All CMOS Exponential Function Generator With Tunable Input And Output Range

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Abstract-**An ultra low-voltage low-power all CMOS exponential function generator is proposed, with tunable input and output ranges. The proposed circuit uses 'Pre-distortion" technique to extend the dB linear output range. The Taylor series expansion is used for realizing the exponential characteristic. The simulations, based on a 0.25 μm CMOS process, show a 25 dB linear output current range at 1.25V supply voltage. The average power consumption is less than 0.1 mW.**

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 the 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

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

This paper proposed an all CMOS exponential V-I converter based on the current-mode functional circuit [9]. With the uses of "pre-distortion" technique, the proposed circuit can extend the dB linear range from 12 dB to 25 dB while dissipates very low power (less than 0.1 mW) at low voltage application (less than 1.25 V). The proposed circuit has advantages that its input voltage swings 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 $|ax| \ll 1$, can be written as

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

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].

In this paper, the "pre-distortion" technique, adopted from [8], is used to improve the performance of the proposed circuit. As in [8], considering the output current, $f(x)$, is a direct function of input current, x, and an indirect function of input voltage, t, such that the proposed circuit can be processed in the current domain to get rather higher dB-linear range. In Fig. 1, if the x is relatively a squaring function of t (i.e pre-distortion of x, $x = f_1(t)$ shown by the dashed curve). Then the $f(x) = f[f_1(t)]$ shown by the dash-dotted curve, will be shifted closely to the ideal exponential function. As a result, the dB-linear range and the input swing are increased. The Pre-distortion technique can achieve more than 25 dB-linear range with the linearity error less than ± 0.5 dB as shown in Fig. 1 by the dash-dotted curve.

Eq. (2) can also be written as

$$f(x) = \exp(ax) \cong (1/2)\left[1 + (1+ax)^2\right] \qquad (3)$$

the circuit for implementing Eq. (3) will be discussed in section 3.

III. CIRCUIT IMPLEMENTATION

In this section, the design of the current-mode functional circuit is presented firstly [9], and the nonlinear V-I converter is given based on [8]. Then from these two circuits, the complete exponential V-I converter is proposed.

A. Current-mode functional Circuit design

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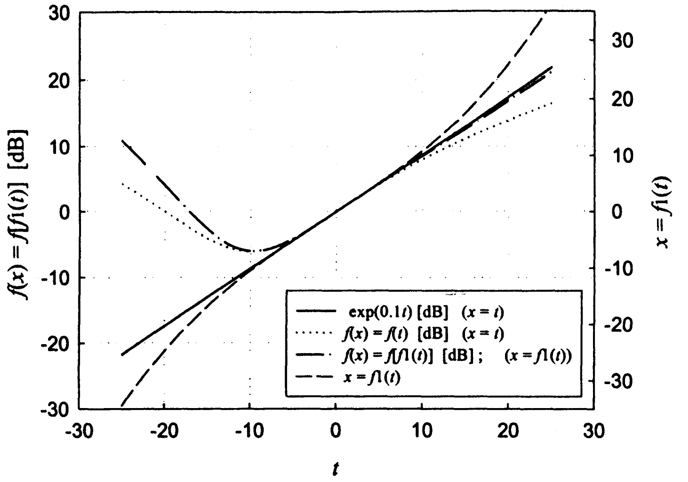


Fig 1. Plots of various functions on dB-scale

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

$$I_{d,M5,6} = K\left(V_{gs,M5,6} - V_t\right)^2 \tag{4}$$

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

$$I_{out} = \frac{1}{2}K\left(V_2 - 2V_t\right)^2 + \frac{\left(I_{d,M6} - I_{d,M5}\right)^2}{2K\left(V_2 - 2V_t\right)^2} \tag{5}$$

using the bias circuit as shown in Fig. 2 (a), the Eq. (5) can be written as

$$I_{out} = I_{d,M6} + I_{d,M5} = 2I_0 + \frac{I_{in}^2}{8I_0} \tag{6}$$

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].

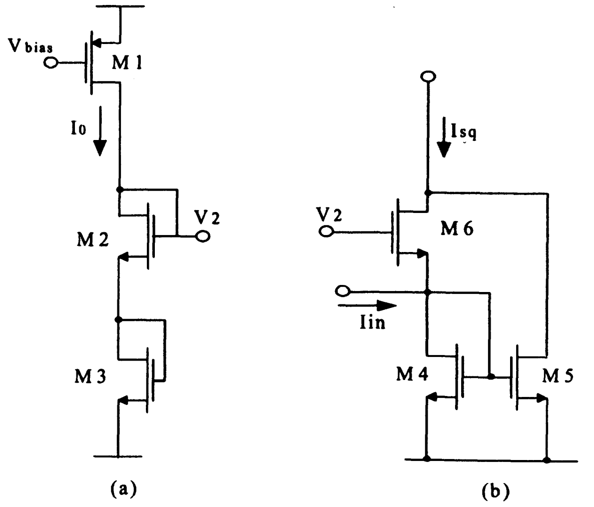
The completed circuit implementations of the Eq. (3) is given in Fig. 3. It can be shown that the output current, I_{out}, in Fig. 3 can be written as

$$\begin{aligned} I_{out} &= 2I_0 + \frac{\left(I_{in} + k_1 I_0\right)^2}{8I_0} - k_2 I_0 \\ &= \frac{k_1^2 I_0}{8}\left[\frac{8\left(2 - k_2\right)}{k_1^2} + \left(1 + \frac{I_{in}}{k_1 I_0}\right)^2\right] \end{aligned} \tag{7}$$

for $k_1 = \sqrt{8\left(2 - k_2\right)}$ the exponential approximation in Eq.(3) is achieved and given as

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

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.(8) is valid in the range $|I_{in}| \le k_1 I_0$. Out of this range, the deviation will be increased.



(a) (b)

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

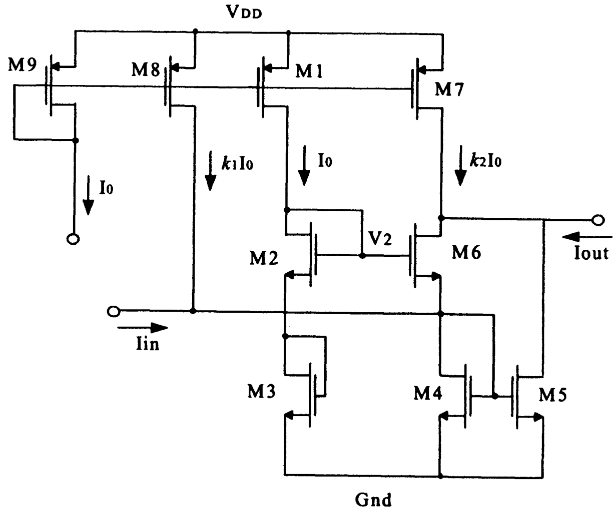


Fig. 3 The circuit implementation of the Eq. (3) based on the current-mode block shown in Fig. 2

Consider 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. (8) the following equation applies

$$\frac{I_{out}+\Delta I_{out}}{I_{out}} = \left(1+\frac{\Delta I_0}{I_0}\right)\exp\left[\frac{-\Delta I_0\; I_0}{k_1 I_0\left(1+\Delta I_0\; I_0\right)}\right] \qquad (9)$$

because $\Delta I_0 / I_0 << 1$, the Eq. (9) can be simplified as

$$\frac{I_{out}+\Delta I_{out}}{I_{out}} = \frac{(1+\Delta M)}{\exp[\Delta M\; k_1 I_0]} \qquad (10)$$

where $\Delta M = \Delta I_0 / I_0$ .From Eq. (10), it is obvious that while the temperature changes, both of the numerator and denominator of Eq. (10) are all increased or decreased, such that the circuit in Fig. 3 is very insensitive to the temperature.

B. Nonlinear V-I converter

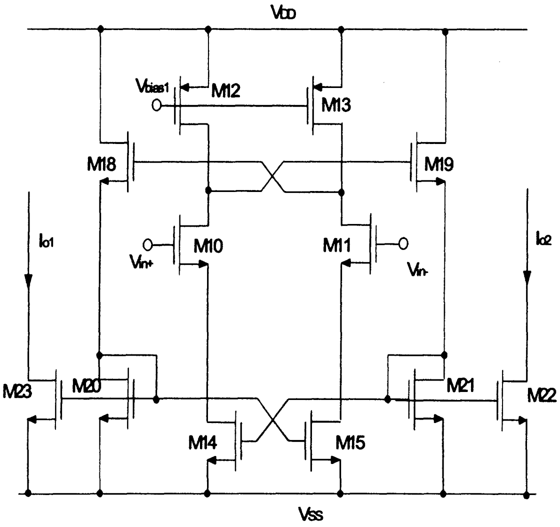


Fig. 4 The nonlinear V-I converter [8]

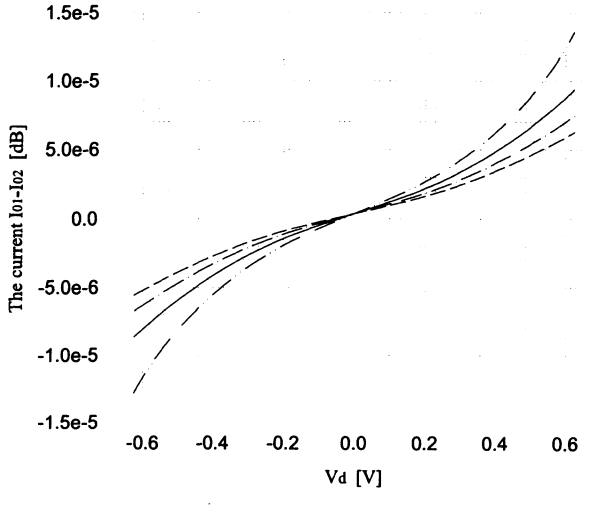


Fig. 5 The I-V characteristics of the circuit in Fig. 4 for various V_{bias1}.

The nonlinear V-I converter is adopted from [8], which is given in Fig. 4. It is shown from [8] that the output current, $I_{01} - I_{02}$, is a nonlinear 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.

IV. SIMULATION RESULTS

The feasibility of the proposed circuit was verified through simulations, using 0.25 μm CMOS process. For different bias current I_0, different input range of the circuit in Fig. 3 is obtained as shown in Fig. 7. Also, for different V_{bias1} the nonlinear V-I converter as shown in Fig.5 generates various Iin curves. The I_{in} is directed to the input of the current-mode circuit shown in Fig. 3. Then the I_0 is chosen such that the I_{in} is relatively linear in the range $|I_{in}| \le I_0$. In this range, the exponential approximation is obtained, and 14 dB ranges can be achieved as shown in Fig. 8. Out of this range, the I_{in} is nonlinear so that the linearity error is reduced. For different I_{in} as shown in Fig. 5, different I-V performance of the circuit in Fig. 6 are given in Fig. 8. It is shown from Fig. 8 by the dashed curve that, 25 dB linear range with linearity error less than ± 0.5 dB is obtained over larger input swing from –0.3 V to 0.625 V.

By adjusting the V_{bias1} and I_0, the input and output range can be tunable.

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 0.1 mW 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}. Another advantage of this circuit is that it is very independence on the temperatures. The proposed V-I converter can achieve 25 dB output current ranges 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.

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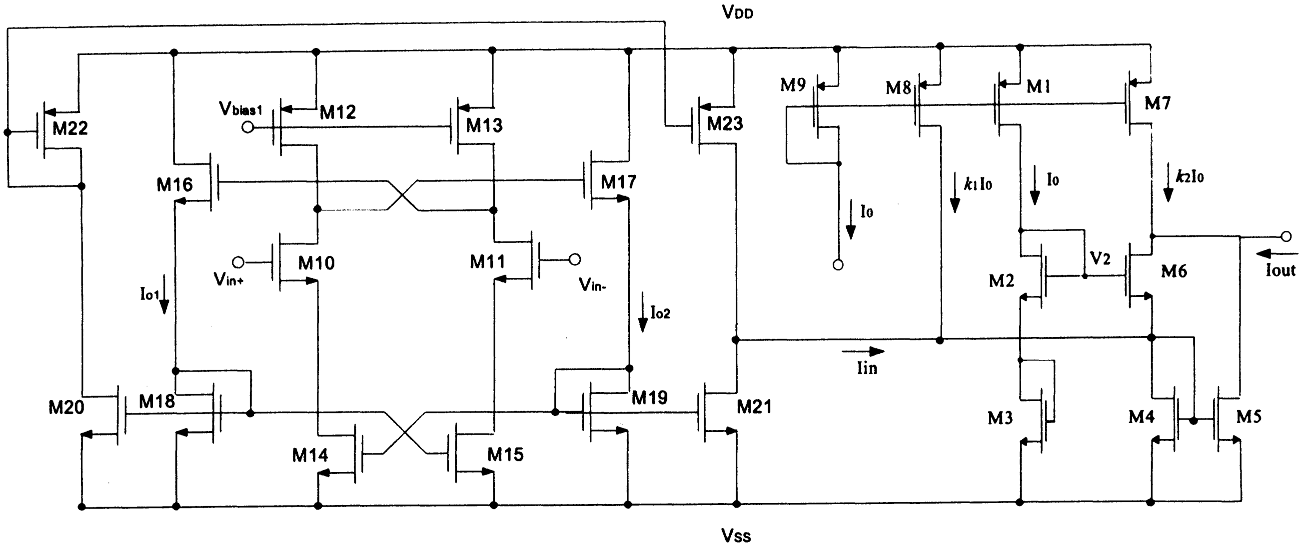

Fig. 6 Complete circuit of the exponential V-I converter

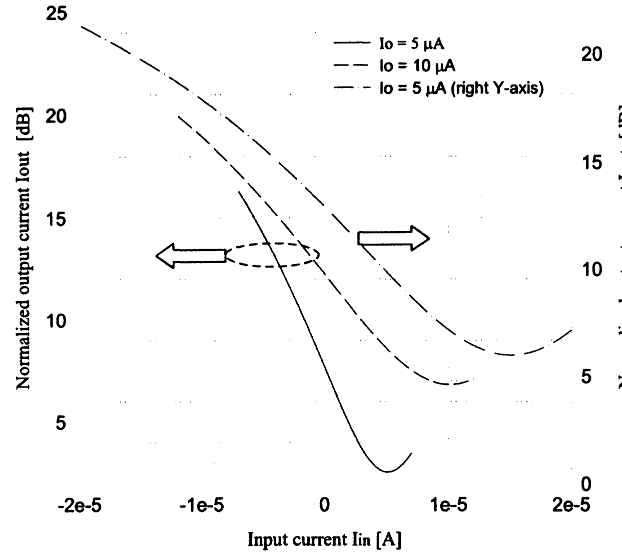

Fig. 7 The I-I characteristic of the circuit shown in Fig. 3 for various I_0.

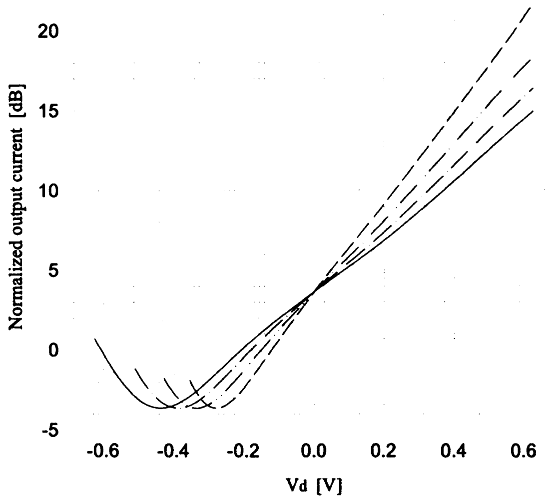

Fig. 8 The I-V performances of the circuit shown in Fig. 6 for various V_{bias1}

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