DESIGN OF A CMOS OPERATIONAL AMPLIFIER

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ABSTRACT

This paper describes the development of an operational amplifier based on the data sheet of the LM741. Usually, this amplifier is made of Bipolar Junction Transistor (BJT) and the purpose of this paper is to develop an operational amplifier composed by MOSFET (Metal Oxide Semiconductor Field Effect Transistor). The circuits were designed with aid of the Eldo (a Spice simulator), implemented in IC_Station (tools of the Mentor Graphics), and verified by comparison between the results obtained from the code and the implementation. Simulations have shown an open-loop gain of 99 dB, phase margin of 60°, gain bandwidth of 3.2 MHz and a power consumption of 0.3 mW.

1. INTRODUCTION

The operational amplifier was developed with the purpose of simulating basics math operations. Initially it was the base of analog computers [1]. Nowadays, microelectronics works with operational amplifiers in large scale, because they are a key element for both analog and mixed-mode designs and widely used in circuits such as comparators, filters, A/D converters, and others devices [2].

The ideal operational amplifier has some special characteristics like an infinites open-loop gain, gain bandwidth and input impedance. It has too, nulls output impedance, input current and offset voltage [3]. These properties cannot be ideal in a practical operational amplifier, for example in the LM741, a very commercial opamp. This paper is focused on the development of a CMOS compatible operational amplifier, based on these properties of the LM741.

This paper is organized as follows: the section 2 explains the chosen project construction flow. Section 3 shows the description of the opamp. The section 4 describes the simulations and the section 5 explains the process and the design of the layout.

This paper was written by students of the third year in electric engineering and participants of a program in the Microelectronic and Embedded Systems Laboratory in Federal University of Rio Grande do Norte.

2. PROJECT CONSTRUCTION FLOW

There are many methods to construct an operational amplifier in analog circuits, and they are very important to guide the designers [4]. For this reason the flow illustrated in the figure 1 was chosen. The main goal is to reach the value of each parameter specified.

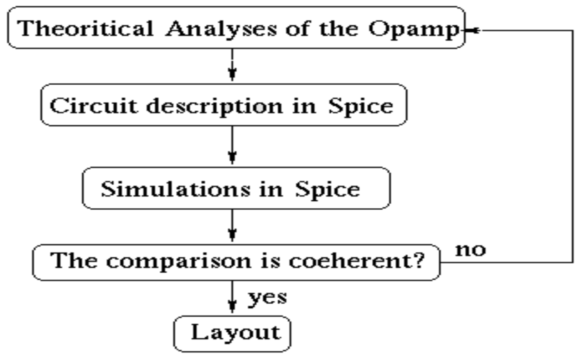


Figure 1 – Project construction flow

This methodology is developed step by step. In the first step, the designer starts by studying the basic characteristics of a simple operational amplifier, one example is the OTA (Operational Transconductance Amplifier). In this step they analyze the circuit and develop some intuitive equations. In the second step, based on the analyses and studies, the architecture is described and implemented in Spice. In the third step the figures of merit of this architecture are extracted by simulations with the same program, in testbenches, and, finally, compared with the specifications. If this comparison is coherent the layout can be developed, otherwise, it becomes necessary to return to the first step.

3. DESCRIPTION OF THE OPERATIONAL AMPLIFIER

The design of the opamp was chosen after several cycles in the flow. This amplifier is illustrated in the Figure 2.

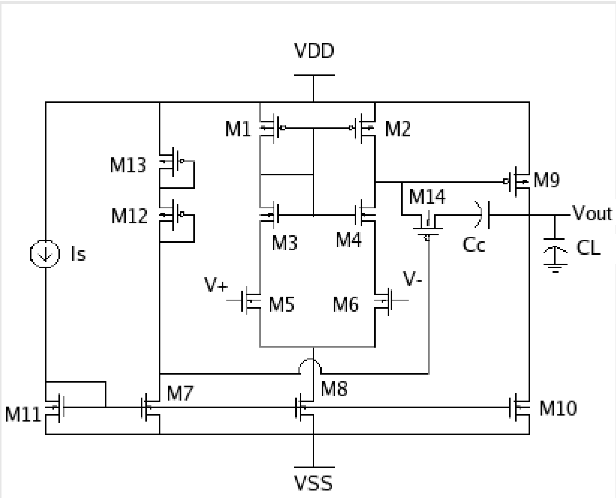


Figure 2 – Schematic of the operational amplifier

This figure shows an opamp with one output stage. This operational amplifier has three main characteristics. The first one is a pair of transistor in Cascode configuration, M3 e M4. This configuration increases the output impedance and thus improves the gain. It is possible to see in the equation 2. The second one is the two capacitors, Cc (Miller Compensator Capacitor) and Cl (Load Capacitor), which are responsible for compensating the phase margin of the amplifier [5], which has the best response in 60°. The Cc capacitor adds a zero in the transfer function of the circuit which allows the designers to control the phase margin. But this capacitor reduces the gain bandwidth, so an insertion of a resistor, the nulling resistor (M14), can decrease such a reduction. This transistor for operating in the linear region, as if it were a resistor, must have an elevated value of the gate voltage. In this purpose the two transistors M12 e M13 are responsible to maintain this voltage. This resistor is the third main characteristic.

The open-loop gain of an opamp is given by,

$$Ad=\frac{vo}{vin} \quad (1)$$

from the circuit as follows,

$$Ad=\frac{[gm_5 ro_1 (gm_3+gm_5)(s+ro_4 \frac{gm_4}{Cc})]}{[(gm_3-k+ro_3 ro_1 gm_1 gm_3^2)(s+\frac{ro_9}{C_L} gm_9)]} \quad (2)$$

where k is given by:

$$k=ro_3 gm_3^2-gm_1+gm_3 gm_1 ro_3+gm_3 ro_1 gm_1 \quad (3)$$

These equations were developed based on the design flow used (in the first step). It is necessary to state that these equations are intuitive and give an idea of the comportment of the opamp.

For this purpose an influence table of the operational amplifier was created. This table shows how some changes in the circuit can influence in the three most important parameters.

Table 1 – This is the influence table.

Parameter	Increase the gain	Increase Gain Bandwidth	Increase Phase Margin
Is	↓	↑	↑
Cc	-	↓	↑
CL	-	↓	↓
M3 and M4(W/L)	-	-	↓
M5 and M6(W/L)	↑	↑	↓
M1 and M2(W/L)	↓	↓	↓
M9 (W/L)	↑	↓	↑

4. CIRCUIT DESCRIPTION AND SIMULATIONS IN SPICE

In this section all the analyses in the first step were utilized. The equation 2 and the influence table were the basis of the implementation in Spice. The Spice was the main tool used in the whole project.

The project has some characteristics that must be respected to a perfect functioning. One of it is that all the transistors should be in saturation, one exception is the M14. Other characteristic is that the transistors that are in pairs have to be matched, that is, they have the same width and length. Finally, the M7, M8, M10 and M11 must mirror the source current. Next the simulations in the typical model case and then in the corner cases will be described [6]. Both cases utilized the model AMI 0.5 micron (BSIM3V3).

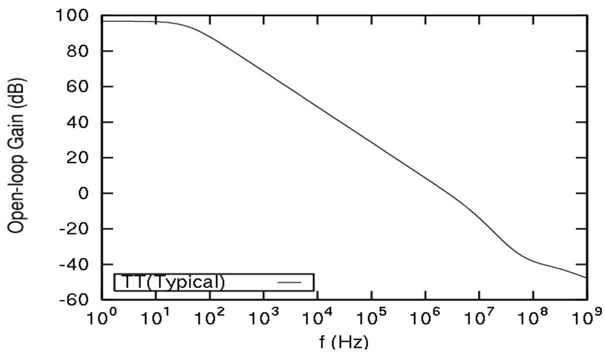
4.1. Simulations

The simulation in Spice used testbenches to verify the parameters of the circuits. These testbenches are scripts that have the description of the test of each parameter. In the table 2 the parameters specified and obtained in the project using the typical model are illustrated.

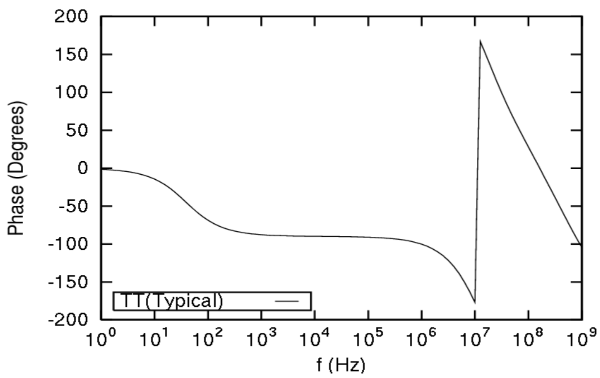
Table 2 – Parameters specified and obtained in the project.

Parameters	Specifications	Typical
Open-loop Gain(dB)	80	99.4
Slew Rate rise(V/us)	0.3	0.65418
Slew Rate fall(V/us)	0.3	0.53034
Gain Bandwidth(MHz)	1.5	3.19
PSRR(Power Supply Rejection Ratio)(dB)	80	127.02
Common Mode Rejection Ratio(dB)	80	140
Phase Margin(degrees)	60	59.9
Power Consumption(mW)	80	0.3

The table 2 shows that the parameter of the project obtained better values that the specifications. It is important to point out that the power consumption reached a very good value, making the project useful for low consumption operational amplifiers.



(a)



(b)

Figure 3 – (a) The response frequency of the gain; (b) Illustrated the phase margin.

4.1.1. Corner Cases

Corner cases are the possible variations in the model of fabrication [7]. If these variations are ignored, there is a chance that the operational amplifier fabricated doesn't work correctly. Hence it is important to simulate the opamp in these corner cases, and, if necessary, change it until it works properly.

In figure 4 it is possible to see the behavior of the gain in the various cases. Below, in table 3, some parameters that had variations in their values with corner cases in comparison with the ideal and specified are illustrated.

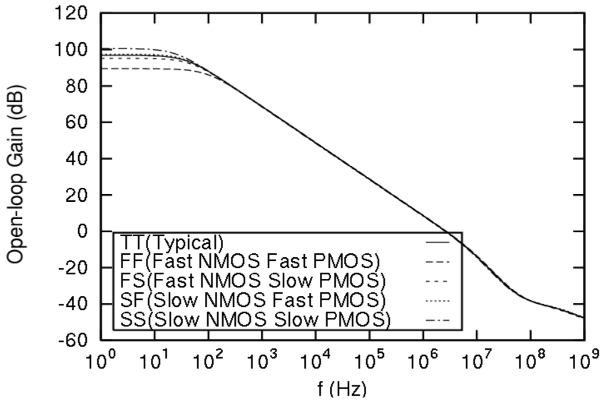


Figure 4 – The changes in the gain with corner cases.

Table 3 – This table illustrated some variations in the parameters in corner cases.

Parameters	Open-loop Gain(dB)	Gain Bandwidth (MHz)	Power Supply Rejection Ratio(dB)	Phase Margin (degrees)
Specification	80	1.5	80	60
TT	99.4	3.19	127	59.9
FF	90.2	2.94	128.1	61.4
SS	101.4	2.8	127.7	59.5
FS	95.9	2.86	127.4	60.1
SF	98.3	2.9	128.4	60

4.2. Comparisons

Finally, the whole project is compared to the specifications. In this part it is important to check if all parameters are coherent before moving on to the next step. If it is incoherent, then it is necessary to go back to the first step, otherwise the layout can be made.

The graphics and tables exposed in this section proved, by comparison, that the opamp developed reached better values than the specifications. Hence the layout can be implemented.

5. LAYOUT

By and large, the layout is the last part of an analog circuit project and its function is to be the pattern for the chip's construction showing how the masks will be settled. In such case, layout consists of a precise specification of the analog circuit's characteristics, showing how the devices are connected and disposed along the wafer. ICstation, a Mentor Graphics' tool, was used to make the layout. Three types of verification are very important to ensure the layout's efficiency: DRC (Design rule Check), LVS (Layout Versus Schematic) and PEX (PostExtraction), which were made using Calibre. The current technology for the entire process was AMI 0.5u.

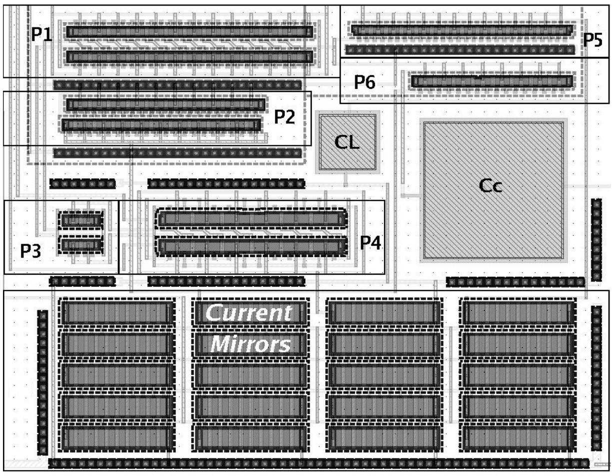


Figure 5 – The layout of the operational amplifier developed.

Table 4 – Size of transistors used in the circuit.

W/L	Transistors	W/L	Transistors
P1 $75\mu m/2\mu m$	M1 and M2	P4 $100\mu m/4\mu m$	M5 and M6
P2 $60\mu m/2\mu m$	M13 and M12	P5 $84\mu m/1.2\mu m$	M9
P3 $12\mu m/1.2\mu m$	M3 and M4	P6 $50\mu m/2\mu m$	M14
$75\mu m/45\mu m$	Current Mirrors	$152.1\mu m^2$	Total area

Several techniques are necessary to improve some aspects of the project. In which case, the MOS transistor matching is the main procedure to be taken. To reach the matching, several techniques were implemented [8]. The differential pair (M5 and M6) and the current mirrors (M7, M8, M10 and M11) require special attention just to be correctly matched. Because of the microscopic scale, series and parallel association was very important to make good use of the available area.

6. CONCLUSION

We have presented in this paper the design flow of an operational amplifier composed by MOSFET based on the data sheet of the LM741. It had low power consumption (about 0.3mW), exceeded the values of the main parameters of the specifications and maintained its characteristics in the different models. Further works can improve the figures of merit with low power consumption.

7. ACKNOWLEDGMENTS

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