A 35 dB-Linear Exponential Function Generator for VGA And AGC Applications

Quoc-Hoang Duong
Tel. (82-42) 866 6184
E-mail: hoang@icu.ac.kr

Sang-Gug Lee
Tel. (82-42) 866 6133
E-mail: sglee@icu.ac.kr

Information and Communication University 58-4 Hwaam-Dong, Yuseong-gu, Daejeon, South Korea.

Abstract – In this paper, a new current-mode based exponential function generator with high dB-linear range is developed. The exponential function is based on Taylor's concept. The proposed circuit is composed of current-to-current squarers, current multipliers, and a linear V-I converter with linearization technique. Based on a 0.25 μm CMOS process, the simulations show a 35 dB-linear output current range with the linearity error less than ± 0.5 dB. The power dissipation is less than 0.3 mW at 1.25 V supply voltage.

I. INTRODUCTION

Since there is no intrinsic logarithmic MOS device operating in the saturation region for CMOS technologies, one method to generate the exponential characteristics is by use of a "pseudo-exponential" generator [1-3]. Alternatively, the Taylor series expansion can also be used for implementation of the exponential [4-7].

By applying the Taylor concept, the dB-linear V-I converter (EVIC) can be implemented by using the composition of a V-I squarer circuit, a linear V-I converter and a constant bias current [4-6], or by using composite NMOS transistors [7]. However, these previously reported EVICs tend to show very small dB-linear variation of the output current (less than 15 dB with a linearity error less than ± 0.5 dB) [6,7]. Moreover, EVICs in [6,7] are not power efficient (≅ 0.9 mW) and operate at high supply voltage (≅ 3 V) [6,7]. Although [5] reported higher dB-linear range, the differential input dynamic range is severely limited (≅ 0.27 V) and the output range is restricted to less than 20 dB.

To overcome these difficulties, this paper presents a new current-mode based EVIC using shifted-symmetrical axis technique to increase the dB-linear output current range as well as the differential input swing. The EVIC in this paper uses the current-to-current squarer [8] instead of voltage-to-current squarer [6] such that the power consumption of the overall circuit is reduced extremely (≅ 0.3 mW), and the V-I linear with new linearization technique so that the circuit can operate at very low voltage application (≤ 1.25 V) [5]. The EVIC is based on current mode, by inserting the current squarer at the output of the core EVIC, a rather high dB-linear range can be obtained

II. PROPOSED BLOCK DIAGRAM

According to the Taylor's series expansion, a general exponential function can be expressed as

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

where a and x are the coefficient and the independent variable, respectively. For $|ax| << 1$, the Eq. (1) can be approximated as

$$e^{ax} \cong 1 + (ax)/1! + (ax)^2/2! \tag{2}$$

for $|ax| < 1$, the Eq. (2) provides 14 dB variation and 12 dB-linear variation with the error less than ± 0.5 dB. Obviously, the squaring function of Eq. (2) [i.e $exp^2(ax)$] will provide double dB-linear range compared to that of the Eq. (2). The comparison of Eq. (1) and (2) is respectively given in Fig. (1) by the solid and dashed lines for $a = 0.1$.

As reported in [6], the dB-linear range and the input voltage swing are improved as shown in Fig. 1 by the o'symbol curve by applying the modified Taylor series expansion as follows

$$e^{ax} \cong 1 + k\left[(ax)/1!\right] + (ax)^2/2! \tag{3}$$

A new function block diagram to realize the squaring function of Eq. (3) is given in Fig. 2, which also includes the transfer function of all blocks. The output current (I_{in}) of the linear V-I converter, which is a function of V_d (= V_{in+} - V_{in-}), is multiplied by K_1 and K_2 to generate two current signals K_1I_{in} and K_2I_{in}, respectively. The K_2I_{in} goes to the **Current squarer** and then is added to the other signal K_1I_{in} to form the Eq. (2). Then, the Eq. (2) is squared by the **Squarer**.

The output current as an approximated exponential function is given as

$$I_{\exp} = 2I_0\left(1 + K_1\frac{I_{in}}{2I_0} + \frac{K_2^2 I_{in}^2}{16 I_0^2}\right) \tag{4}$$

$$I_{out} = I_{\exp}^2 / 8I_{01} \tag{5}$$

where I_0 and I_{01} are the bias currents of the current squarer and the squarer, respectively [8].

To satisfy the condition of exponential function as in Eq. 1, the coefficient a and the independent variable x, have to satisfy the following condition

$$K_2/K_1 = \sqrt{2} \quad and \quad a = K_1/2I_0 \tag{6}$$

From Eq. (6), the exponential characteristic is easily achieved by setting the multiplying factors K_1 and K_2. Also,

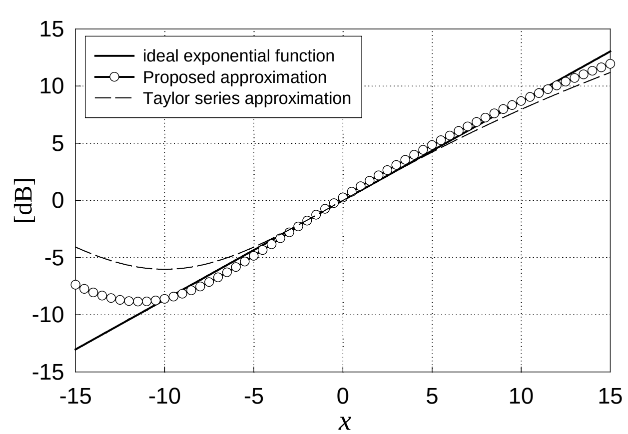

Fig. 1 Plots of various functions on dB-scale

the symmetrical-axis is controlled by K_1 and K_2. The multipliers are actually current mirrors. Hence, K_1 and K_2 are achieved by setting transistors' size in the current mirrors. The other advantage of this method is that the transconductance of the exponential V-I converter can be tunable easily by adjusting the bias voltage V_{bias1} and V_{bias2}. Typically, the output parameter of the dB-linear V-I and I-V converters is a direct function of the input parameter [4,6,7]. Differently, this paper considers the output current of the EVIC is an indirect function of input voltage, and a direct function of input current such that the $exp^2(ax)$ can be done in the current domain easily to get rather higher dB-linear range as depicted in Fig. 2.

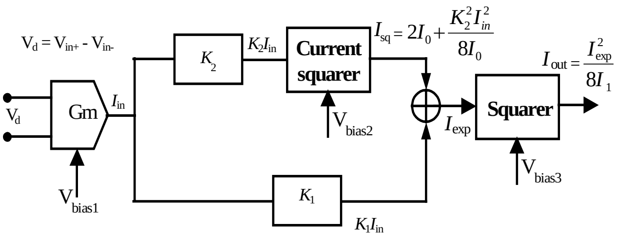

Fig. 2. Proposed block diagram

III. CIRCUIT IMPLEMENTATION

A. V-I linear converter design

As shown in [9], the linear V-I converter has significant drawbacks at low voltage applications. As reported in [5], by using linearization technique, the V-I linear converter can operate at very low supply voltage. Fig. 3 depicts the completed linear V-I converter [5].

The V-I converter shown in Fig. 3 combines the two previously reported linearization techniques: source degeneration using MOS transistors M^*_1 and M^*_2, and class-AB linearization [10]. This circuit provides rail-to-rail differential input range. Fig. 4 shows the I-V characteristic of the V-I converter.

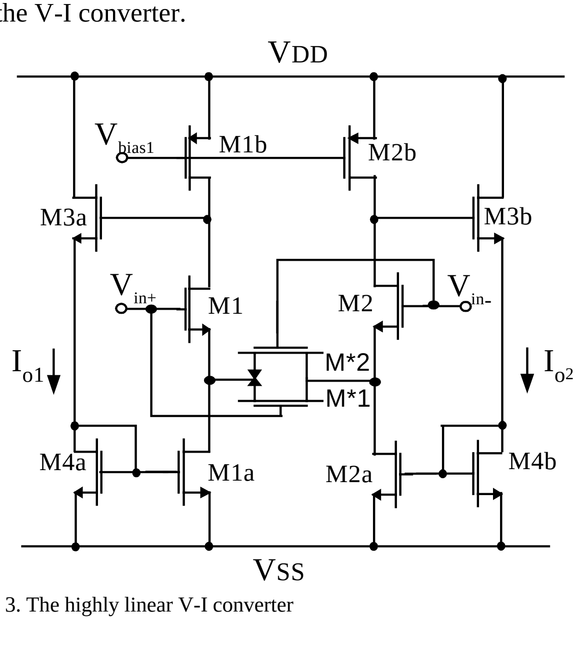

Fig. 3. The highly linear V-I converter

As reported in [5], the output current $I_{o1} - I_{02}$ is a linear function of the differential input voltage V_d, where $V_d = V_{in+} - V_{in-}$. The V-I characteristic of the circuit in Fig. 3 is shown in Fig. 4 for various V_{bias1}.

As shown in this figure, a fixed transconductance can be obtained by controlling the bias voltage V_{bias1} of the load transistors M_3 and M_4. In Fig. 4, the V-I characteristic stays linear for various slopes.

B. Current-to-current squaring circuit

The low-voltage and low-power current squaring circuit adopted from [8] is shown in Fig. 5. It can be shown that, in Fig. 6, the output current I_{sq} is given by [8]

$$I_{sq} = 2I_0 + \left(K_2^2 I_{in}^2\right) / \left(8I_0\right) \qquad (7)$$

where I_0 is the bias current as shown in Fig. 5 and Eq. (6). As V_{bias2} in Fig.5 varies, the I_0 changes such that the constant I_0 in Eq. 3 is modified, leading to the modification of the overall V-I dB-linear characteristic.

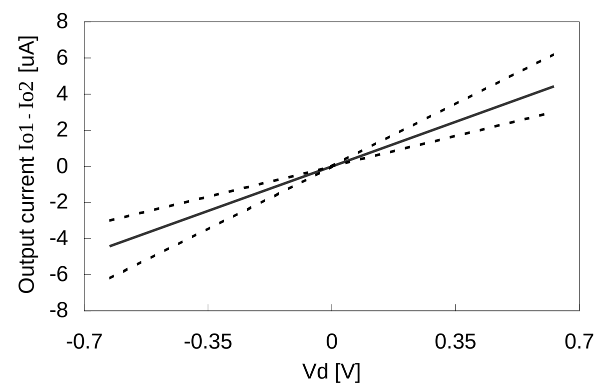

Fig. 4. The V-I characteristic of the circuit shown in Fig. 3 for various V_{bias1}.

C. Current Multipliers and Squarer

The current multipliers are actually current mirrors, by setting the transistors sizes properly; the current K_1I_{in} and K_2I_{in} can be easily achieved. The Squarer is adopted from [9]. In Fig. 5, for the input current equal to I_{exp}, by subtracting I_{sq} by $2I_{01}$ the current in Eq. (5) is obtained.

The complete implementation of the exponential V-I converter is shown in Fig. 5.

4. SIMULATION RESULTS

In Fig. 5, the V_{bias2} and V_{bias3} define the current I_0 and I_{01}, respectively. The input current I_{in} in Eq.(3), in order to satisfy the condition $|ax| << 1$ in Eq.(2), should satisfies the condition $|K_1I_{in}| < 2I_0$. The bias voltage V_{bias1} can be adjusted to get the I-V curve that satisfies $|K_1I_{in}| < 2I_0$. In this case, 14 dB-linear output current could be obtained.

By adjusting the K_1 and K_2, we can shift the symmetrical-axis and higher dB-linear output current range can be achieved. In this paper, the K_1 and K_2 are adjusted to extend the dB-linear range from 12 dB to about 18 dB-linear range, and the squarer doubles the output current range to nearly 35 dB-linear with the linearity error less than ± 0.5 dB as can be seen in Fig. 6 by the solid curve. Fig. 6 depicts the normalized dB I-V characteristic of the complete exponential V-I converter which show 35 dB-linear range over the differential voltage swing ranging from –0.625 V to 0 V.

For various Vbias1, many I-V curves of the linear V-I converter can be obtained as shown in Fig. 6.

The dB-linear range can be programmed by adjusting

V_{bias1}, V_{bias2} and V_{bias3}.

5. CONCLUSIONS

A novel approximation function to realize the exponential relation, which is found in almost all VGA and AGC circuits, is presented with programmable dB-linear range for extremely low-voltage low-power applications. The proposed ideas, block diagrams, and circuit implementation are described in this paper. The average power consumption is less than 0.3 mW at 1.25 V supply voltage. The proposed EVIC can achieve more than 35 dB-linear range over a wide input voltage swing 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.

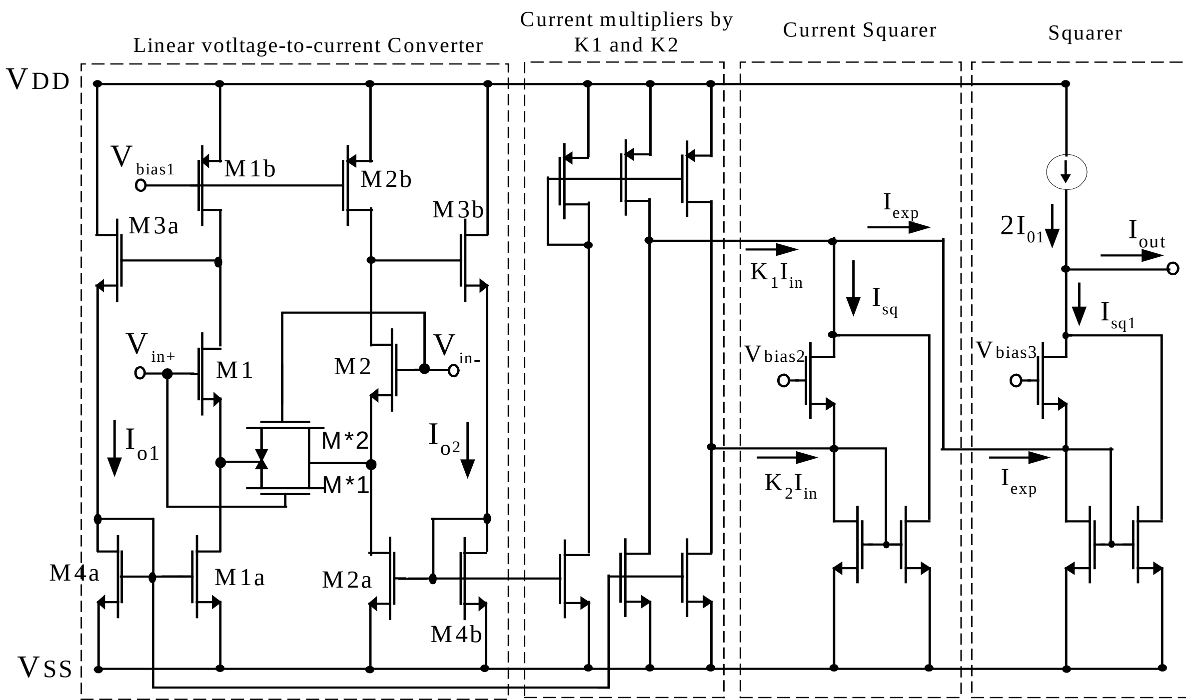

Fig. 5 The proposed exponential V-I converter

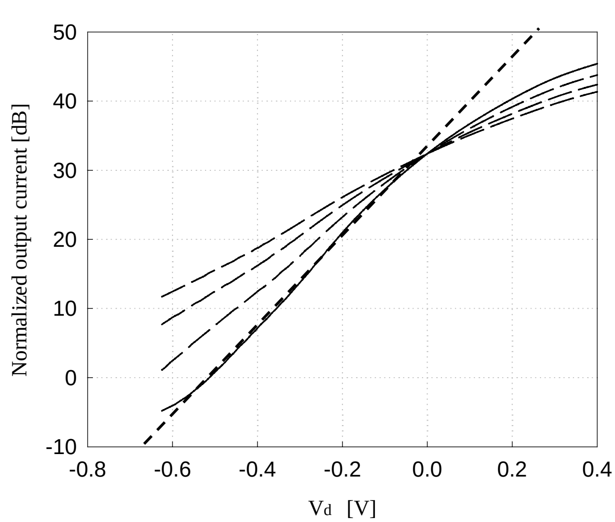

Fig. 6. The I-V characteristic of the complete proposed exponential V-I converter for various V_{bias1}.

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] 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.

[3] 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.

[4] 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.

[5] Quoc-Hoang Duong, T.Kien N, and Sang-Gug Lee, “a low-voltage low-power, and high dB-linear CMOS exponential V-I Converter,” *IEEE, Asia-Pacific Microwave Symposium*, pp. 409-412, November 2003.

[6] Lin, C., Pimenta, T., and Ismail, M., “Universal exponential function implementation using highly-linear CMOS V-I converters for dB-linear (AGC) application”. *Proc. 1998 IEEE Midwest symp. Circuits and Systems*, 1999, pp. 360-363.

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

[8] 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

[9] C.-H. Lin, M. Ismail and T. Pimenta “A 1.2 V Micropower CMOS Class AB V-I converter for VLSI Cells Library Design,” *IEEE Midwest Symp. on Circuit and Systems*, September, 1998.

[10] K. Ko-Chi and L. Adrian, “A linear MOS Transconductor Using Source Degeneration and Adaptive Biasing,” IEEE Trans. Circuits Syst, vol. 48, pp. 937-943, October 2001.

ACKNOWLEDGEMENT

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