SIMPLE AND ACCURATE MACROMODEL FOR CURRENT OPERATIONAL AMPLIFIER (COA)

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ABSTRACT

In this study, we present a simple and accurate macromodel for current operational amplifier (COA). It is expected that this macromodel would allow reliable analysis of the analog circuits that use COA. It would also reduce the computing time in the simulations. The COA characteristics are simulated by using the macromodel and are compared with the simulation results obtained by SPICE device models. The results show that the COA macromodel represents the CMOS COA with approximately the same accuracy as semiconductor SPICE device models.

I. INTRODUCTION

Current operational amplifier (COA) can be treated as the current-mode dual of the conventional voltage operational amplifier. Since the voltage operational amplifier has been used in wide range of applications operated in voltage-mode for a long time, its current-mode counterpart, COA, seems to be the suitable candidate as the active element of current-mode circuits. There are some CMOS implementations of this relatively new building block in the literature [1-8]. Also, some filter and oscillator circuits that employ COA has previously been reported [7,9,10].

The purpose of this study is to present a simple COA macromodel that models its high frequency and nonlinear behaviors. It is aimed, by this macromodel, to reduce the computing time in the simulations of COA-based circuits and to investigate the effects of COA non-idealities on the circuit performance. The validity of the presented macromodel has been verified with SPICE simulations by comparing it with a CMOS COA.

II. BEHAVIOR OF CURRENT OPERATIONAL AMPLIFIER

The circuit symbol of the COA is illustrated in Figure 1. It is a current-controlled current source whose defining equation can be given as

$$\begin{bmatrix} V_{IN+} \\ V_{IN-} \\ I_{O+} \\ I_{O-} \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ K & -K & 0 & 0 \\ -K & K & 0 & 0 \end{bmatrix} \begin{bmatrix} I_{IN+} \\ I_{IN-} \\ V_{O+} \\ V_{O-} \end{bmatrix} \quad (1)$$

where K is the open-loop current gain and ideally approaches infinity.

As it is seen from its defining equation, both input terminals of COA are characterized by low impedance, thereby eliminating response limitations incurred by capacitive time constants. The input terminals are internally grounded leading to circuits that are less sensitive to the stray capacitances. The output terminals of COA exhibit high impedance so that COA-based current-mode circuits can easily be cascaded without additional buffers. For ideal operation, the open-loop current gain, K, approaches infinity forcing the input currents to be equal. Thus, the COA must be used in feedback configuration that is similar to the classical voltage operational amplifier. The use of high open-loop gain of COA allows obtaining accurate transfer function. The current differencing and internally grounded inputs of COA make it possible to implement the COA-based circuits with MOS-C realization.

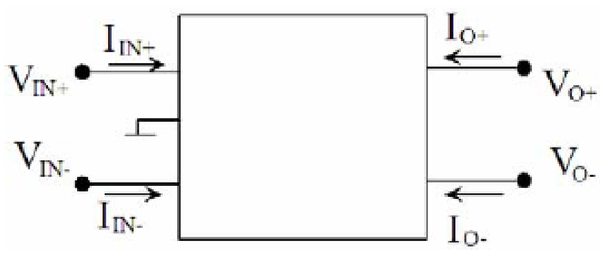

Figure 1. Circuit symbol of COA

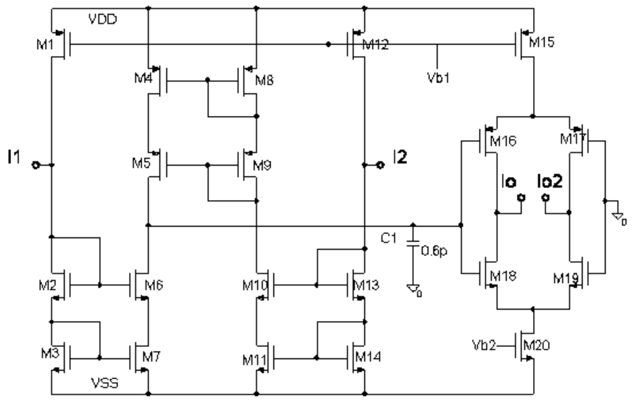

Figure 2. A CMOS realization of COA [8]

A CMOS realization of COA [8] is shown in Figure 2. It is constructed by cascade connection of transresistance and transconductance amplifiers. The first stage takes the difference of the input currents and converts it into an amplified voltage signal. This information is then transformed into two balanced currents at the output of the COA by the transconductance stage. Capacitor is for frequency compensation [8].

III. MACROMODEL DEVELOPMENT

The COA macromodel is shown in Figure 3. It accurately models the behavior of COA realized in either CMOS or BJT technology. The macromodel consists of three stages, namely the input stage (Figure 3(a)), the inner stage (Figure 3(b)) and the output stage (Figure 3(c)).

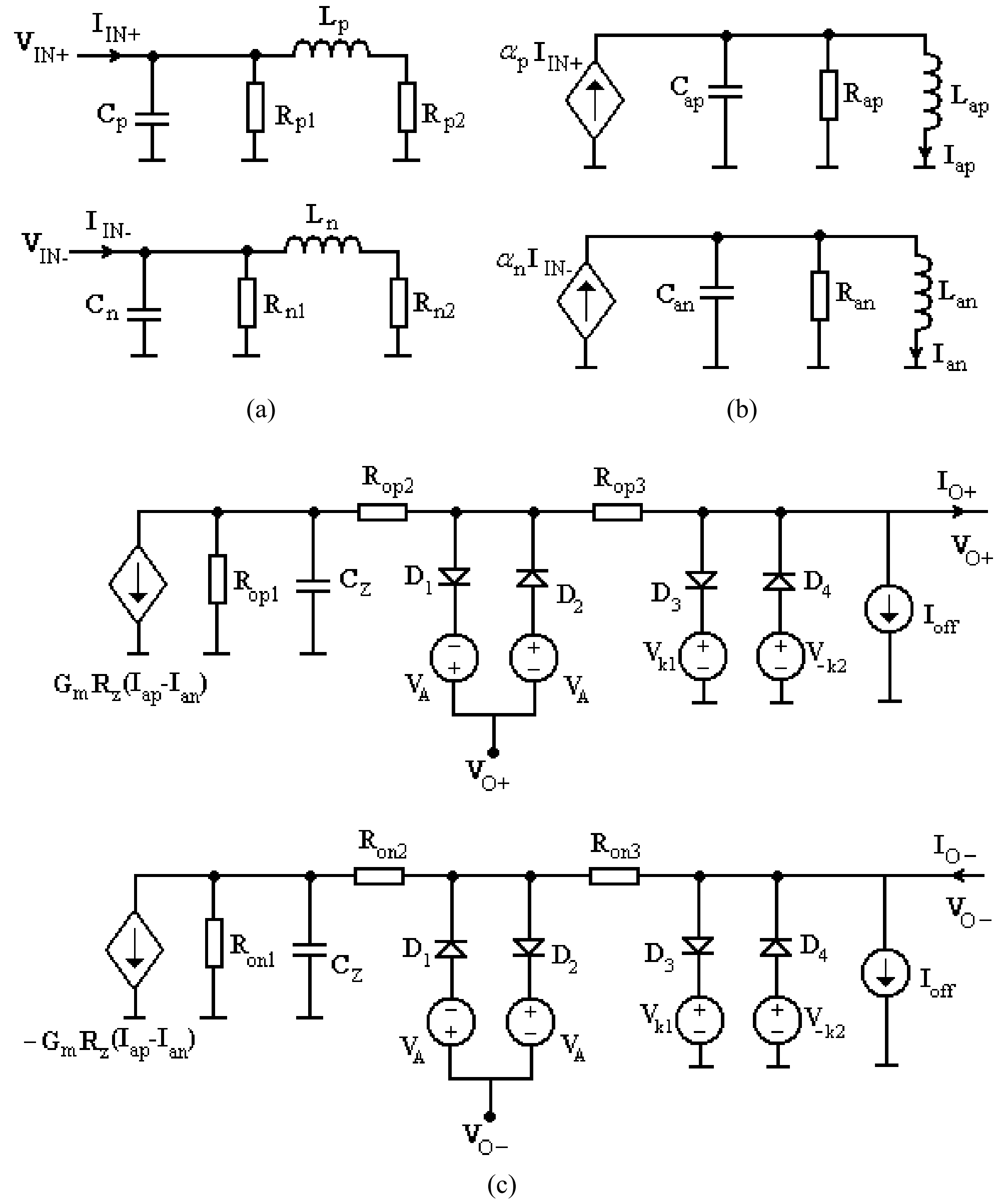

Figure 3. The macromodel for COA (a) input stage, (b) inner stage, (c) output stage

Since COA shows the same input characteristic as current differencing buffered amplifier (CDBA), the input and inner stages are same as in [11].

The input stage models the input impedances of COA. From Figure 3(a), the equation for the input impedance can be written as

$$Z_{in} = \frac{L_i R_{i1} s + R_{i2} R_{i1}}{L_i C_i R_{i1} s^2 + (L_i + C_i R_{i2} R_{i1}) s + R_{i2} + R_{i1}} \qquad (2)$$

where $i = p$, n. As it is seen from this expression, input terminals show a single zero, double pole characteristic.

The inner stage is for modeling the frequency response of the open-loop current gain. I_{ap} and I_{an} can be written from Figure 3(b) as

$$I_{ai} = \frac{\alpha_i R_{ai}}{L_{ai} C_{ai} R_{ai} s^2 + L_{ai} s + R_{ai}} I_{IN+/-} \qquad (3)$$

where $i = p$, n and α_i is for including the current tracking errors into the model. It would approximately be equal to unity.

Figure 3(c) depicts the output stage of the COA macromodel. It models the value of open-loop current gain, output impedance, voltage and current limitations at the output and the offset current. From this model, K can be written as

$$K = G_m R_z \qquad (4)$$

where R_z is the resistance of the high impedance node in the COA circuit and G_m is the transconductance parameter that converts voltage of the high impedance node into current at the output of COA.

Output impedances are modeled by the R_{op1}, R_{op2}, R_{on1}, R_{on2} and C_Z parameters. Equation for the output impedances of the COA macromodel can be expressed as

$$Z_{out} = \frac{C_Z R_{oi2} R_{oi1} s + R_{oi2} + R_{oi1}}{C_Z R_{oi1} s + 1} \qquad (5)$$

where $i = p$, n.

In the model of Figure 3, D_1, D_2 diodes and V_A, $V_{O+/-}$ voltage sources model current limitation. Maximum output current is expressed as

$$I_{out,\max} = \frac{V_A - V_{D(1,2)}}{R_{oi3}} \qquad (6)$$

where $i = p$, n and $V_{D(1,2)}$ is the voltage drop on diodes D_1 and D_2. Here, the inner capacitances of the diodes are not included in the model in order no to affect the frequency response of COA by these parameters.

To model voltage limitation, the diodes D_3, D_4 and the voltage sources V_{k1}, V_{k2} are included in the macromodel. Maximum output voltage is

$$V_{out,\max} = V_{kl} - V_{Dj} \qquad (7)$$

where $l = 1, 2$ and $j = 3, 4$. Again, the inner capacitances of the diodes are excluded from the model.

Finally, to model the output current offset, a DC current source, I_{off}, is included in the macromodel.

IV. DETERMINATION OF MACROMODEL PARAMETERS

To determine the values of the parameters in the macromodel, the simulation results of the CMOS COA presented in [8] are used. Some simulated values of this CMOS COA are given in Table 1.

Some of the relations used in the calculation of model parameters are given in Table 2. Using the information derived from the simulation results of CMOS COA [8] and these relations together with the equations given in Section III, the parameter values in the COA macromodel can be determined. In Table 3, we tabulate the values for these parameters.

The COA characteristics are simulated by using the macromodel and are compared with the simulation results obtained by SPICE device models. Figure 4-7 illustrate some of these simulation results, which show that the COA macromodel represents the CMOS COA with approximately the same accuracy as semiconductor SPICE device models but with a significantly reduced computing time.

Table 1. Some simulated values of the performance parameters for the CMOS COA presented in [8]

Parameter	Value
Open-loop current gain	123 dB
Gain-bandwidth product	60 MHz
Phase margin	68°
Input impedance	2 kΩ
Output impedance	115 MΩ

Table 2. Some relations used in the calculation of model parameters

$$\frac{L_{ap}}{4R_{ap}^{2}C_{ap}} - 1 < 0$$

$$\omega_0 = \frac{1}{\sqrt{L_{ap}C_{ap}}}$$

$$G_m = \frac{g_{m16} + g_{m18}}{2}$$

$$V_A = I_{out,\max} R_{op3} + V_D$$

$$V_k = V_{out,\max} + V_D$$

Table 3. The values of the macromodel parameters determined using simulation results of CMOS COA [8]

Parameter	Value	Parameter	Value
R_{i1}	5 kΩ	R_{oi1}	3 MΩ
R_{i2}	3.75 kΩ	R_{oi2}	30 kΩ
C_i	0.431 pF	R_{oi3}	60 kΩ
L_i	0.1 µH	C_Z	60 nF
R_{ai}	0.6 Ω	V_A	26 V
C_{ai}	1.07 nF	V_{k1}	1.412 V
L_{ai}	1.07 nH	V_{k2}	-1.06 V
G_m	400 µS	I_{off}	-1.073 µA
R_z	4.69 GΩ	α_i	1

$i = p, n$

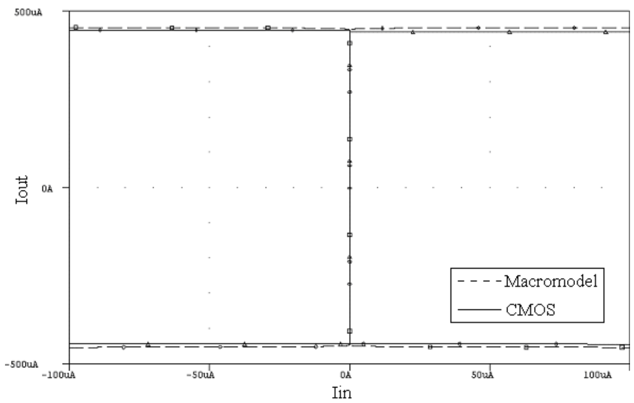

Figure 4. DC responses of COA obtained by the macromodel and the CMOS implementation

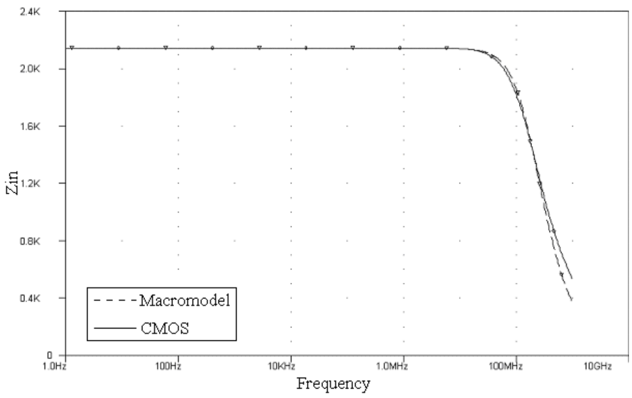

Figure 6. Input impedance of COA obtained by the macromodel and the CMOS implementation

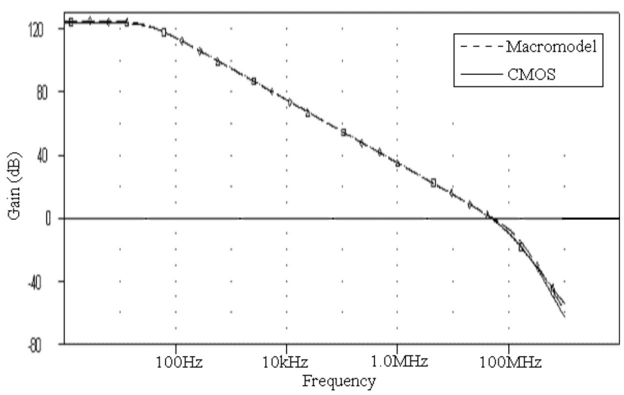

Figure 5. Open-loop gain of COA obtained by the macromodel and the CMOS implementation

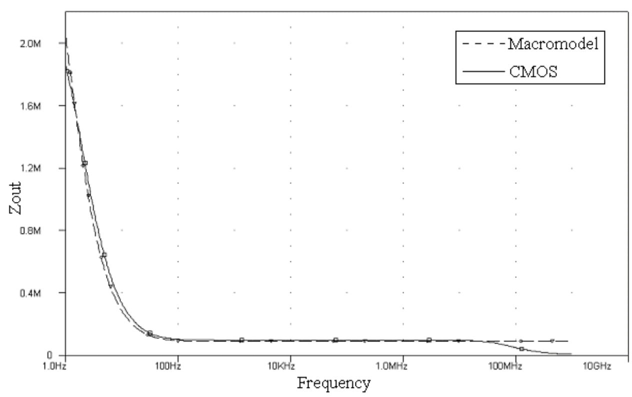

Figure 7. Output impedance of COA obtained by the macromodel and the CMOS implementation

V. CONCLUSION

In this study, a simple and accurate nonlinear macromodel for COA is presented. It models high frequency and nonlinear behaviors of COA. This macromodel is expected to allow reliable analysis of COA-based circuits. It accurately models the behavior of COA realized in either CMOS or BJT technology. The utilization of the macromodel in the analysis of analog circuits would reduce the computing time. It would also be easier to investigate the effects of COA non-idealities on the circuit performance. The validity of the presented macromodel has been verified with SPICE simulations by comparing it with a CMOS COA.

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