$

Now we can find  $W_1$  and  $L_1$  individually:

$$\left. \begin{array}{l} W_1 L_1 = 102 \mu\text{m}^2 \\ \frac{W_1}{L_1} = 126 \end{array} \right\} \Rightarrow W_1 = \sqrt{W_1 L_1 \cdot \frac{W_1}{L_1}} \cong 114 \mu\text{m} \quad L_1 = W_1 \cdot \left( \frac{W_1}{L_1} \right)^{-1} \cong 0.9 \mu\text{m} \quad (1.16)$$

Applying the same procedure to  $M_3$ :

$$\left. \begin{array}{l} W_3 L_3 = 38 \mu\text{m}^2 \\ \frac{W_3}{L_3} = 2.92 \end{array} \right\} \Rightarrow W_3 = \sqrt{W_3 L_3 \frac{W_3}{L_3}} \cong 10.5 \mu\text{m} \quad L_3 = W_3 \cdot \left( \frac{W_3}{L_3} \right)^{-1} \cong 3.6 \mu\text{m}$$

In this way, we have determined all is needed for  $M_1$  and  $M_3$ . We can propagate  $L_3$  to  $M_5$ , according to the arbitrary choice  $L_3=L_5$ , introduced to keep a precise current ratio between  $M_3$  and  $M_5$  in rest conditions.

Since we have determined  $W_5 / L_5$  earlier, we now can find  $M_5$  individual width and length:

$$\left. \begin{array}{l} L_5 = 3.6 \mu\text{m} \\ \frac{W_5}{L_5} = 26.1 \end{array} \right\} \Rightarrow W_5 \cong 94 \mu\text{m} \quad (1.17)$$

Let us now complete the op-amp design. The only parameters that are still missing belong to  $M_7$  and  $M_6$ . Opting for a symmetrical output swing, we set:

$$(V_{GS} - V_t)_6 = (V_{GS} - V_t)_5 \quad (1.18)$$

Since  $I_{D6}=I_{D5}$ , this means that  $M_5$  and  $M_6$  should have the same  $\beta$ . Then:

$$\mu_p C_{OX} \frac{W_6}{L_6} = \mu_n C_{OX} \frac{W_5}{L_5} \Rightarrow \frac{W_6}{L_6} = \frac{\mu_n C_{OX}}{\mu_p C_{OX}} \frac{W_5}{L_5} \cong 125 \quad (1.19)$$

We have now to individually choose  $W_6$  and  $L_6$ . Let us recall that  $L_6$  is one of the DOFs in our model of the op-amp.  $L_6$  will affect mainly the dc gain. We can make  $L_6$  equal to  $L_5$  in order to have a balanced effect of the dc gain of the second stage. Larger  $L_6$  values does not result in important advantages (the gain becomes dominated by  $r_{d5}$ ); much smaller values begin to have a serious impact on the gain. Setting  $L_5=L_6$ , we find  $W_6$ :

$$L_6 = L_5 = 3.6 \text{ } \mu\text{m} \Rightarrow W_6 = L_6 \left( \frac{W_6}{L_6} \right) = 450 \text{ } \mu\text{m} \quad (1.20)$$

Finally, we set  $M_7$  parameters. Using the equal-length condition to improve precision of the  $I_{D6}$  over  $I_{D7}$  ratio, we have:

$$L_7 = L_6 = 3.6 \text{ } \mu\text{m} \quad (1.21)$$

Let now exploit the condition for null output short-circuit current when  $V_d=0$  (null systematic offset):

$$\frac{\beta_6}{\beta_7} = \frac{1}{2} \frac{\beta_5}{\beta_3} \quad (1.22)$$

Note that the factors  $\mu_{COX}$  cancel each other in both hands of equation (1.22). Then, we obtain a condition on the aspect ratios that allows us to  $M_7$  aspect ratio.

$$\frac{\frac{W_6}{L_6}}{\frac{W_7}{L_7}} = \frac{1}{2} \frac{\frac{W_5}{L_5}}{\frac{W_3}{L_3}} \Rightarrow \frac{W_7}{L_7} = 2 \frac{W_6}{L_6} \frac{L_3}{W_5} \cong 28 \quad (1.23)$$

This allow us to find  $M_7$  parameters:

$$L_7 = L_6 = 3.6 \text{ } \mu\text{m} \Rightarrow W_7 = L_7 \left( \frac{W_7}{L_7} \right) = 101 \text{ } \mu\text{m} \quad (1.24)$$

Device  $M_8$  is not strictly part of the amplifier, since it can be shared among several different op-amps. We consider that We have to design a cell that is to be biased by a current ( $I_B$ ), than  $M_8$  is necessary. To simplify the design, we set  $M_8=M_7$ , thus  $I_B=I_0$ .

### Calculation of the bias currents

$$\begin{aligned} I_0 &= 2I_{D1} \cong 2g_{m1}V_{TE1} = 2g_{m1} \frac{(V_{GS} - V_t)_1}{2} \cong 63 \text{ } \mu\text{A} \\ I_B &= I_0 = 63 \text{ } \mu\text{A} \\ I_1 &\cong g_{m5}V_{TE5} = g_{m5} \frac{(V_{GS} - V_t)_5}{2} \cong 282 \text{ } \mu\text{A} \end{aligned} \quad (1.25)$$

*Final component table*

	W (μm)	L (μm)			
M <sub>1</sub> , M <sub>2</sub>	114	0.9	M7	101	3.6
M <sub>3</sub> , M <sub>4</sub>	10.5	3.6	M8	101	3.6
M <sub>5</sub>	94	3.6	R	532 Ω	
M <sub>6</sub>	450	3.6	C <sub>C</sub>	10 pF	
			I <sub>B</sub>	63 μA	

*Verification of the original hypotheses*

$$C_1 = C_{GS5} + C_{DB2} + C_{DB4} \tag{1.26}$$

with

$$\left. \begin{aligned} C_{GS5} &= \frac{2}{3} C_{OX} W_5 L_5 \cong 1.4 \text{ pF} \\ C_{DB2} &= C_{jp} L_C W_2 \cong 0.246 \text{ pF} \\ C_{DB4} &= C_{jn} L_C W_4 \cong 0.023 \text{ pF} \end{aligned} \right\} \Rightarrow C_1 \cong 1.67 \text{ pF} \tag{1.27}$$

$$C'_2 = C_{DB5} + C_{DB6} = C_{jn} L_C W_5 + C_{jp} L_C W_6 \cong 0.2 \text{ pF} + 0.97 \text{ pF} = 1.17 \text{ pF} \tag{1.28}$$

It can be easily shown that hypotheses (1.8) are verified.

### 1.5 Performance estimation

We have designed the amplifier according to offset and GBW specifications. It is possible to estimate the remaining performance figures using approximate expressions.

*Total current consumption:*

Excluding the bias transistor M<sub>8</sub>, the amplifier is marked by the following current consumption:

$$I_{supply} = 2I_0 + I_1 = 345 \text{ μA} \tag{1.29}$$

Considering also M<sub>8</sub>, to total current consumption is:

$$I_{tot} = I_{supply} + I_B = 408 \text{ μA} \tag{1.30}$$

*Thermal noise density*

$$S_{v_{th}} \cong 2 \frac{8}{3} kT \frac{1}{g_{m1}} (1+F) \cong 4.5 \times 10^{-17} \text{ V}^2 / \text{Hz} \quad ( 6.7 \text{ nV} / \sqrt{\text{Hz}} ) \tag{1.31}$$

*Flicker noise density*

$$k_F = 2 \left( \frac{N_{fp}}{W_1 L_1} + F^2 \frac{N_{fn}}{W_3 L_3} \right) \cong 7.42 \times 10^{-12} \text{ V}^2 \quad (1.32)$$

*Flicker corner frequency*

$$f_k = \frac{k_F}{S_{VTh}} \cong 165 \text{ kHz} \quad (1.33)$$

*Slew rate*

$$s_R = \frac{I_0}{C_c} = 6.3 \text{ V}/\mu\text{s} \quad (1.34)$$