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Linear Bipolar OTAs Employing Multi-tanh Doublet and Exponential-law Circuits

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Abstract: In this paper, new linearization technique for bipolar OTAs using exponential-law circuits is described. The core circuit of the proposed OTAs is the multi-TANH doublet. The OTAs have adaptively biasing current sources, which consists of the exponential-law circuits. Three types of the OTAs are presented. The linear input voltage ranges of the OTAs are almost the same as the multi-TANH triplet. Further, the OTAs have lower power dissipation than the multi-TANH triplet.

1. Introduction

An operational transconductance amplifier (OTA) is a useful function block for analog signal processing and thus is employed in various analog circuits, such as continuous-time filters, multipliers and oscillators.

The simplest bipolar OTA is an emitter-coupled pair. This circuit can operate from 1V supply voltage. The output current is expressed as hyperbolic tangent of the differential input voltage. Therefore, the linear input voltage range is quite narrow.

Multi-tail cells[1, 2] and multi hyperbolic tangent (multi-TANH) cells (doublet, triplet,... etc)[3] are well-known linearization technique for bipolar OTAs. The transconductance of the linearized OTA is lower than that of the emitter-coupled pair. This implies that linearization is attained by victimizing power dissipation.

The authors have already proposed linear OTAs composed of an emitter-coupled pair and exponential-law circuits[4]. Although the linear input voltage range is as wide as that of the multi-TANH doublet, the power dissipation is lower.

This paper proposes new linear OTAs, whose linear input voltage ranges are wider than that of the conventional OTA and as wide as that of the multi-TANH triplet.

2. Exponential-Law Circuit and Conventional OTAs

Figure 1 shows an exponential-law circuit[4, 5]. The output current of this circuit is given by

$$I_{o+} = I_{CC} \cdot e^{|x|} \qquad (v_{in} > 0) \tag{1}$$

$$I_{o-} = I_{CC} \cdot e^{-|x|} \qquad (v_{in} < 0) \tag{2}$$

$$x = \frac{v_{in}}{V_T} = \frac{v_1 - v_2}{V_T}. \tag{3}$$

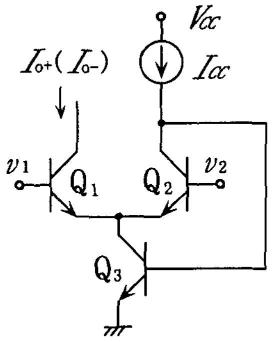

Figure 1: Exponential-law circuit.

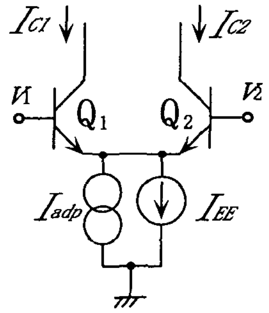

Figure 2: Conventional Linear OTA using an adaptively biasing current source.

The exponential-law circuit is a building block of a hyperbolic sine (SINH) circuit and a hyperbolic cosine (COSH) circuit. Combining the hyperbolic circuits with an emitter-coupled pair, we have obtained two linear OTAs[4]. One is realized employing the SINH circuit. The output terminals of the emitter-coupled pair and the SINH circuit are connected in parallel. The other OTA is realized employing the COSH circuit, which is used as an adaptively biasing current source. The frequency response of the latter is superior, because the frequency characteristic of the COSH circuit hardly affects the frequency response of the OTA core circuit[5]. The basic configuration of the OTA using an adaptively biasing circuit is shown in Figure 2. The COSH circuit for the biasing circuit is shown in Figure 3. The

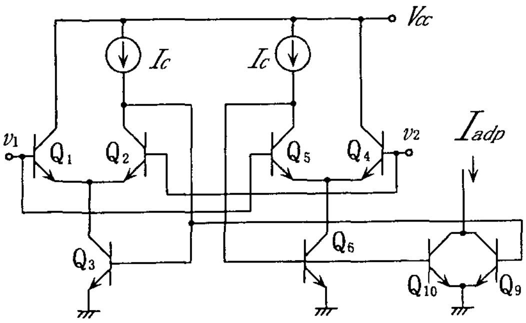

Figure 3: Hyperbolic cosine circuit.

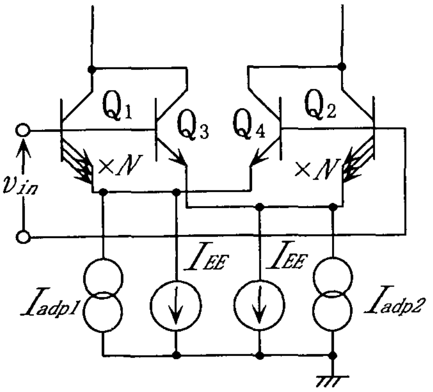

Figure 4: Proposed Linear OTA using the multi-TANH doublet and an adaptively biasing current source.

adaptively biasing current I_{adp} is given by

$$I_{adp} = 2I_C(1 + \cosh x) \tag{4}$$

where x is given by Eq.(3).

3. Proposed OTAs

3.1 Basic Configuration

The proposed linear OTAs are realized by the development of the linearization technique using the adaptively biasing current sources. The OTA core circuit is the multi-TANH doublet, and the adaptively biasing current is realized using the exponential-law circuits. The basic configuration is shown in Figure 4. The output current of this circuit is given by

$$\begin{aligned} I_{out} &= (I_{EE} + I_{adp1})\left(\frac{N \cdot e^x - 1}{N \cdot e^x + 1}\right) \\ &\quad +(I_{EE} + I_{adp2})\left(\frac{e^x - N}{e^x + N}\right) \end{aligned} \tag{5}$$

where N is the ratio of the emitter area of the multi-TANH doublet.

3.2 Circuit Realization

Three combinations of realization for the adaptively biasing circuits are presented. The circuit configurations of the OTAs are shown in Figures 5–7. The current I_C is the biasing current of the exponential-law circuits in the OTAs. The current MI_C corresponds to I_{EE} in Figure 4, and then, we have

$$I_{EE} = MI_C. \tag{6}$$

In the first OTA shown in Figure 5, the COSH circuit is employed as the adaptively biasing current source. We call this 'OTA1'. An exponential-law circuit is composed of Q_5, Q_6 and Q_{14}. The transistors Q_9 and Q_{11} copy the current flowing through Q_{14}. The other exponential-law circuit is composed of Q_7, Q_8 and Q_{15}. The transistors Q_{10} and Q_{12} copy the collector current of Q_{15}. The sum of the collector currents of Q_9 and Q_{10} and that of Q_{11} and Q_{12} correspond to the currents I_{adp1} and I_{adp2} in Figure 4, respectively. These are given by

$$I_{adp1} = I_{adp2} = I_{adp} = 2I_C(1 + \cosh x) \tag{7}$$

where x is given by Eq.(3). From Eqs.(5), (6) and (7), we obtain the output current of OTA1 that is given by

$$I_{out1} = I_C(2 + M + 2\cosh x)\left(\frac{N \cdot e^x - 1}{N \cdot e^x + 1} + \frac{e^x - N}{e^x + N}\right). \tag{8}$$

The second OTA shown in Figure 6, which we call 'OTA2', is obtained removing Q_{10} and Q_{11} from OTA1. The biasing circuit is not expressed as the hyperbolic cosine function, and thus we have

$$\begin{aligned} I_{adp1} &= I_C + e^x && (9) \\ I_{adp2} &= I_C + e^{-x}. && (10) \end{aligned}$$

The output current of OTA2 is given by

$$\begin{aligned} I_{out2} &= I_c\left(1 + M + e^x\right)\left(\frac{N \cdot e^x - 1}{N \cdot e^x + 1}\right) \\ &\quad + I_c\left(1 + M + e^{-x}\right)\left(\frac{e^x - N}{e^x + N}\right). \end{aligned} \tag{11}$$

The third OTA shown in Figure 7, which we call 'OTA3', is obtained removing Q_9 and Q_{12} from OTA1. Then, we have

$$\begin{aligned} I_{adp1} &= I_C + e^{-x} && (12) \\ I_{adp2} &= I_C + e^x. && (13) \end{aligned}$$

The output current of OTA3 is given by

$$\begin{aligned} I_{out3} &= I_c\left(1 + M + e^{-x}\right)\left(\frac{N \cdot e^x - 1}{N \cdot e^x + 1}\right) \\ &\quad + I_c\left(1 + M + e^x\right)\left(\frac{e^x - N}{e^x + N}\right). \end{aligned} \tag{14}$$

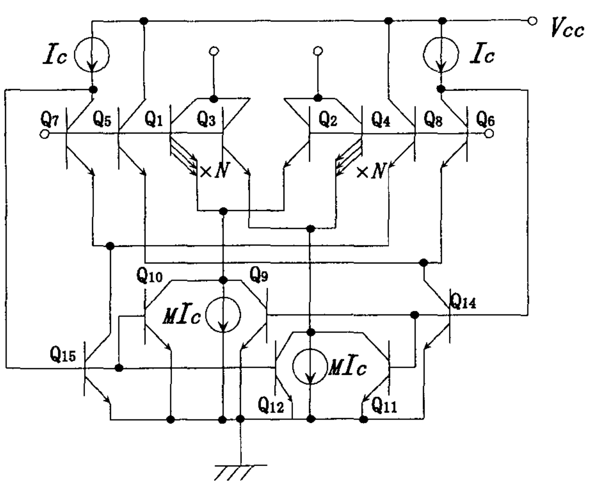

Figure 5: Proposed linear OTA (OTA1).

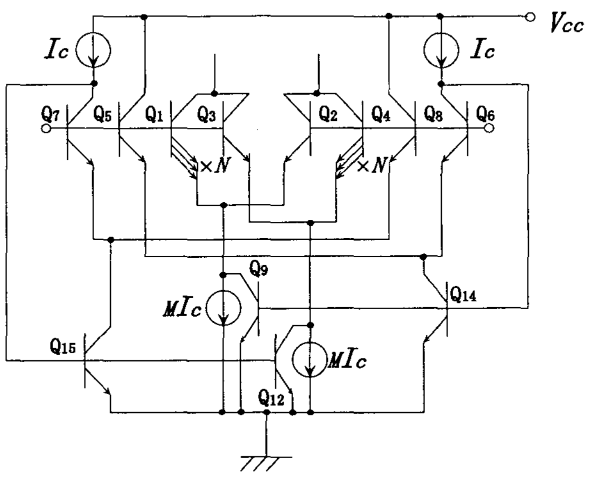

Figure 6: Proposed linear OTA (OTA2).

4. Linearization

The values of the parameters are obtained from maximally flat approximation[3]. If the number of the parameter variables in the function of the output current is n, the solutions, namely, the right values of the parameters are obtained by solving

$$\left.\frac{d^3 I_{out}}{dV_{in}^3}\right|_{V_{in}=0} = \cdots = \left.\frac{d^{(2n+1)} I_{out}}{dV_{in}^{(2n+1)}}\right|_{V_{in}=0} = 0. \qquad (15)$$

The proposed OTA has two parameters, which are the ratio of the emitter area N in the asymmetry emitter-coupled pairs and the current ratio of the DC biasing current, M. Thus, the third and the fifth derivatives can be zero. Solving the simultaneous equations, we obtain the solutions for the maximally flat transconductance, which are listed in Table 1.

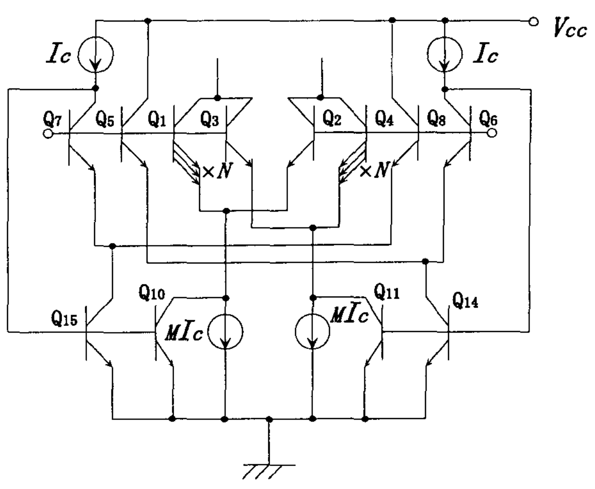

Figure 7: Proposed linear OTA (OTA3).

Table 1: Solutions for the maximally flat transconductance.

	OTA1	OTA2	OTA3
M	26	$\frac{26-\sqrt{5}}{2}$	$\frac{26+\sqrt{5}}{2}$
N	$\frac{3+\sqrt{5}}{2}$	$\frac{3+\sqrt{5}}{2}$	$\frac{3+\sqrt{5}}{2}$

5. Transconductance and Power Dissipation

5.1 Normalized Transconductance

The transconductances of the proposed OTAs are compared with those of the conventional OTAs, which are the emitter-coupled pair, the multi-TANH doublet and the multi-TANH triplet. The normalized transconductance characteristic is defined as the ratio of the transconductance to the transconductance for $V_{in} = 0$ $(G_m(0))$. The calculated results of the normalized transconductance characteristics are illustrated in Figure 8. It should be noted that the theoretical normalized transconductances of the proposed OTAs are equal. It is observed in the figure that the linear input range of the proposed OTA is almost the same as that of the multi-TANH triplet.

Simulation results obtained using PSpice are shown in Figure 9. The parameters used in the simulation determine details of the transistor characteristics exposed in the actual standard bipolar process[6]. The supply voltage is 1.5V. The transconductances of the OTAs are set to $G_m(0) = 2\pi \times 10^{-4}$[S] (628$\mu$S). It is found that the linearity of OTA3 is superior.

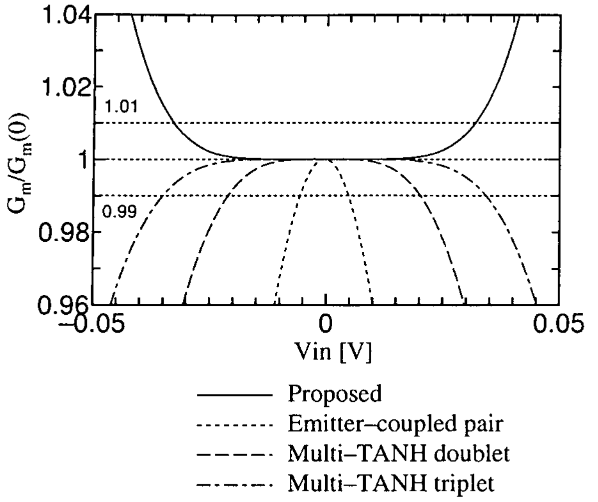

Figure 8: Normalized transconductance characteristics.

Table 2: Ratio of the power dissipation.

OTA	Theoretical	Simulation
multi-TANH triplet	1.000	1.000
Proposed (OTA1)	0.7273	0.7346
Proposed (OTA2)	0.7219	0.7299
Proposed (OTA3)	0.8235	0.8326

5.2 Power Dissipation

The power dissipation of the proposed OTA is compared to that of the multi-TANH triplet under the condition of the same transconductance. Because the supply voltages can be equal, the ratio of the current consumption is regarded as the power ratio. The ratios of the power dissipation are listed in Table 2. In the table, 'Simulation' denotes the power ratio obtained from DC analysis of PSpice simulation. It should be noted that the power dissipated in the proposed OTAs is lower than that in the multi-TANH triplet.

6. Conclusion

New linear OTAs using the exponential-law circuits and the multi-TANH doublet have been proposed. The proposed OTAs are based on adaptively biasing technique. Three types of the circuit design have been presented. The linear input voltage ranges of the OTAs are as wide as that of the multi-TANH triplet. However, the power dissipation of the proposed OTAs is lower than that of the multi-TANH triplet. It is found from the simulation results that the third OTA, namely OTA3, is superior as to linearity. To clarify the reason for this is a subject to be solved in future.

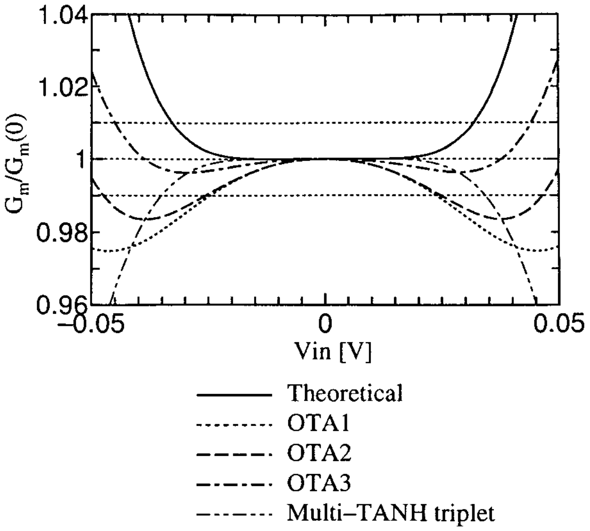

Figure 9: Simulation results and theoretical characteristics of normalized transconductances.

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