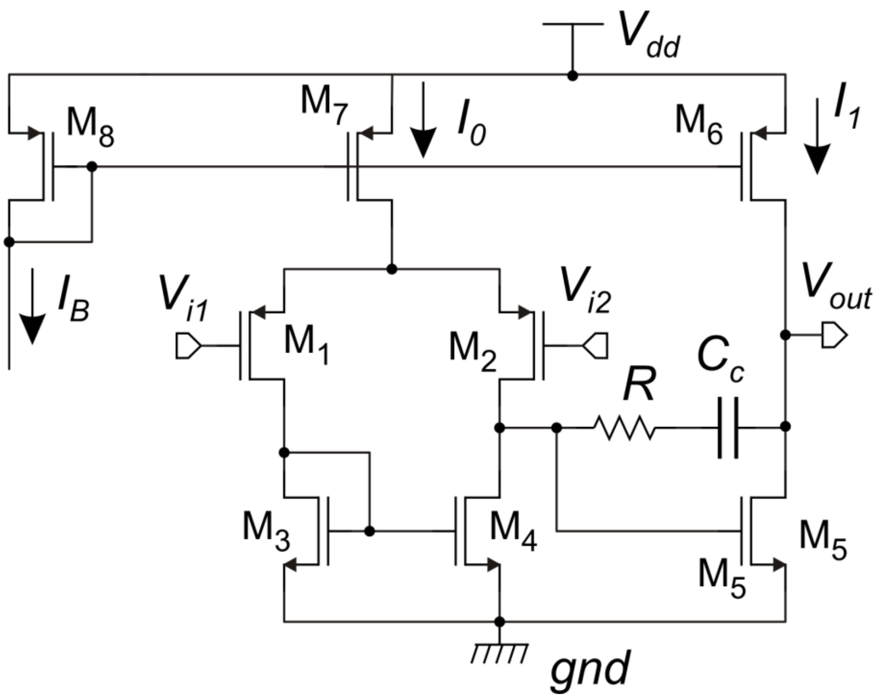
1 Design of a CMOS operational amplifier with Offset and GBW/stability specifications.

1.1 Amplifier topology



1.2 Process parameters

Parametro	n-MOS	p-MOS
μ_nCox, μ_pCox	240×10^{-6} A/V^2	50×10^{-6} A/V^2
V_{tn},V_{tp}	0.43 V	-0.56 V
γ (effetto body)	0.44 V$^{1/2}$	0.59 V$^{1/2}$
k_λ	50 V/μm	50 V/μm
α (coeff. termico della Vt)	-1 mV / ºC	1 mV / ºC
N_{fn}, N_{fp} (fattore rumore flicker)	6×10^{-10} V^{2}μm^2	2×10^{-10} V^{2}μm^2
C_{Vt} (matching Vt)	8.5 mV·μm	8.5 mV·μm
C_β (matching beta)	0.03 μm	0.03 μm
C_{OX}	6.2 fF/ μm^2	6.2 fF/ μm^2
L_C (lunghezza minima D/S)	1.2 μm	1.2 μm
C_J	1.8 fF/μm^2	1.8 fF/μm^2
Cgdo	0.6 fF/μm	0.6 fF/μm
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:

$$3\sigma_{vio} = 3 \text{ mV} \;\Rightarrow\; \sigma_{vio} = 1 \text{ mV} \tag{1.1}$$

We can express the standard deviation with the following relationship:

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

where:

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

and

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

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_1L_1 and W_3L_3 gate areas) required to obtain the desired σ_{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:

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

With these overdrive voltages, coefficients A and B are:

$A=74.5\times10^{-6}\ V^2\mu m^2$

$B=10.3\times10^{-6}\ V^2\mu m^2$

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:

$$\frac{W_3L_3}{W_1L_1} = \sqrt{\frac{B}{A}} = 0.37 \tag{1.6}$$

from which we find:

$$\begin{aligned} W_1L_1 &= \frac{1}{\sigma_{vio}^2}\left(A + \sqrt{AB}\right) \cong 102\ \mu\text{m}^2 \\ W_3L_3 &= W_1L_1\sqrt{\frac{B}{A}} \cong 38\ \mu\text{m}^2 \end{aligned} \tag{1.7}$$

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:

$$C_1 << C_c, C_2 \quad \text{and} \quad C_2 \cong C_L \tag{1.8}$$

We have:

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

where we choose σ=3 to obtain a phase margin of nearly 70°.

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:

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

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

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

$$g_{m1} = \frac{1}{\sigma}\frac{C_C}{C_L}g_{m5} \tag{1.11}$$

Using the practical rule C_C=C_L= 10 pF and σ=3, we obtain:

$$g_{m1} = \frac{g_{m5}}{3} \cong 0.63\ \text{mS} \tag{1.12}$$

Design completion

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

$$g_{m3} = F \cdot g_{m1} = 0.21 \ \mu\text{S} \tag{1.13}$$

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

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

From $(V_{GS}\text{-}V_t)_3$=300 mV, we can find W_3/L_3:

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

Now we can find W_1 and L_1 individually:

$$\left.\begin{aligned} & W_1 L_1 = 102 \ \mu\text{m}^2 \\ & \frac{W_1}{L_1} = 126 \end{aligned}\right\} \Rightarrow W_1 = \sqrt{W_1 L_1 \cdot \frac{W_1}{L_1}} \cong 114\,\mu\text{m} \qquad L_1 = W_1 \cdot \left(\frac{W_1}{L_1}\right)^{-1} \cong 0.9\,\mu\text{m} \tag{1.16}$$

Applying the same procedure to M_3:

$$\left.\begin{aligned} & W_3 L_3 = 38 \ \mu\text{m}^2 \\ & \frac{W_3}{L_3} = 2.92 \end{aligned}\right\} \Rightarrow W_3 = \sqrt{W_3 L_3 \frac{W_3}{L_3}} \cong 10.5\,\mu\text{m} \qquad L_1 = W_3 \cdot \left(\frac{W_3}{L_3}\right)^{-1} \cong 3.6\,\mu\text{m}$$

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:

$$\left.\begin{aligned} & L_5 = 3.6 \ \mu\text{m} \\ & \frac{W_5}{L_5} = 26.1 \end{aligned}\right\} \Rightarrow W_5 \cong 94 \ \mu\text{m} \tag{1.17}$$

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:

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

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

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

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:

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

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

$$L_7 = L_6 = 3.6 \;\; \mu\text{m} \tag{1.21}$$

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

$$\frac{\beta_6}{\beta_7} = \frac{1}{2}\frac{\beta_5}{\beta_3} \tag{1.22}$$

Note that the factors μC_{OX} 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.

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

This allow us to find M_7 parameters:

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

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

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

Final component table

	W (μm)	L (μm)
M_1, M_2	114	0.9
M_3, M_4	10.5	3.6
M_5	94	3.6
M_6	450	3.6

M7	101	3.6
M8	101	3.6
R	532 Ω	
C_C	10 pF	
I_B	63 μA	

Verification of the original hypotheses

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

with

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

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

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_8, the amplifier is marked by the following current consumption:

$$I_{\sup ply} = 2I_0 + I_1 = 345 \ \mu\text{A} \tag{1.29}$$

Considering also M8, to total current consumption is:

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

Thermal noise density

$$S_{Vth} \cong 2\frac{8}{3} kT \frac{1}{g_{m1}} \left(1+F\right) \cong 4.5\times10^{-17} \ V^2 / H_z \ \ (\text{ 6.7 nV} / \sqrt{\text{Hz}} \ ) \tag{1.31}$$

Flicker noise density

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

Flicker corner frequency

$$f_k = \frac{k_F}{S_{VTh}} \cong 165\ \mathrm{kHz} \tag{1.33}$$

Slew rate

$$s_R = \frac{I_0}{C_c} = 6.3\ \mathrm{V/\mu s} \tag{1.34}$$