Analog CMOS Low-Voltage Current-Mode Implementation of Digital Logic Gates

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Abstract: In this paper a new approach is introduced for implementing the basic logic functions using analog current-mode techniques. By expanding the logic functions in power series expressions, and using summers and multipliers, realization of the basic logic functions is simplified. To illustrate the proposed technique, a CMOS circuit for simultaneous realization of the logic functions NOT, OR, NAND and XOR is considered. HSPICE simulation results, obtained with ± 3.5V supply, are included.

Key Words: Current-mode, Digital logic gates

1 Introduction

Mixed analog/digital electronic circuits are becoming increasingly important. Digital electronic circuits are mostly designed in CMOS technology. To be able to integrate the digital and analog parts on to one chip, high performance analog CMOS circuits are required [1] and a large number of mixed analog/digital VLSI integrated circuits realized in state-of-the-art digital CMOS technologies are now available [2]. In fact the emergence of ICs incorporating mixed analog and digital functions on a single chip has led to an advanced level of analog design [3]. Of particular interest here is the current-mode approach for designing analog ICs. It is well known that current-mode analog signal processing offers some important speed advantages over the traditional voltage-mode signal processing [4].

At present current-mode implementations are available for a wide range of analog electronic circuits including A/D and D/A converters, continuous time filters, neural-networks, sampled data filters and microwave and optical systems. This raises the following question: Can digital ICs be realized using current-mode analog techniques? In fact analog-based realizations of digital logic circuits may result in avoiding the traditional problems of fan-in and fan-out, inherent in digital-based implementations, less complexity, low-voltage as well as higher speed of operation [5]. In an attempt to answer this question, the translinear principle [6] has been used to realize a digital inverter circuit [7],[8], a bistable element [9] and NOT/OR/NAND/XOR functions [10] . All the realizations reported in references [7]-[10] use bipolar technology. No attempt has been made to use CMOS technology in designing digital circuits using analog techniques. This paper is an attempt to present such a realization.

2 Power Series Representation of Logic Functions

Using their truth tables, it is easy to show that the input-output relations of the basic digital logic functions can be expressed as [5]:

$$z = 1 - x \tag{1}$$

for the NOT operation,

$$z = x * y \tag{2}$$

for the AND operation,

$$z = x + y - x * y \tag{3}$$

for the OR operation, and

$$z = x + y - 2x * y \tag{4}$$

for the XOR operation. In equations (1)-(4) the signs +, - and * carry their normal mathematical meanings, that is add, subtract and multiply respectively. Using equations (2)-(4) in combination with equation (1) the digital-logic functions NAND, NOR and XNOR can be realized.

Analog implementation of the basic logic functions (1)-(4) requires analog multipliers, inverters and summers. Using a modified version of the four-quadrant multiplier reported in [11], voltage-mode analog implementation of two-input AND, NOT and OR functions have been reported [5]. These implementations, however, are built around voltage-mode operational amplifiers, analog switches and use a large number of resistors and requires relatively large supply voltages. This paper presents alternative current-mode analog implementations of the digital logic functions. Using, no resistors, except for realizing constant current-sources, no switches, no operational amplifiers, and only a small number of transistors, the proposed implementations requires low supply voltages and are very attractive for integration. The proposed implementation is designed for CMOS technology, which is now the most preferable technology for integrated circuit fabrication.

3 Proposed Circuit

Figure 1 shows a block diagram for the possible implementation of equations (1)-(4). It appears from Fig. 1 that the analog current-mode implementation of the logic functions INV/OR/AND/XOR requires current multiplication, addition and subtraction. In current-mode operation, addition and subtraction can be easily obtained by joining the current-carrying wires. While many current-multipliers are available in the literature, here we propose to use the current-multiplier circuit shown in Fig. 2 [12]. Transistors $M_1 - M_4$ form a traditional class-AB current mirror. Assuming that transistors M_1 and M_2 as well as transistors M_3 and M_4 are well matched and that all transistors are operating in their saturation region and having the same value of the transconductance parameter, that is $\beta_n = \beta_p$, then applying the translinear principle, we obtain

$$2\sqrt{I_q} = \sqrt{I_{D2}} + \sqrt{I_{D4}} \tag{5}$$

Combining (5) with

$$I_{D2} + (I_x - I_y) = I_{D4} \tag{6}$$

and using simple mathematical manipulations, the currents I_{D2} and I_{D4} can be expressed as

$$\frac{I_{D2}}{I_q} = 1 - \frac{1}{2}\frac{(I_x - I_y)}{I_q} + \left(\frac{I_x - I_y}{I_q}\right)^2 \tag{7}$$

and

$$\frac{I_{D4}}{I_q} = 1 + \frac{1}{2}\frac{(I_x - I_y)}{I_q} + \left(\frac{I_x - I_y}{I_q}\right)^2 \tag{8}$$

From (7) and (8) we get

$$\frac{I_{D5}}{I_q} = \frac{I_{D2} + I_{D4}}{I_q} = 2 + \frac{1}{8}\left(\frac{I_x - I_y}{I_q}\right)^2 \tag{9}$$

By subtracting a constant current = $2I_q$ from I_{D5}, the current I_{A1} can be expressed as

$$\frac{I_{A1}}{I_q} = \frac{1}{8}\left(\frac{I_x - I_y}{I_q}\right)^2 \tag{10}$$

Following the same procedure, assuming that transistors M_{11} and M_{12} as well as transistors M_{13} and M_{14} are well matched and that all transistors are operating in their saturation region and having the same value of the transconductance parameter, that is $\beta_n = \beta_p$, the current I_{A2} can be expressed as

$$\frac{I_{A2}}{I_q} = \frac{1}{8}\left(\frac{I_x + I_y}{I_q}\right)^2 \tag{10}$$

Using current mirrors with transistors having appropriate aspect ratios, the current I_C can be expressed as

$$I_C = -\frac{I_x I_y}{I_q} \qquad (11)$$

Thus, a multiplier circuit can be realized. Current mirroring, using transistors with appropriate aspect ratios, yields the currents

$$I_{out1} = \frac{1}{I_q} I_x I_y \qquad (12)$$

and

$$I_{out2} = \frac{2}{I_q} I_x I_y \qquad (13)$$

Using equations (12) and (13) it is easy to verify that the output currents $I_{NOT}, I_{OR}, I_{NAND}$ and I_{XOR} realize the logic functions NOT, OR, NAND and XOR given by equations (1)-(4). Realization of the logic functions NOR, AND and XNOR is a straightforward extension of the implementations of Fig. 1.

4 Simulation Results

The proposed implementation of Fig. 1 was simulated using the HSPICE level 49 simulator and the transistors were modeled using BSIM3v3 model of AMS 0.8 μm process technology, with supply voltage $V_{DD} = -V_{SS} = 3.5V$. The results obtained from the NOT, OR, NAND and XOR operations are shown in Fig. 3. In Figure (3) the currents are sensed using $1k\Omega$ load resistances. From Fig. 3, it appears that, the results obtained are in excellent agreement with the theory presented in equations (1)-(13).

5 Conclusion

Starting from the truth tables of logic functions, it is possible to obtain power series expansions of the basic logic functions. In these expansions the signs +, - and * carry their traditional mathematical meanings, that is add, subtract and multiply respectively. Thus, using these expansions, it is possible to implement the basic logic functions using analog current-mode techniques. In this paper a simple circuit, using 3.5 V supply voltage, has been presented for simultaneous realization of the basic logic functions NOT, OR, NAND and XOR using techniques widely used in realizing analog current-mode circuits. The proposed circuit can be easily extended to realize the functions NOR, AND and XNOR. Moreover, extension of the proposed circuit to realize basic logic functions with number of inputs greater than two is also straightforward.

It is expected that using this approach for implementing more sophisticated logic circuits, for example encoders/decoders, will result in simpler and faster realizations. Finally, by realizing analog and digital circuits using the same basic building blocks, it is expected that simple design procedures for mixed analog/digital circuits and systems may emerge.

Acknowledgement

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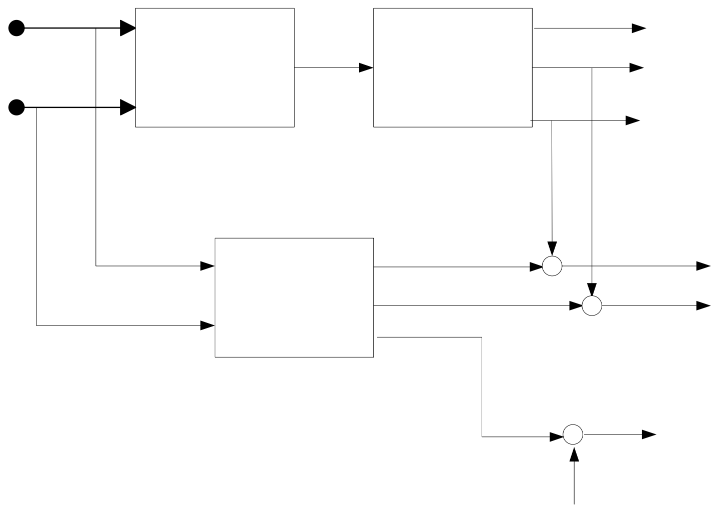

Fig. 1 Block diagram of the proposed current-mode analog implementation of the INV/OR/AND/XOR logic functions

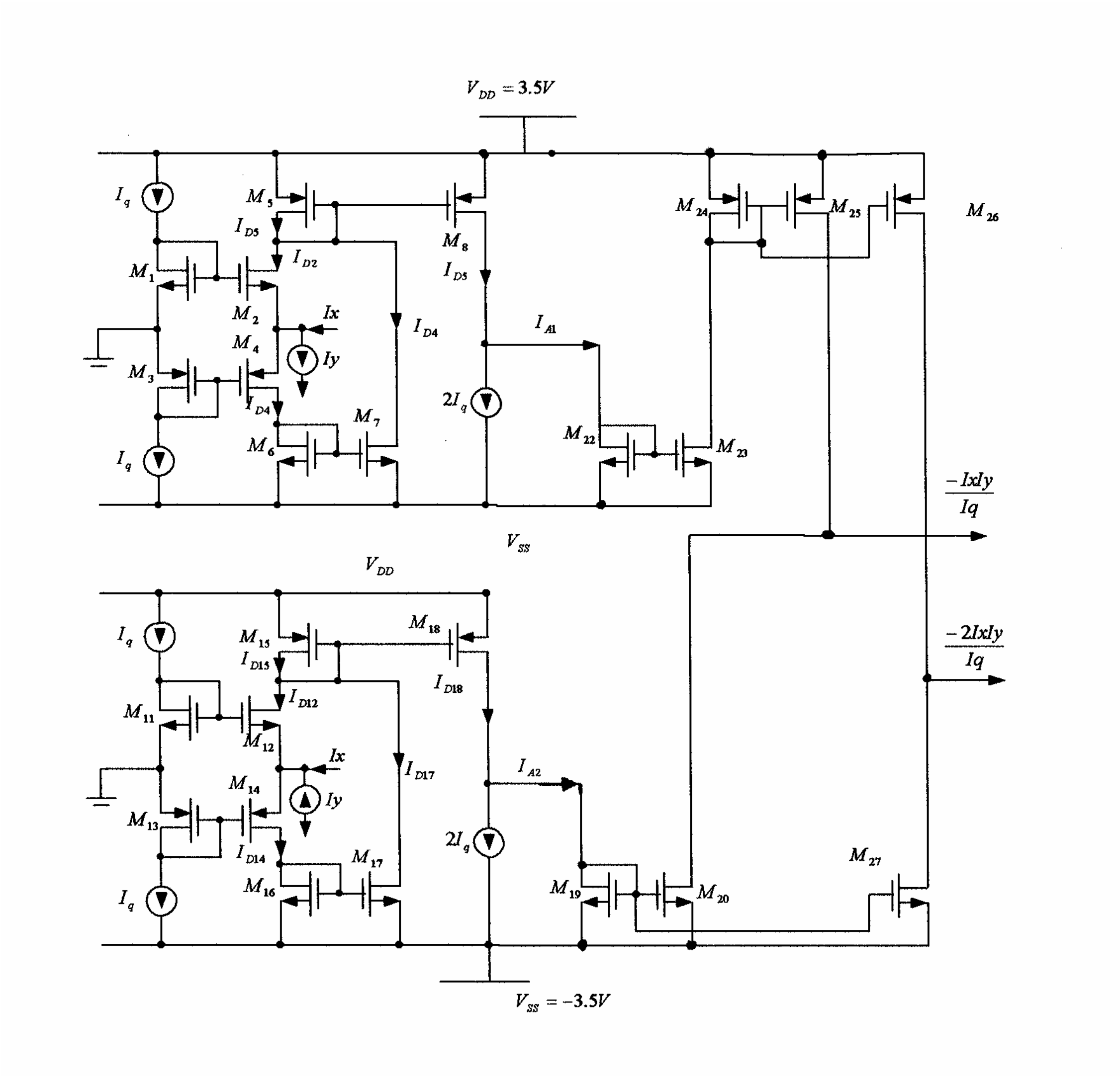

Fig. 2 Proposed CMOS realization of the current multiplication functions

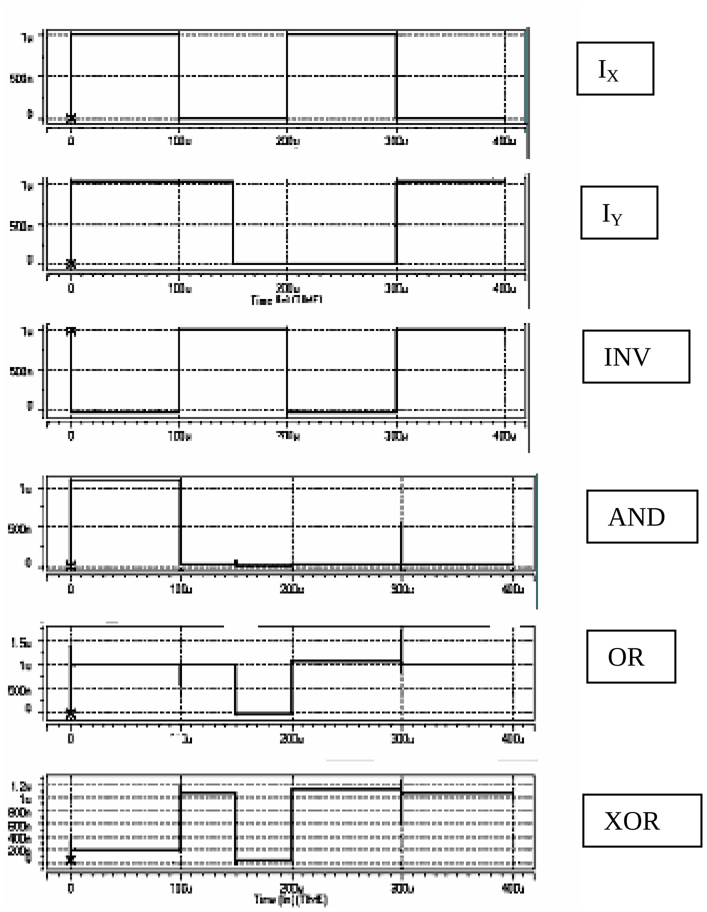

Fig. 3 Results obtained from the proposed implementation of Fig. 1 with DC supply voltage = ± 3.5 V