Linear Bipolar OTAs Employing Hyperbolic Function Circuits and Triple-Tail Cell

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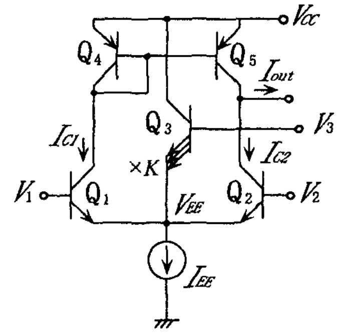
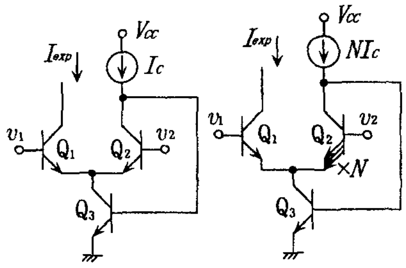


Fig. 1: Triple-tail cell.



(a) basic circuit (b) modified circuit

Fig. 2: Exponential-law circuit.

Abstract— This paper proposes design of new linear bipolar OTAs composed of an hyperbolic function circuit and a triple-tail cell. Two types of the OTAs are presented; one employs a hyperbolic sine circuit and the other contains a hyperbolic cosine circuit. The linear input voltage ranges of the proposed OTAs are wider than that of the conventional triple-tail cell, though the power dissipation is smaller. The results of SPICE simulation show that satisfactory characteristics are obtained.

Keywords— **Operational transconductance amplifiers (OTAs), Linear circuits, Low-voltage circuits, Analog integrated circuits**

I 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.

Relatively high transconductance in bipolar devices contributes to economy of power dissipation on analog integrated circuits. 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 technique[1][2] and multi hyperbolic tangent (multi-TANH) technique[3][4] 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 increase of power dissipation.

The authors have already proposed linear OTAs employing hyperbolic function circuits[5]-[8]. In the design, the core circuits, which are combined with the hyperbolic function circuit, are an emitter-coupled pair and the multi-TANH circuits. This paper proposes new linear OTAs composed of the triple-tail cell and the hyperbolic function circuits.

II Design of linear OTAs

The proposed linear OTAs are designed employing the hyperbolic function circuits and the triple-tail cell[2], which is shown in Fig. 1. The output current of the triple-tail cell is given by

$$I_{out} = I_{C1} - I_{C2} = \frac{2I_{EE}\sinh x}{2\cosh x + K}, \tag{1}$$

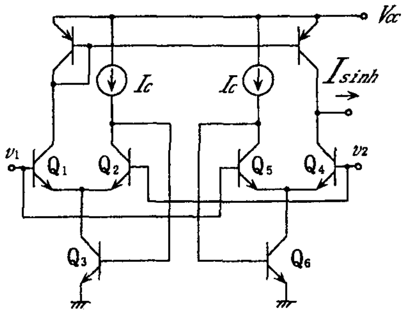
where

$$x = \frac{v_{in}}{2V_T} = \frac{v_1 - v_2}{2V_T}. \tag{2}$$

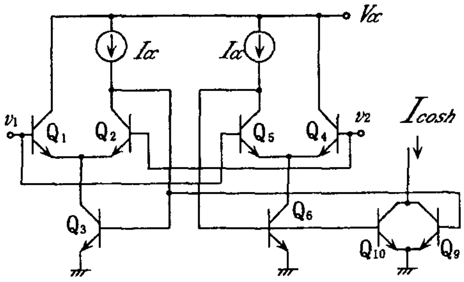
The output current of an exponential-law circuit, which is shown in Fig. 2 (a), is given by

$$I_{exp} = I_C e^x, \tag{3}$$

where x is given by Eq. (2). The hyperbolic function circuits are realized using the exponential-law circuit. Figure 3 (a) and (b) show the hyperbolic sine (SINH) and the hyperbolic cosine (COSH) circuits, respectively. The output current of the SINH and the COSH circuits,



(a) SINH circuit



(b) COSH circuit

Fig. 3: Hyperbolic function circuits.

I_{sinh} and I_{cosh}, are respectively given by

$$\begin{aligned} I_{sinh} &= I_C(e^x - e^{-x}) = 2I_C \sinh x, & (4) \\ I_{cosh} &= I_C(2 + e^x + e^{-x}) = 2I_C(1 + \cosh x). & (5) \end{aligned}$$

The proposed linear OTAs are shown in Fig. 4. The OTA shown in Fig. 4 (a) is composed of the triple-tail cell and the SINH circuit. Here, we call this OTA1. The output current of OTA1 is given by

$$I_{out1} = \frac{LI_C(e^x - e^{-x})}{e^x + e^{-x} + K} + I_C(e^{2x} - e^{-2x}). \qquad (6)$$

Solving the simultaneous equations derived from maximally flat approximation[3], we obtain solutions given by

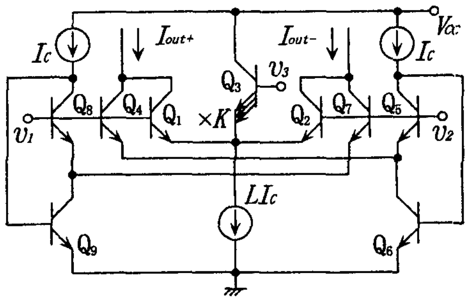
$$K = -3 + \sqrt{41}, \quad L = 212 + 28\sqrt{41}. \qquad (7)$$

The OTA Fig. 4 (b) employs the COSH circuit. The output current is given by

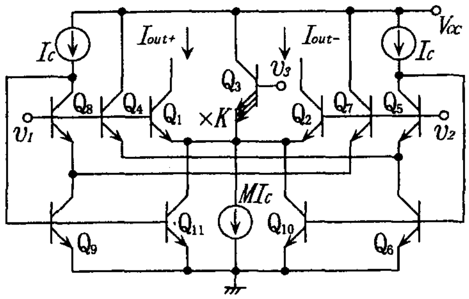
$$I_{out2} = \frac{I_2(M + 2 + e^{2x} - e^{-2x})(e^x - e^{-x})}{e^x + e^{-x} + K}. \qquad (8)$$

The solutions for the maximally flat transconductance are given by

$$K = \frac{32}{9}, \quad M = 296. \qquad (9)$$



(a) OTA employing SINH circuit (OTA1)



(b) OTA employing COSH circuit (OTA2)

Fig. 4: Proposed linear OTAs.

III Transconductance and power dissipation

The transconductance of OTA1, G_{m1}, is given by

$$G_{m1} = \frac{LI_C}{2V_T}\left[\frac{K(e^x + e^{-x}) + 4}{(e^x + e^{-x} + K)^2} + \frac{2}{L}(e^{2x} + e^{-2x})\right]. \qquad (10)$$

Around $v_{in} = 0$, we have

$$G_{m1}(0) = \frac{I_C}{V_T}\left(\frac{L}{K+2} + 2\right). \qquad (11)$$

The transconductance of OTA2, G_{m2}, is given by

$$\begin{aligned} G_{m2} &= \frac{I_C}{2V_T(e^x + e^{-x} + K)^2}\left[2(e^{4x} + e^{-4x})\right. \\ &+ 3K(e^{3x} + e^{-3x}) + 4(e^{2x} + e^{-2x}) \\ &+ \left. K(M+1)(e^x + e^{-x}) + 4(M+1)\right]. \qquad (12) \end{aligned}$$

Around $v_{in} = 0$, we have

$$G_{m2}(0) = \frac{I_C}{V_T} \cdot \left(\frac{M+4}{K+2}\right). \qquad (13)$$

The normalized transconductance characteristic is defined as the ratio of the transconductance to that for $V_{in} = 0$, $G_m(0)$. Here, the linear range is determined as the maximum input voltage where the error of the

Table 1: Linear input range and power ratio

	Linear range	Power ratio
conventional	41 [mV]	1
OTA1	56 [mV]	0.885
OTA2	54 [mV]	0.938

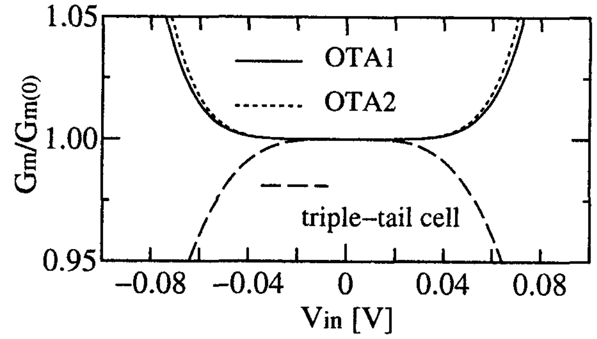


Fig. 5: Normalized transconductance characteristics.

normalized transconductance is within 1%. The theoretical normalized transconductance characteristics are illustrated in Fig. 5. It is seen in this figure that the maximum linear input voltages of the proposed OTAs are wider than that of the conventional triple-tail cell. The linear input voltage range and the power ratio of the conventional and the proposed OTAs for the same transconductance[9] are listed in Table 1.

The values of L and M are about 391 and 296 from Eqs. (7) and (9). It is difficult to realize current sources to give large current ratios, such as $LI_C : I_C = 391 : 1$. In order to alleviate this problem, we use the exponential-law circuit shown in Fig. 2 (b). The output signal currents of the exponential-law circuits shown in Fig. 2 are the same. Thus, we can make N large without changing the signal current.

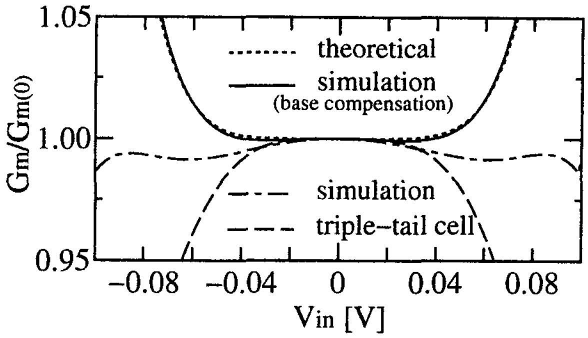
Employing the circuit in OTA1, the ratio of the bias currents of the triple-tail cell and the exponential-law circuit becomes $L : N$. Table 2 lists the power ratio and the bias current ratio for several values of N. The bias current ratio of OTA2 is given by

$$M - 2(N-1) : N. \qquad (14)$$

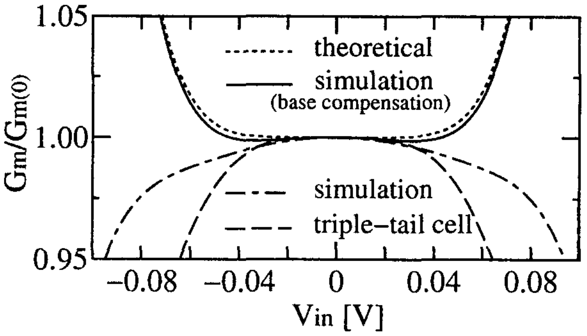
It should be noted that the power dissipation of OTA1 is lower than that of the triple-tail cell and the bias current ratio is reduced to about 20 : 1 even $N = 20$.

IV SPICE simulation

In simulation, the transconductances of the OTAs are set to $2\pi \times 10^{-4}$[S] (628μS), and the supply voltage is 2V. The theoretical normalized transconductance and SPICE simulation results are illustrated in Fig. 6. The base current of Q_3 in the exponential-law circuit makes



(a) OTA1



(b) OTA2

Fig. 6: Simulation results of normalized transconductance of the proposed OTAs.

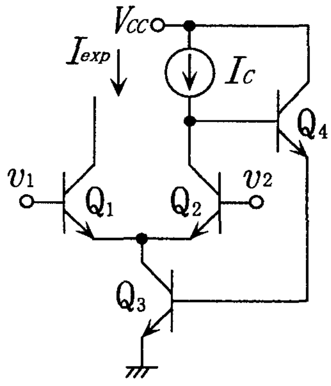


Fig. 7: Exponential-law circuit with base compensation.

Table 2: Power ratios and current ratios

N	Power ratio	Current ratio
OTA1		
1	0.855	391.29
5	0.903	78.26
10	0.926	39.13
20	0.970	19.56
30	1.015	13.04
OTA2		
1	0.938	296
5	0.963	57.6
10	0.994	27.8
20	1.055	12.9
30	1.117	7.93

the simulation result quite different from the theoretical characteristic. Note that base current compensation performed by Q_4 shown in Fig. 7 improves the transfer characteristics of the proposed OTAs.

The normalized transconductances for various N are illustrated in Fig. 8. It should be noted that the transconductance characteristics are hardly deteriorated by large N.

V Conclusion

New linear OTAs composed of the hyperbolic function circuit and the triple-tail cell are proposed. The linear input voltage range of the OTA is wider than that of the triple-tail cell. However, the power dissipation of the proposed OTA can be lower than that of the triple-tail cell. Further, impossibly large ratio of the bias currents can be improved without degrading the transfer characteristics.

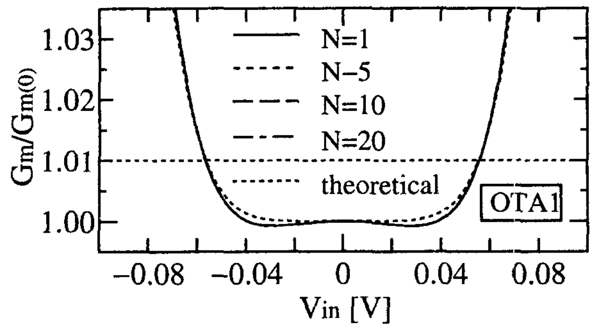
References

[1] J.O. Voorman, "Transconductance amplifier," US Patent 4,723,110,Feb. 2, 1988.

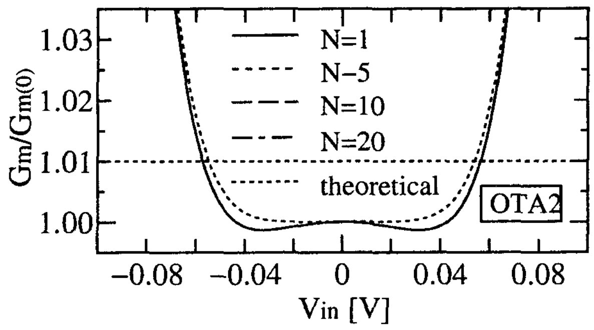
[2] K. Kimura, "Circuit design techniques for very low-voltage analog functional blocks using triple-tail cells," IEEE Trans. Circuits and Syst.- I, vol.42, no.11, pp.873-885, Nov. 1995.

[3] H. Tanimoto, M. Koyama and Y. Yoshida, "Realization of a 1-V active filter using a linearization technique employing plurality of emitter-coupled pairs," IEEE J. Solid-State Circuits, vol.26, pp.937-945, July 1991.

[4] B. Gilbert, "The Multi-tanh Principle : A Tutrial Overview," IEEE J. Solid-State Circuits, vol.33, no.1, pp.2-17, 1998.



(a) OTA1



(b) OTA2

Fig. 8: Normalized transconductance of the proposed OTAs with N-area hyperbolic function circuits.

[5] F. Matsumoto and Y. Noguchi, "Linearization Technique for Bipolar OTAs Employing Exponential-law Circuits," Proc. of ITC-CSCC '99, pp.1064-1067, Jul. 1999.

[6] F. Matsumoto, I. Yamaguchi and Y. Noguchi, "Linear bipolar OTAs employing multi-tanh doublet and exponential-law circuits," Proc.of ITC-CSCC'00, pp.579-582, July, 2000.

[7] H. Wasaki, F. Matsumoto, Y. Noguchi," Linear Bipolar OTAs Employing Multi-tanh Triplet and Hyperbolic Function Circuits," Proc. of 2001 IEEJ International Analog VLSI Workshop, pp.45-50, May 2001.

[8] F. Matsumoto, H. Wasaki and Y. Noguchi, "Linear Bipolar OTAs Employing Hyperbolic Circuits with an Intermediate Voltage Terminal," Proc. of ITC-CSCC 2001, pp.208-211, Jul. 2001.

[9] F. Matsumoto and Y. Noguchi,"A low-voltage linear OTA employing a triple-tail cell and an active voltage divider," T. IEE Japan, vol.120-C, no.10, pp.1312-1318, Oct. 2000 (in Japanese).