Wide dynamic range variable-gain amplifier based on new approximated exponential equation

Q.-H. Duong and S.-G. Lee

A new approximated exponential equation is proposed, which offers a wide decibel linear range for use in many applications such as exponential converters, log-domain filters, variable gain amplifiers (VGAs), automatic gain control amplifiers, etc. The proposed equation is implemented into a circuit as a two-stage VGA, which is fabricated in 0.18 µm CMOS technology and offers a gain range of 90 dB (−54–36 dB) and about 82 dB with linearity error of less than ±1 dB. The 3 dB bandwidth is 50 MHz at a maximum gain of 36 dB and P1 dB is from −40 to −17 dBm. The power dissipation is 3.7 mA from a 1.8 V supply. The chip, excluding bond pads, occupies 0.34 mm^2.

Introduction: Variable gain amplifiers (VGAs) are used to maximise the dynamic range of overall systems in medical equipment, telecommunications systems, hearing aids, disc drives and others [1]. One of the most important characteristics of the VGA is that the gain must be an exponential function of the control signal (voltage or current); however, this exponential relation is not easily obtained in CMOS technology owing to the square-law I–V characteristic of MOS transistors in saturation-mode operation. Consequently, the conventional VGA design has been based on approximated exponential equations and circuit techniques such as signal-summing, master–slave control, switched-capacitor techniques, etc.

The approximated exponential equations adopted in conventional VGA designs are pseudo-exponential and Taylor series approximation equations [1], which offer less than 15 and 12 dB gain variation with gain error of less than ±0.5 dB, respectively. Unfortunately, many applications require a wide dynamic gain range, e.g. the code-division multiple access system (CDMA) requires more than 80 dB of dynamic range so that many VGAs must be used, resulting in high power consumption and large chip size. Consequently, a VGA with wide gain variation is desirable to reduce the number of VGAs, leading to reduction of power consumption and chip size.

To achieve a wide decibel linear range, Abdelfattah and Soliman reported the implementation of the pseudo-exponential equation given as [2]

$$f(x) = \left\{ \begin{array}{ll} \dfrac{(1+3x/4)}{(1-x/4)} & \text{for } x > 0 \\ \dfrac{(1-x/4)}{(1-3x/4)} & \text{for } x < 0 \end{array} \right\} \tag{1}$$

As reported in [2], (1) can offer about 40 dB linear range with linearity error of less than ±0.5 dB.

Another approximated exponential equation was proposed in [1] and given as

$$f(x) = \frac{[k + (1 + ax)^2]}{[k + (1 - ax)^2]} \tag{2}$$

where k and a are constant. As reported in [1], (2) can provide 60 dB range. This equation has been adopted for a two-stage VGA design with 95 dB of gain variation [1]. However, the slope of $f(x)$ in (2) in decibel scale is strongly dependent on the constant k such that the gain of the VGA that adopts (2) can be sensitive to temperature and process variation.

In this Letter, a new approximated exponential equation is proposed and given as

$$f(x) = \frac{[1 + ax + k(ax)^2/2]}{[1 - ax + k(ax)^2/2]} \tag{3}$$

where k is a constant. The numerical analysis of (3) shows that, for k less than unity, the decibel linear range of (3) can be extended drastically, as shown in Fig. 1 by the dashed ($k = 1$), dash–dotted ($k = 0.7$) and solid ($k = 0.55$) lines. As can be seen in Fig. 1, the slope of all lines of (3) for different values of k is constant. For $k = 0.55$ (solid line), the decibel linear range extends to 65 dB with a linearity error of less than ±0.5 dB. Theoretically, by a circuit implementation of (3), only the one-stage VGA can offer more than 65 dB gain range with linearity error of less than ±0.5 dB, which is a huge improvement compared to conventional techniques.

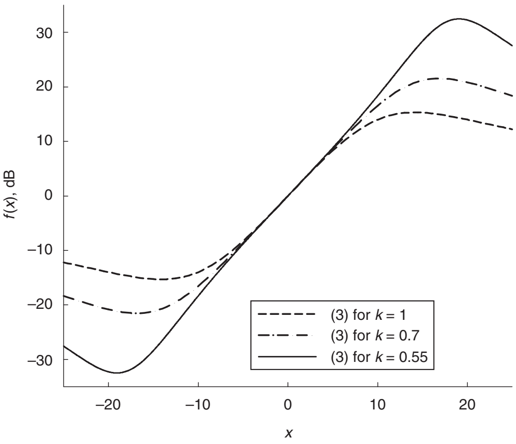

Fig. 1 *Plots of (3) for different values of k*

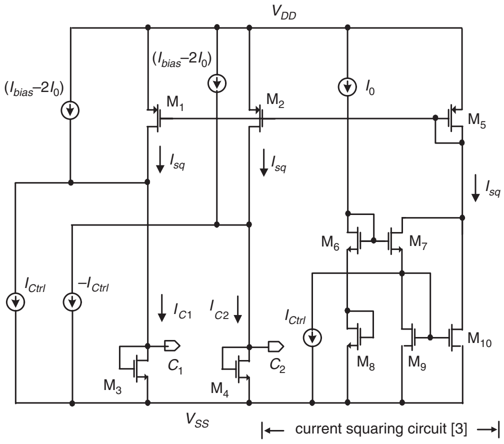

Fig. 2 *Schematic of control circuit*

Circuit implementation: The control circuit for controlling the gain of the VGA is shown in Fig. 2, where the current squaring circuit is adopted from [3]. In Fig. 2, all transistors are in saturation mode operation, and the current, I_{Ctrl}, is used to control the gain of the VGA, as described later. As reported in [3], the drain current of M$_5$, I_{sq}, in Fig. 2 is a squaring function of the input current I_{Ctrl}, which is given as

$$I_{sq} = 2I_0 + I_{Ctrl}^2/8I_0 \tag{4}$$

where I_0 is the bias current. In Fig. 2, the current, I_{sq}, is mirrored to transistors M$_1$ and M$_2$ and added with the bias current $I_{bias} - 2I_0$. The resulting currents I_{C1} and I_{C2} in Fig. 2 are calculated as

$$\begin{aligned} I_{C1} &= I_{sq} + (I_{bias} - 2I_0) - I_{Ctrl} \\ &= I_{bias} - I_{Ctrl} + \frac{I_{Ctrl}^2}{8I_0} = I_{bias}\left(1 - \frac{I_{Ctrl}}{I_{bias}} + \frac{I_{Ctrl}^2}{8I_0 I_{bias}}\right) \end{aligned} \tag{5}$$

$$\begin{aligned} I_{C2} &= I_{sq} + (I_{bias} - 2I_0) + I_{Ctrl} \\ &= I_{bias} + I_{Ctrl} + \frac{I_{Ctrl}^2}{8I_0} = I_{bias}\left(1 + \frac{I_{Ctrl}}{I_{bias}} + \frac{I_{Ctrl}^2}{8I_0 I_{bias}}\right) \end{aligned} \tag{6}$$

From (5) and (6), the currents I_{C1} and I_{C2} in Fig. 2 as a function of the control current, I_{Ctrl}, resemble the denominator and numerator of (3), respectively. These two currents are mirrored to the variable gain circuit to control the gain of the VGA.

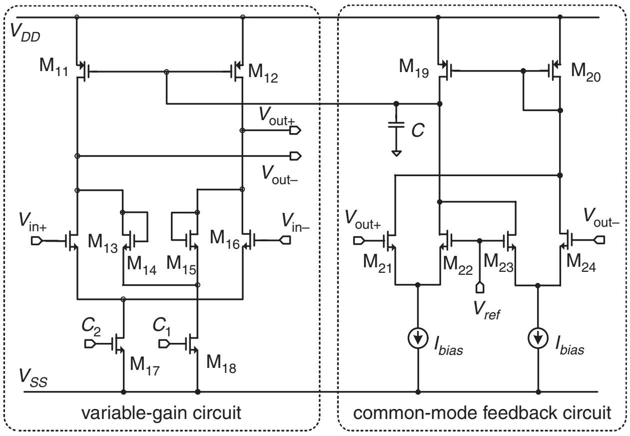

Fig. 3 *Schematic of one-stage VGA*

The one-stage VGA shown in Fig. 3 includes a source-coupled pair $M_{13,16}$ with diode-connected loads $M_{14,15}$ [1]. The two currents I_{C1} and I_{C2} in Fig. 2 are mirrored to transistors M_{18} and M_{17} in Fig. 3, respectively. As reported in [1], the gain of the variable gain circuit in Fig. 3 is given as

$$A_v = \frac{g_{m,M_{13,16}}}{g_{m,M_{14,15}}} = \sqrt{\frac{\mu_n C_{ox}(W/L)_{M_{13,16}} I_{C2}}{\mu_n C_{ox}(W/L)_{M_{14,15}} I_{C1}}} \tag{7}$$

where $g_{m,M_{13,16}}$ and $g_{m,M_{14,15}}$ are the transconductance of the corresponding transistors. By substituting (5) and (6) into (7), the gain of the one-stage VGA in Fig. 3 is given as

$$\begin{aligned} A_v &= M\frac{(1 + (I_{Ctrl}/I_{bias}) + (I_{Ctrl}^2/8I_0 I_{bias}))^{1/2}}{(1 - (I_{Ctrl}/I_{bias}) + (I_{Ctrl}^2/8I_0 I_{bias}))^{1/2}} \\ &= M\left(\frac{1 + ax + k(ax)^2/2}{1 - ax + k(ax)^2/2}\right)^{1/2} \end{aligned} \tag{8}$$

where $M = (W/L)_{M_{13,16}}/(W/L)_{M_{14,15}}$, $a = 1/I_{bias}$ and $k = 4I_0/I_{bias}$. Equation (8) is obviously the same form of expression as (3). In (8), by controlling the value of the bias current I_0 and/or I_{bias}, the value of k can be adjusted and the gain range of the VGA is thus controlled.

Measurement results: The two-stage VGA is fabricated in 0.18 µm CMOS technology with $V_{DD} = 1.8$ V, $V_{SS} = 0$ V and 3.7 mA of bias current. As previously discussed, by adjusting the bias current I_0 and/or I_{bias} in Fig. 2 such that the constant k in (8) is equal to 0.55, the two-stage VGA can theoretically provide 130 dB of gain range.

Fig. 4 shows the measured gain against I_{Ctrl}. In Fig. 4, the proposed VGA offers 90 dB gain range and 82 dB with linearity error of less than ± 1 dB. The measured 3 dB bandwidth is 50 MHz at a maximum gain of 36 dB and P1 dB varies from −40 to −17 dBm.

In Fig. 2, the proposed VGA is controlled by current I_{Ctrl}; however, it can also be controlled by voltage V_{Ctrl} by adopting the voltage-to-current converter before the control circuit shown in Fig. 2.

Conclusions: A wide dynamic range VGA based on a new approximated exponential equation has been presented. The wide gain range characteristic reduces the number of required VGAs, which leads to lower power consumption and smaller chip size. The proposed VGA can be used in many low-power applications, such as medical equipment, telecommunications systems, hearing aids, disc drives, etc.

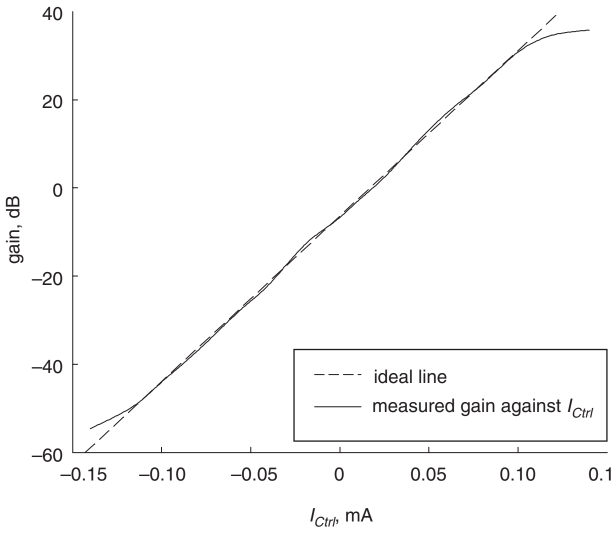

Fig. 4 *Measured gain against I_{Ctrl} of the two-stage VGA*

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