dB-Linear V-I Converter With Tunable Input And Output Range

Quoc-Hoang Duong, Trung-Kien Nguyen and Sang-Gug Lee

Information and Communication University, 58-4 Hwaam-Dong, Yuseong-gu, Daejeon, South Korea
Email: Hoang@icu.ac.kr Tel. (82-42) 866 6184

***Abstract* - This paper proposed an ultra low-voltage low-power all CMOS exponential V-I converter with tunable input and output ranges. The Taylor series expansion is used for realizing the exponential characteristic. The simulations, based on a 0.25 μm CMOS process, show a 20 dB linear output current range and a 15 dB-linear range with the linearity error less than ± 0.5 dB at 1.25V supply voltage. The average power consumption is less than 80 μW.**

I. INTRODUCTION

Among the mostly used circuits in mixed signal VLSI circuits are variable gain amplifier (VGA) and automatic gain control (AGC), which play an important role in telecommunications applications, medical equipment, hearing aid, disk drives and others [1-3]. The key component for the design of VGAs and AGCs is the exponential function generator. Unfortunately, there is no intrinsic logarithmic MOS device that operates in saturation region, which is necessary to design such generators. Therefore, to generate exponential characteristics, two following methods are used. The first one is based on a "pseudo-exponential" generator [1-4] in which the exponential characteristics can be approximated as

$$e^{2ax} \cong \frac{1+ax}{1-ax} \qquad (1^*)$$

where a and x are the coefficient and the independent variable, respectively. The second method uses Taylor series expansion for realizing the exponential characteristics [5-9] in which the exponential characteristic can be expressed as

$$e^{ax} = 1 + \frac{a}{1!}x + \frac{a^2}{2!}x^2 + \ldots + \frac{a^n}{n!}x^n + \ldots \qquad (1)$$

This paper proposed an all CMOS exponential V-I converter based on the current-mode functional circuit [9]. The proposed circuit has advantages that it can operate at extremely low-voltage applications and ultra low-power dissipations, and its input voltage swing as well as output dynamic range can be tunable easily. Moreover, the circuit is very independent on the temperature. The Simulation results will be given to verify the validity of this approach.

II. BASIC CONCEPT

The approximation equation, obtained by eliminating the higher order terms of Eq. (1) with small error for $|ax| << 1$, can be written as

$$e^{ax} \cong 1 + \frac{a}{1!}x + \frac{a^2}{2!}x^2 \qquad (2)$$

The primary drawback of this method is that the region over which the above equation is valid is restricted to $|x| \leq 1/a$. Beyond this region, the difference between the original exponential function and the approximation function will be more than 2.6 dB. For $|x| \leq 1/a$ the approximated function provides 14 dB amplitude variation, and the linearity error is less than ± 0.5 dB within 12 dB range [5,9]. This paper uses the modified Taylor series approximation as follows [9]:

$$f(ax) \cong k + \frac{a}{1!}x + \frac{a^2}{2!}x^2 \qquad (3)$$

For $k = 1$, Eq. (3) actually becomes Eq. (2). Using Matlab simulation tool for simulating Eq. (3), the results show that for k slightly less than 1, the approximation in Eq. (3) shows higher dB-linear range than that of Eq. (2). As shown in Fig. 1 by the o'symbol line for $k = 0.95$, the dB-linear range is extended to about 15 dB with linearity error less than ± 0.5 dB. While k decreases, the dB-linear ranges can be extended to even much higher values as depicted in Fig. 2.
Eq. (2) can also be written as

$$e^{ax} \cong (1/2)\left[1 + (1+ax)^2\right] \qquad (4)$$

respectively, the Eq. (3) can be written as

$$f(ax) \cong (1/2)\left[(2k-1) + (1+ax)^2\right] \qquad (5)$$

the circuit for implementing Eq. (5) will be discussed in section III.

III. CIRCUIT IMPLEMENTATION

In this section, the design of the current-mode functional circuit is presented firstly [9], and the linear V-I converter is given based on [5]. Then from these two circuits, the complete exponential V-I converter is proposed.

A. Current-mode functional Circuit design

The current-mode functional circuit in this section is adopted from [9]. Considering the circuit in Fig.2 (b), where all transistors are supposed to be in the saturation region. Then the drain currents of transistors M5 and M6 are given as

$$I_{d,M5,6} = K\left(V_{gs,M5,6} - V_t\right)^2 \qquad (6)$$

0-7803-8294-3/04/$20.00 ©2004 IEEE

It is shown from [9] that the output current, $I_{out} = I_{d,M5} + I_{d,M6}$ of the circuit in Fig. 2 (b) can be given as

$$I_{out} = \frac{1}{2}K(V_2 - 2V_t)^2 + \frac{(I_{d,M6} - I_{d,M5})^2}{2K(V_2 - 2V_t)^2} \tag{7}$$

using the bias circuit as shown in Fig. 2 (a), the Eq. (7) can be written as

$$I_{out} = I_{d,M6} + I_{d,M5} = 2I_0 + \frac{I_{in}^2}{8I_0} \tag{8}$$

where the I_0 is given as $I_0 = (K/4)(V_2 - 2V_t)^2$ and $I_{in} = I_{d,M6} - I_{d,M5}$ as shown in Fig. 2(b).

In order to keep all devices in the ON state the input current should be in the range $|I_{in}| < 4I_0$ [10].

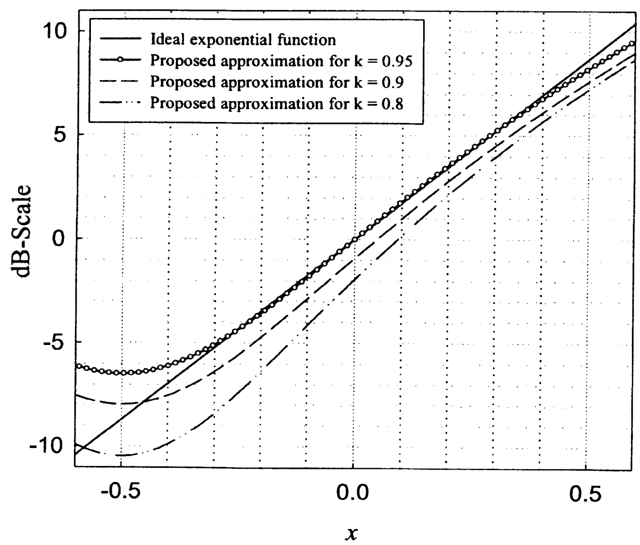

Fig 1. Plots of Eq. (3) for various k on dB-scale

The completed circuit implementations of the Eq. (5) are given in Fig. 3. It can be shown that the output current, I_{out}, in Fig. 4 can be written as

$$I_{out} = 2I_0 + \frac{(I_{in} + k_1 I_0)^2}{8I_0} - k_2 I_0$$

$$= \frac{k_1^2 I_0}{8}\left[\frac{8(2-k_2)}{k_1^2} + \left(1 + \frac{I_{in}}{k_1 I_0}\right)^2\right] \tag{9}$$

for $k_1 = \sqrt{8(2-k_2)}$ the exponential approximation in Eq.(4) is achieved and given as

$$I_{out} = \frac{k_1^2 I_0}{8}\exp\left(\frac{I_{in}}{k_1 I_0}\right) \tag{10}$$

The current, I_{out}, is thus an exponential approximation function of the input current I_{in}, where $a = 1/(k_1 I_0)$. The Eq.(10) is valid in the range $|I_{in}| \le k_1 I_0$. Out of this range, the deviation will be increased. From Eq. (9) one can also realize that by adjusting k_1 and k_2 in Eq. (9) functions as Eq. (5).

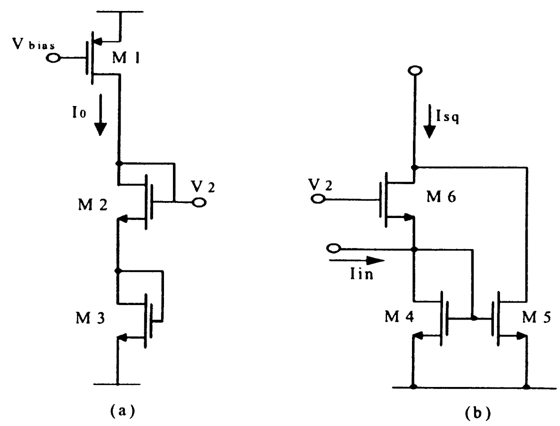

Fig. 2. (a) The bias circuit for the circuit in (b)
(b) The current-mode building block for the proposed exponential approximation.

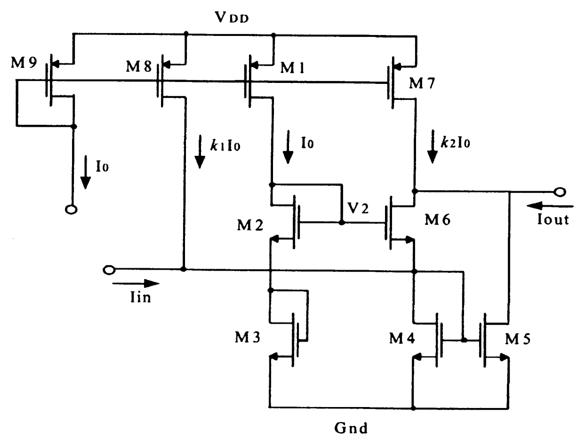

Fig. 3 The circuit implementation of the Eq. (4) and (5) based on the current-mode block shown in Fig. 2

Considering the temperature stability of the circuit in Fig.3, as the temperature changes, assume that the bias current and the output current will be varied by $I_0 + \Delta I_0$, and $I_{out} + \Delta I_{out}$, respectively. From Eq. (6) the following equation applies

$$\frac{I_{out} + \Delta I_{out}}{I_{out}} = \left(1 + \frac{\Delta I_0}{I_0}\right)\exp\left[\frac{-\Delta I_0/I_0}{k_1 I_0(1 + \Delta I_0/I_0)}\right] \tag{11}$$

because $\Delta I_0/I_0 << 1$, the Eq. (11) can be simplified as

$$\frac{I_{out} + \Delta I_{out}}{I_{out}} = \frac{(1 + \Delta M)}{\exp[\Delta M/k_1 I_0]} \tag{12}$$

where $\Delta M = \Delta I_0/I_0$. From Eq. (12), it is obvious that while the temperature changes, both of the numerator and denominator of Eq. (12) are all increased or decreased, such that the circuit in Fig. 5 is very insensitive to the temperature.

B. Linear V-I converter

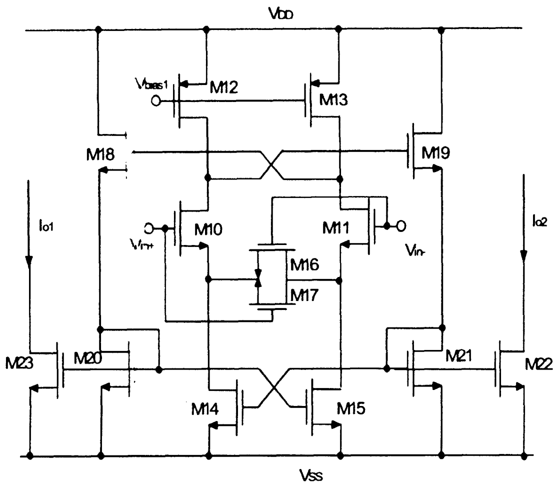

Fig. 4 The linear V-I converter [5]

The linear V-I converter is adopted from [5], which is given in Fig. 4. It is shown from [5] that the output current, $I_{01} - I_{02}$, is a linear function of input differential voltage, V_d, where $V_d = V_{in+} - V_{in-}$. The I-V characteristics of this circuit are given in Fig. 5.

From Fig. 3 and Fig. 5, the complete circuit of the exponential V-I converter is given as shown in Fig. 6.

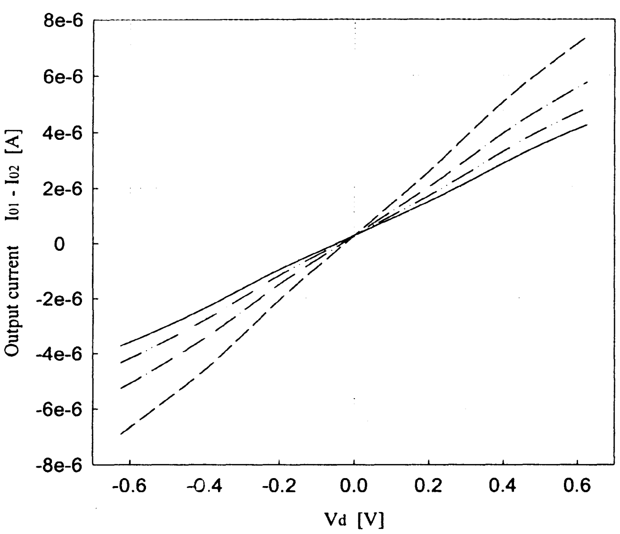

Fig. 5 The I-V characteristics of the circuit in Fig. 4 for various V_{bias1}.

IV. SIMULATION RESULTS

The feasibility of the proposed circuit was verified through simulations, using 0.25 μm CMOS process. When I_0 and k_1 are fixed. The k_2 can be found to achieve the exponential approximation as in Eq. (10). Fig. 7 illustrates the I-I performances of the circuit in Fig. 3. As can be seen in this figure, while k_2 increases, the dB ranges are extended [9].

From Fig. 5, for various V_{bias1}, the I-V performances stay linear for many slopes such that we can find one line, which satisfies the condition of the exponential approximation. Then 15 dB linear range with linearity error less than ± 0.5 dB is achieved over the entire input differential voltage swing as shown in Fig. 8 by the solid curve. By controlling the V_{bias1}, one can control the input swing as shown in Fig. 8. The dashed curve in Fig. 8 shows 20 dB output range, and 15 dB range with the linearity error less than ± 0.5 dB. The power dissipation is less than 80 μW from 1.25 V supply voltage.

By adjusting the I_0, the overall I-V performances are shifted. And, the output range can be controlled by adjusting both V_{bias1} and I_0.

V. CONCLUSIONS

A novel approximation function to realize the exponential relation is presented at extremely low-voltage low-power applications. The average power consumption is less than 80 μW at 1.25 V supply voltage. The proposed circuit has its input and output dynamic range tuned by the bias current I_0 and the V_{bias1}. Anpther advantage of this circuit is that it is very independent on the temperatures. The proposed V-I converter can achieve 20 dB output current range and 15 dB-linear range with the error less than ±0.5 dB. The proposed circuit could be used in the design of an extremely low-voltage and low-power VGA and AGC.

REFERENCES

[1] R. Harijani, "A Low-power CMOS VGA for 50 Mb/s Disk Drive Read Channels," *IEEE Trans. Circuits and Syst.* vol. 42, no. 6, pp. 370-376, June, 1995.

[2] K. M. Abdelfattah and A. M. Soliman, "Variable Gain Amplifier Based on a New Approximation Method to Realize the Exponential Function," *IEEE Trans. Circuits Syst.*, vol. 49, no. 9, Sep 2002.

[3] H. Elwan, A. M. Soliman, and M. Ismail, "A. digitally controlled dB-linear CMOS variable gain amplifier," *Elect. Lett.*, vol. 35, no.20, pp. 1725-1727, 1999.

[4] A. Motanemd, C. Hwang and M. Ismail, "CMOS exponential current-to-voltage converter," *Elect. Let.*, vol. 33, no. 12, pp. 998-1000, 5th June, 1997.

[5] Quoc-Hoang Duong, T.Kien N, and Sang-Gug Lee, "Low-Voltage Low-Power High dB-Linear CMOS Exponential Function Generator Using Highly-linear V-I Converter," *IEEE International symposium on Low Power Electronics and Designs*,pp. 349-352 August 2003.

[6] Cheng-Chieh Chang and Shen-luan Liu, "Current-mode pseudo-exponential circuit with tunable input range," Electronic Letter, vol. 36, no. 16, pp 1335-1336, 3rd August, 2000.

[7] W. Liu, C. Chang, and S. Liu, "Realization of Exponential V-I Converter using composite NMOS transistors," *Elect. Let.*, vol. 36, no. 1, pp. 8-10, 6th Jan, 2000.

[8] Quoc-Hoang Duong and Sang-Gug Lee, "A low-voltage, low-power, and high db-linear all cmos exponential function generator for AGC and VGA applications," will be presented at AMPC'03 Conference on November, South Korea.

[9] Quoc-Hoang Duong and Sang-Gug Lee, "All CMOS Current-Mode Exponential Function Generator With Tunable Input Range,", will be presented at *IEEE ICACT2004 conference*, Feb 2004, Korea.

[10] K. Bult and H. Wallinga, "A Class of Analog CMOS Circuits Based on the Square-Law Characteristic of an MOS Transistor in Saturation," *IEEE J. of Solid-State Circuits*, vol. sc-22, no. 3, June 1987.

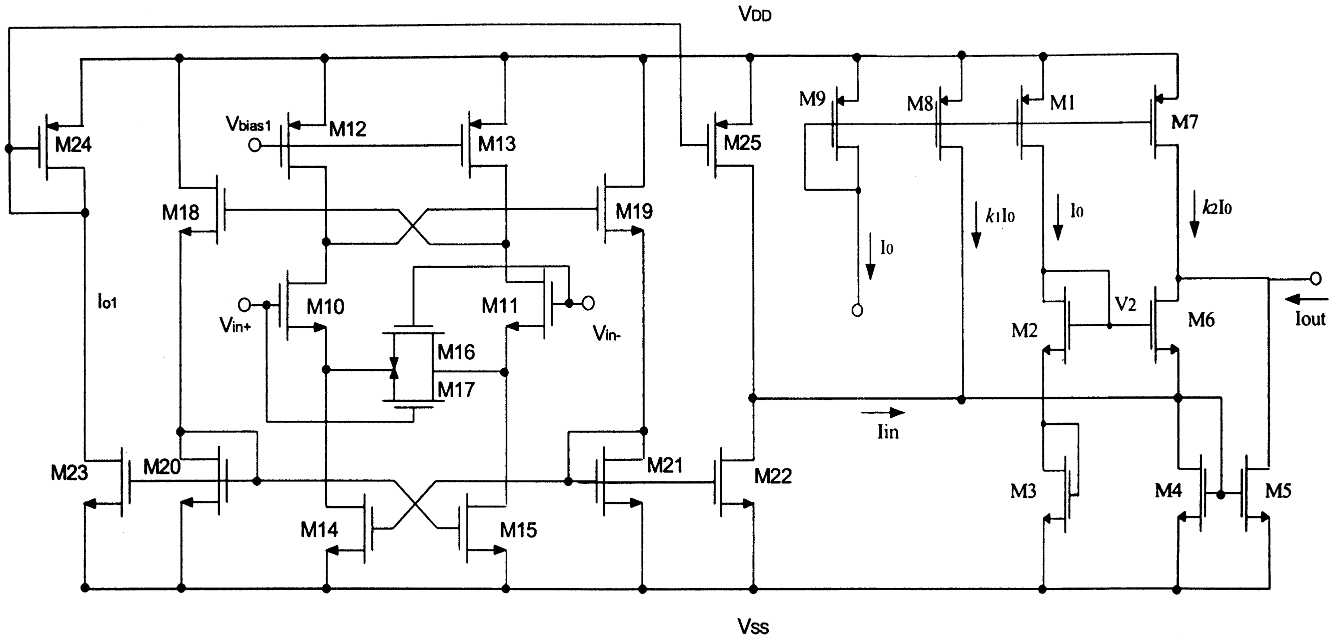

Fig. 6 Complete circuit of the exponential V-I converter

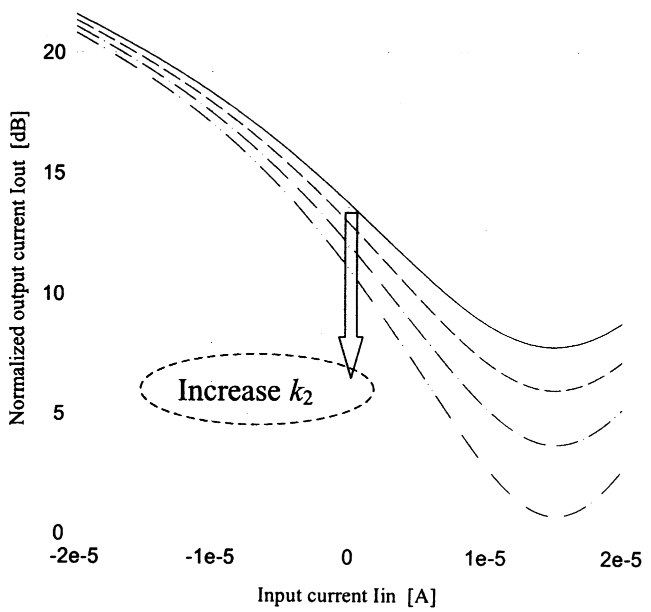

Fig. 7 The I-I characteristic of the circuit shown in Fig. 3 for different k_2 and k_1 = 1.

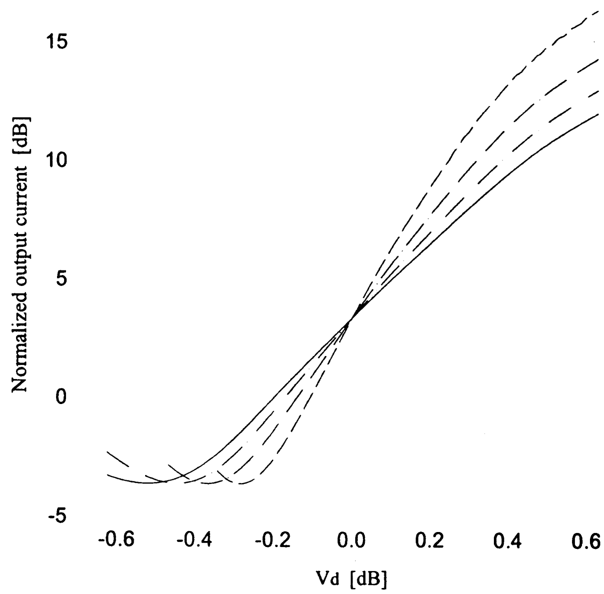

Fig. 8 The I-V performances of the circuit shown in Fig. 6 for various V_{bias1}

ACKNOWLEDGEMENT

The work is supported by Digital Media Lab which is funded by Ministry of Information and Communication; Korea.