Paper

Low-Voltage Linear OTAs Employing Multi-TANH Doublet and Exponential-Law Circuits

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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. Two kinds of the OTAs have been designed. One has parallel configuration and the other is adaptively biasing configuration. The core circuit is combined with the SINH circuit for the parallel configuration or the COSH circuit as an adaptively biasing current source. In addition, two other designs of linear OTAs are proposed, and thus altogether four new linear OTAs are presented. Although these designs of the proposed OTAs are different, the theoretical normalized transconductances of the OTAs are expressed as the same function. The performance of the OTAs is compared with that of the multi-TANH circuits, which are known as conventional linear bipolar OTAs. The linear input voltage ranges of the OTAs are wider than that of the multi-TANH doublet and almost the same as that of the multi-TANH triplet. Furthermore, the power dissipated in the proposed OTAs is lower than that in the multi-TANH doublet and triplet. SPICE simulation shows that each OTA has different advantages.

Keywords: analog integrated circuits, transconductors, OTAs, low-voltage analog circuits, linearization, linear circuits

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, whose transconductance is tunable. Tunability is important in order to adjust cut-off frequencies of continuous-time filters, oscillation frequencies of oscillators and so on. The emitter-coupled pair is suited for low-voltage application and can operate from 1V supply voltage. However, the output current is expressed as hyperbolic tangent of the differential input voltage, so that the linear input voltage range is quite narrow.

Multi-tail cells [(1)(2)] and multi hyperbolic tangent (multi-TANH) cells (doublet, triplet,... etc) [(3)(4)] are known as linearized tunable bipolar OTAs. These circuits are also suited for low-voltage application because their configuration is multiple connection based on the emitter-coupled pair. The transconductances of these linear OTAs are 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 linearization technique using exponential-law circuits [(5)(6)], which is shown in Fig. 1. The core circuit of the proposed OTAs is an emitter-coupled pair. The hyperbolic sine (SINH) and the hyperbolic cosine (COSH) circuits, which are composed of two exponential-law circuits, are combined with the emitter-coupled pair. Although the linear input voltage range of the OTAs is as wide as that of the multi-TANH doublet, the power dissipation is reduced.

In this paper, new low-voltage linear OTAs employing the exponential-law circuits are presented. The core circuit of the proposed OTAs is the multi-TANH circuit with two coupled pairs (doublet), which is combined with the SINH circuit for the parallel configuration or the COSH circuit as an adaptively biasing current source. In addition, two other designs of linear OTAs are proposed, and thus altogether four new linear OTAs are presented. The linear input voltage ranges are wider than that of the OTAs composed of the exponential-law circuits and the emitter-coupled pair. Further, the linearity is superior to that of the multi-TANH doublet and almost the same as that of the multi-TANH triplet. The power dissipation of the proposed OTAs is lower than that in the multi-TANH doublet and triplet.

2. Basic Design of New Linear OTAs

The proposed OTAs are composed of the multi-TANH doublet as a core circuit and the exponential-law circuits. In this section, these circuits and the OTA design are described.

2.1 Multi-TANH doublet The core circuit of the proposed OTAs is the multi-TANH doublet shown in Fig. 2. The output current of this circuit is given by

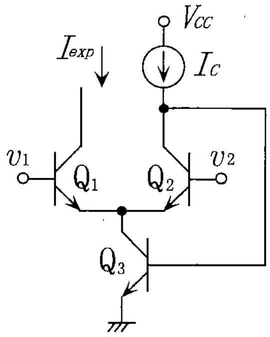


Fig. 1. Exponential-law circuit.

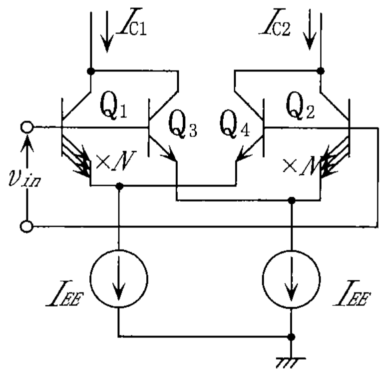


Fig. 2. Multi-TANH doublet.

$$I_{out} = I_{C1} - I_{C2} = I_{EE}\left(\frac{Ne^x - 1}{Ne^x + 1} + \frac{e^x - N}{e^x + N}\right). \quad (1)$$

where N is the emitter ratio of the asymmetry emitter-coupled pair and

$$x = \frac{v_{in}}{V_T} = \frac{v_1 - v_2}{V_T}. \quad \cdots\cdots\cdots\cdots (2)$$

Throughout this paper, variable x is given by this equation. Assuming that the base-emitter voltage of transistors is 0.7V and the collector-emitter saturation voltage is 0.2V, the minimum operating voltage is 1.1V. Giving the proper value to the parameter N, we obtain linear transfer characteristic (described in Sect. 4).

2.2 Exponential-Law Circuit and Hyperbolic Circuits The output current of the exponential-law circuit shown in Fig. 1 is given by

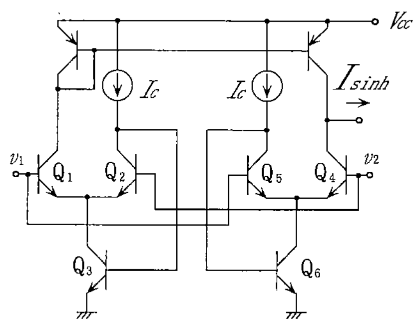
$$I_{exp} = I_C e^x. \quad \cdots\cdots\cdots\cdots (3)$$

A SINH circuit and a COSH circuit are composed of two exponential-law circuits. The hyperbolic circuits are shown in Fig. 3. The output currents of these circuits are respectively given by

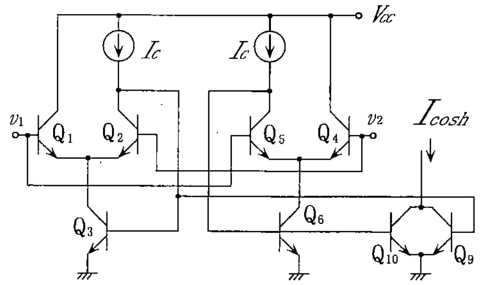
$$I_{sinh} = 2I_C \sinh x, \quad \cdots\cdots\cdots\cdots (4)$$

$$I_{cosh} = 2I_C(1 + \cosh x). \quad \cdots\cdots\cdots\cdots (5)$$

The minimum operating voltage of the exponential-law circuit is 0.9V [6]. Therefore, OTAs composed of the exponential-law circuits and the multi-TANH doublet is suitable for low-voltage application.



(a) SINH circuit



(b) COSH circuit

Fig. 3. Hyperbolic circuits.

3. Proposed Linear OTAs

Two kinds of OTAs are proposed. One is parallel configuration. The output terminals of the core circuit and the SINH circuit are connected in parallel. The other is adaptively biasing configuration. The exponential-law circuits are used as adaptively biasing current sources for the OTA core circuit.

In the following subsections, realization circuits of the proposed OTAs are presented. The output currents the transconductances of the OTAs are defined as

$$I_{out} = I_{out+} - I_{out-}, \quad \cdots\cdots\cdots\cdots (6)$$

$$G_m = \frac{dI_{out}}{dv_{in}}. \quad \cdots\cdots\cdots\cdots (7)$$

3.1 Parallel Configuration Figure 4 shows an OTA with parallel configuration [9]. We term this circuit 'OTA1'. The multi-TANH doublet as a core circuit is composed of Q_1–Q_4. The output terminals of the SINH circuit, which is composed of Q_5–Q_7 and Q_8–Q_{10}, are connected in parallel with the core circuit. The ratio of the tail current of the multi-TANH doublet and the operating current of the exponential-law circuit is expressed as M.

The output current of OTA1 is given by

$$I_{out1} = I_C(e^x - e^{-x}) + MI_C\left(\frac{Ne^x - 1}{Ne^x + 1} + \frac{e^x - N}{e^x + N}\right). \quad \cdots\cdots (8)$$

The transconductance is given by

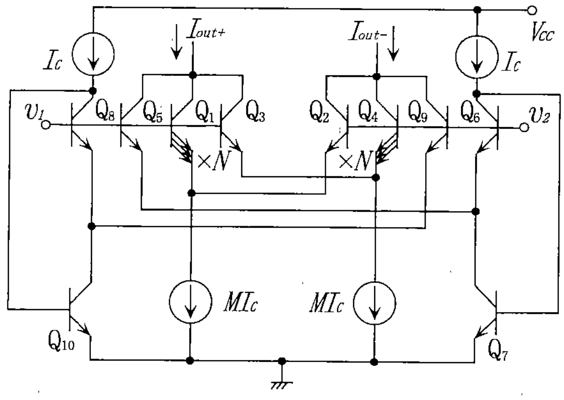


Fig. 4. Linear OTA with parallel configuration (OTA1).

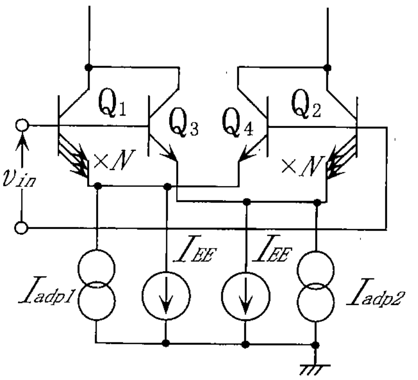


Fig. 5. Basic design of proposed linear OTA using the multi-TANH doublet and an adaptively biasing current source.

$$G_{m1} = \frac{I_C}{V_T}(e^x + e^{-x}) + \frac{2MNI_C e^x}{V_T}\left[\frac{1}{(Ne^x+1)^2} + \frac{1}{(e^x+N)^2}\right]. \quad (9)$$

3.2 Adaptively Biasing Configuration The basic configuration of the OTA composed of the multi-TANH doublet and adaptively biasing circuits is shown in Fig. 5 [10]. The output current of this circuit is given by

$$I_{out} = (I_{EE} + I_{adp1})\left(\frac{Ne^x - 1}{Ne^x + 1}\right) + (I_{EE} + I_{adp2})\left(\frac{e^x - N}{e^x + N}\right). \quad \cdots\cdots\cdots (10)$$

The adaptively biasing currents I_{adp1} and I_{adp2} are realized using the exponential-law circuits. Three combinations for this configuration are possible and thus three linear OTAs are designed. The tail current I_{EE} is given by MI_C in the following OTAs.

3.2.1 OTA using COSH biasing circuit In the OTA shown in Fig. 6, which is termed 'OTA2' hereafter, an exponential-law circuit is composed of Q_5–Q_7. The transistors Q_{11} and Q_{13} copy the current flowing through Q_7. Another exponential-law circuit is composed of Q_8–Q_{10}. The transistors Q_{12} and Q_{14} copy

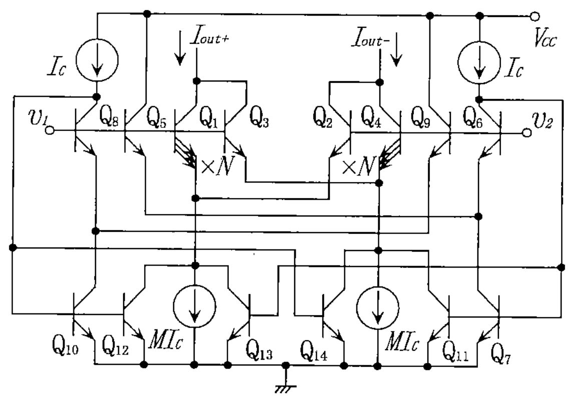


Fig. 6. Linear OTA employing COSH circuit as an adaptively biasing circuit (OTA2).

the collector current of Q_{10}. The sum of the collector currents of Q_{11} and Q_{14} and that of Q_{12} and Q_{13} correspond to the currents I_{adp1} and I_{adp2} in Fig. 5, respectively. These are given by

$$I_{adp1} = I_{adp2} = I_C(1+e^x) + I_C(1+e^{-x}) = 2I_C(1+\cosh x). \quad \cdots\cdots\cdots (11)$$

As is seen in this equation, the adaptively biasing circuit of OTA2 is the COSH circuit. From Eqs.(10) and (11), we obtain the output current of OTA2 that is given by

$$I_{out2} = I_C(2+M+2\cosh x)\left(\frac{Ne^x-1}{Ne^x+1} + \frac{e^x-N}{e^x+N}\right). \quad (12)$$

The transconductance is given by

$$G_{m2} = \frac{I_C}{V_T}(e^x - e^{-x})\left(\frac{Ne^x-1}{Ne^x+1} + \frac{e^x-N}{e^x+N}\right) + \frac{2NI_C e^x(2+M+e^x+e^{-x})}{V_T} \times \left[\frac{1}{(Ne^x+1)^2} + \frac{1}{(e^x+N)^2}\right]. \quad \cdots\cdots (13)$$

3.2.2 OTA using exponential biasing circuits The OTA shown in Fig. 7, which is termed 'OTA3', is obtained removing Q_{11} and Q_{12} from OTA2. The biasing circuit is not expressed as the COSH function but exponential function, and thus we have

$$I_{adp1} = I_C(1+e^x), \quad \cdots\cdots\cdots (14)$$

$$I_{adp2} = I_C(1+e^{-x}). \quad \cdots\cdots\cdots (15)$$

The output current of OTA2 is given by

$$I_{out3} = I_C(1+M+e^x)\left(\frac{Ne^x-1}{Ne^x+1}\right) + I_C(1+M+e^{-x})\left(\frac{e^x-N}{e^x+N}\right). \quad \cdots (16)$$

The transconductance is given by

$$G_{m3} = \frac{I_C}{V_T}\left[e^x\left(\frac{Ne^x-1}{Ne^x+1}\right) + \frac{2Ne^x(1+M+e^x)}{(Ne^x+1)^2} - e^{-x}\left(\frac{e^x-N}{e^x+N}\right) + \frac{2Ne^x(1+M+e^{-x})}{(e^x+N)^2}\right]. \quad \cdots\cdots\cdots (17)$$

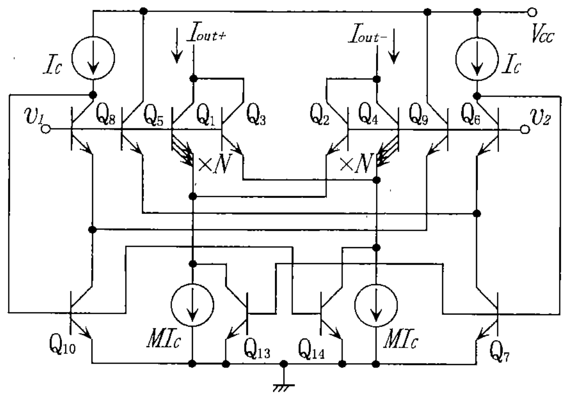


Fig. 7. Linear OTA employing single-exponential adaptively biasing circuits (OTA3).

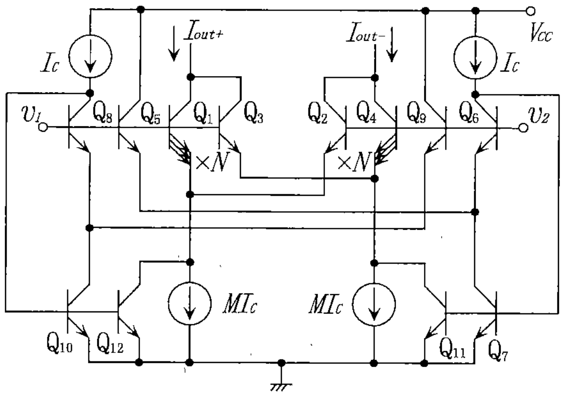


Fig. 8. Linear OTA single-exponential adaptively biasing circuits (OTA4). the biasing circuits are connected reversely against OTA3.

The OTA shown in Fig. 8, which is termed 'OTA4', is obtained removing Q_{13} and Q_{14} from OTA2. The exponential biasing circuits are connected reversely against OTA3. Then, we have

$$I_{adp1} = I_C(1 + e^{-x}), \quad \cdots\cdots (18)$$
$$I_{adp2} = I_C(1 + e^{x}). \quad \cdots\cdots (19)$$

The output current of OTA4 is given by

$$I_{out4} = I_C\left(1 + M + e^{-x}\right)\left(\frac{Ne^x - 1}{Ne^x + 1}\right) + I_C(1 + M + e^x)\left(\frac{e^x - N}{e^x + N}\right). \quad \cdots\cdots (20)$$

The transconductance is given by

$$G_{m4} = \frac{I_C}{V_T}\left[e^x\left(\frac{e^x - N}{e^x + N}\right) + \frac{2Ne^x(1 + M + e^x)}{(e^x + N)^2} - e^{-x}\left(\frac{Ne^x - 1}{Ne^x + 1}\right) + \frac{2Ne^x(1 + M + e^{-x})}{(Ne^x + 1)^2}\right]. \quad \cdots\cdots (21)$$

4. Linearization

The values of the parameters are obtained from maximally flat approximation [4]. If the number of the parameter variables in the function of the output current is n, the proper values of the parameters for maximally flat transconductance are obtained by solving

$$\left.\frac{d^3 I_{out}}{dV_{in}^3}\right|_{V_{in}=0} = \cdots = \left.\frac{d^{(2n+1)} I_{out}}{dV_{in}^{(2n+1)}}\right|_{V_{in}=0} = 0, \quad (22)$$

because the output currents of OTAs in general are expressed as odd functions of the input voltage, V_{in}, theoretically.

The proposed OTA has two parameters, which are the current ratio of the DC biasing current, M, and the ratio of the emitter area N in the asymmetry emitter-coupled pairs. 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. It should be noted that the values of N are the same for all of the proposed OTAs.

Substituting the values in Table 1 into Eqs.(9), (13), (17) and (21), we have a remarkable property that the transconductances are expressed as

$$G_{m1} = \frac{I_C e^{2x}}{V_T} \frac{7 + 3\sqrt{5}}{\left(\frac{3+\sqrt{5}}{2} + e^x\right)^2\left(1 + \frac{3+\sqrt{5}}{2}e^x\right)^2} \times (\cosh 3x + 6\cosh 2x + 87\cosh x + 112) = G_{m3} = G_{m4} = \frac{G_{m2}}{2}. \quad \cdots\cdots (23)$$

It should be noticed that the transconductances of the proposed OTAs are expressed as the same function except that G_{m2} is twice as much as others. This means that the difference of the transconductances is only the coefficient and thus the theoretical normalized transconductance characteristics (described in 5.1) of the proposed OTAs are wholly identical.

Table 1. Solutions for the maximally flat transconductance.

	OTA1	OTA2	OTA3	OTA4
M	$\frac{25}{2}$	26	$\frac{26-\sqrt{5}}{2}$	$\frac{26+\sqrt{5}}{2}$
N	$\frac{3+\sqrt{5}}{2}$	$\frac{3+\sqrt{5}}{2}$	$\frac{3+\sqrt{5}}{2}$	$\frac{3+\sqrt{5}}{2}$

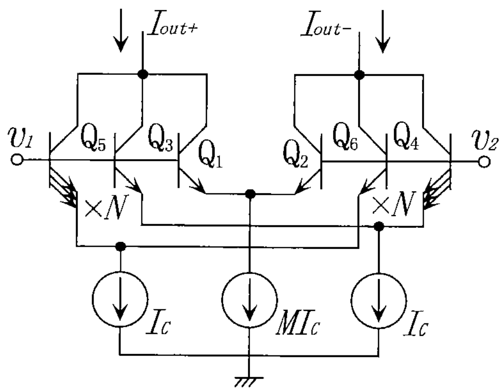


Fig. 9. Multi-TANH triplet.

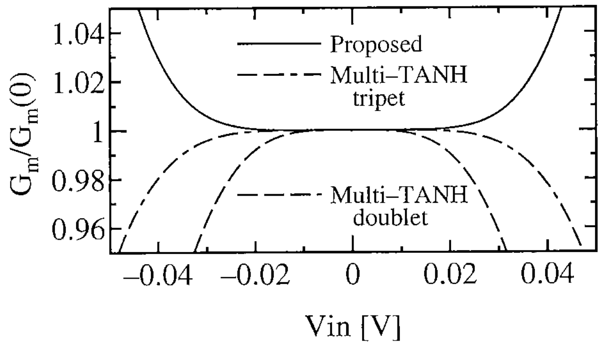


Fig. 10. Normalized transconductance characteristics.

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 multi-TANH doublet and triplet. The output current of the multi-TANH doublet is given by Eq.(1). The condition for the transconductance to be maximally flat characteristic is given by

$$N = 2 + \sqrt{3}. \quad \cdots\cdots (24)$$

The multi-TANH triplet is shown in Fig. 9. The output current is given by

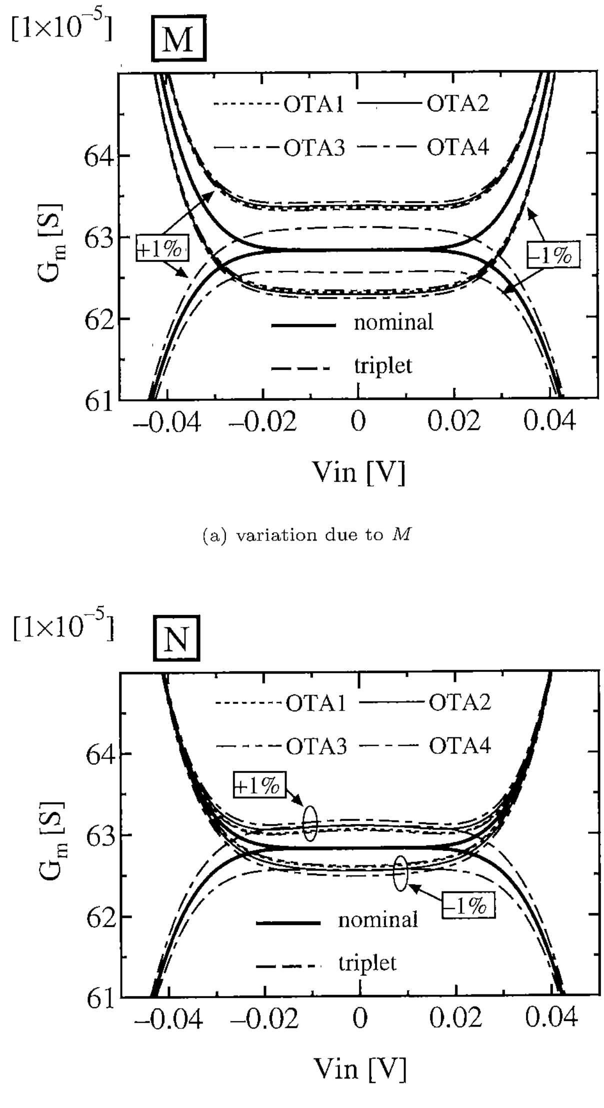
$$I_{out} = I_{EE}\left(\frac{Ne^x - 1}{Ne^x + 1} + \frac{e^x - N}{e^x + N} + M\frac{e^x - 1}{e^x + 1}\right). \quad (25)$$

The condition for the transconductance to be maximally flat characteristic is given by

$$M = \frac{16}{25}, \quad N = 4 + \sqrt{15}. \quad \cdots\cdots (26)$$

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 Fig. 10. The linear input voltage ranges of the OTAs are listed in Table 2, where the linear range is designated by V_{lin}. Here, the linear range is determined as the maximum input voltage where the error of the normalized transconductance is within 1%. It should be noted that the linear input range of the proposed OTA is wider than that of the multi-TANH doublet and almost the same as that of the multi-TANH triplet.

5.2 Sensitivity to Parameter Variation The parameters M and N probably deviate from the nominal values because of process variation. This causes the error of the transconductance. It is adequate to consider a parameter variation of ±1% because the relative accuracy of elements is high on integrated circuits. The transconductance sensitivity against parameter variations are illustrated in Fig. 11. It is found that the transconductance variations of the proposed OTAs due to the variation of M are larger than that of the multi-TANH triplet. The variation of M means the mismatch



(a) variation due to M

(b) variation due to N

Fig. 11. Transconductance sensitivity against parameter variation.

of bias currents. If the emitter-degeneration technique is employed in biasing current sources [7], however, the mismatch is considerably eliminated [4].

5.3 Power Dissipation The power dissipation of the proposed OTA is compared to that of the multi-TANH circuits under the condition of the same transconductance. Because the supply voltages can be equal, the ratio of the total current consumption is regarded as the power ratio.

The relationships between the operating current I_C and $G_m(0)$ of the proposed linear OTAs are given by

$$I_{C1} = I_{C3} = I_{C4} = 2I_{C2} = \frac{V_T G_m(0)}{12} \quad \cdots\cdots (27)$$

where I_{C1}–I_{C4} are the current I_C to obtain $G_m(0)$ in OTA1–OTA4. Assuming that the base currents of transistors are sufficiently smaller than the collector currents and thus can be neglected, the operating current of each exponential-law circuit is $2I_C$. The total operating current of OTA1, I_{all1} is given by

$$I_{all1} = 2(2+M)I_{C1} = \frac{29}{12}V_T G_m(0). \quad \cdots\cdots (28)$$

Similarly, the total operating currents of other OTAs are respectively given by

$$I_{all2} = 2(6+M)I_{C2} = \frac{8}{3}V_T G_m(0), \quad \cdots\cdots (29)$$

$$I_{all3} = 2(4+M)I_{C3} = \frac{34-\sqrt{5}}{12}V_T G_m(0), \quad \cdot (30)$$

$$I_{all4} = 2(4+M)I_{C4} = \frac{34+\sqrt{5}}{12}V_T G_m(0). \quad \cdot (31)$$

The relationships for the multi-TANH circuits are given by

$$I_{EE2} = \frac{3}{2}V_T G_m(0), \quad \cdots\cdots (32)$$

$$I_{EE3} = \frac{25}{18}V_T G_m(0) \quad \cdots\cdots (33)$$

where I_{EE2} and I_{EE3} are the current I_{EE} to obtain $G_m(0)$ in the multi-TANH doublet and triplet, respectively.

The ratios of the current consumption are listed in Table 2, where W_d and W_t denote the ratios of the total operating current to that of the multi-TANH doublet and that of the multi-TANH triplet, respectively. It should be noted that the power dissipated in the proposed OTAs is lower than that in the multi-TANH triplet. Moreover, The power of the OTAs except OTA4 is lower than the multi-TANH doublet.

Table 2. Linear input voltage range and ratio of total operating current of proposed and conventional OTAs

OTA	V_{lin} [mV]	W_d	W_t
OTA1	32	0.806	0.659
OTA2	32	0.889	0.727
OTA3	32	0.882	0.722
OTA4	32	1.007	0.824
doublet	20	1.000	0.818
triplet	34	1.222	1.000

6. Simulation

In order to confirm the validity of the proposed technique, SPICE simulation was carried out. The parameters used in the simulation determine details of the transistor characteristics exposed in the actual standard bipolar process [8]. 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).

The normalized transconductances of the OTAs are illustrated in Fig. 12. It is observed that OTA1 and OTA4 have wide linear input range, while the linearity of OTA2 and OTA3 becomes worse. The deterioration of the linearity seems to be caused by the error of the

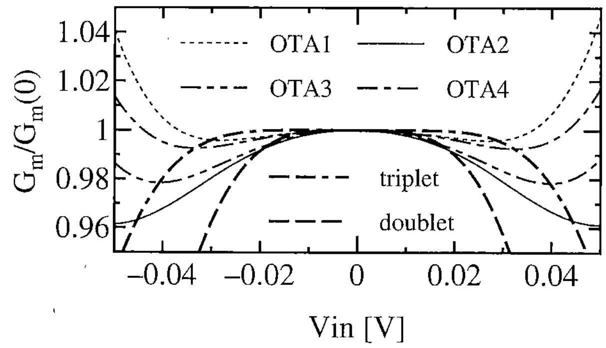


Fig. 12. Simulation results of normalized transconductances.

signal current transfer gain in the adaptively biasing circuits due to finite magnitude of the common-emitter current amplification factor, so-called β of transistors. However, it is found that OTA4 is hardly influenced such error.

If an OTA consumes lower current than another with equal linearity or if the linearity of an OTA is better than other OTAs with equal current consumption, it can be said that the OTA is superior.

The linearity of OTA2 and OTA3 is almost the same as the multi-TANH doublet. The total currents of OTA2 and OTA3 are about 89% and 88% of the multi-TANH doublet. Thus, these OTAs are superior to the multi-TANH doublet from the above-mentioned viewpoint. The linearity of OTA1 and OTA4 is almost the same as the multi-TANH triplet. The total currents of OTA1 and OTA4 are about 66% and 82% of the multi-TANH triplet. These OTAs are superior to not only the multi-TANH doublet but also the multi-TANH triplet.

Frequency responses of the OTAs are illustrated in Fig. 13. It is shown Fig. 13(a) that the transconductances of the OTAs are constant at less than 10MHz. We see that OTA2 has a good frequency characteristic. Observing the phase characteristics around 1MHz and higher, we see that OTA1 is the worst of the OTAs.

Characteristics of total harmonic distortion (THD) are illustrated in Fig. 14. The frequency of the input signal is 1MHz. It is seen that OTA3 and OTA4 have low THD for signals larger than 60mV, while the THD of the multi-TANH triplet is the lowest for smaller signals.

7. Conclusion

New linear OTAs using the multi-TANH doublet as a core circuit and the exponential-law circuits have been proposed. The multi-TANH doublet becomes a linear OTA in itself by having proper parameter value. However, it has been shown that the circuit can be an element of other linear OTAs.

Two kinds of the OTAs have been designed. One has parallel configuration, in which the core circuit and the SINH circuit are connected in parallel. The other is adaptively biasing configuration. In addition to the COSH circuit, two exponential biasing techniques have been proposed, and thus four OTAs have been obtained in all. Although the designs of four OTAs are differ-

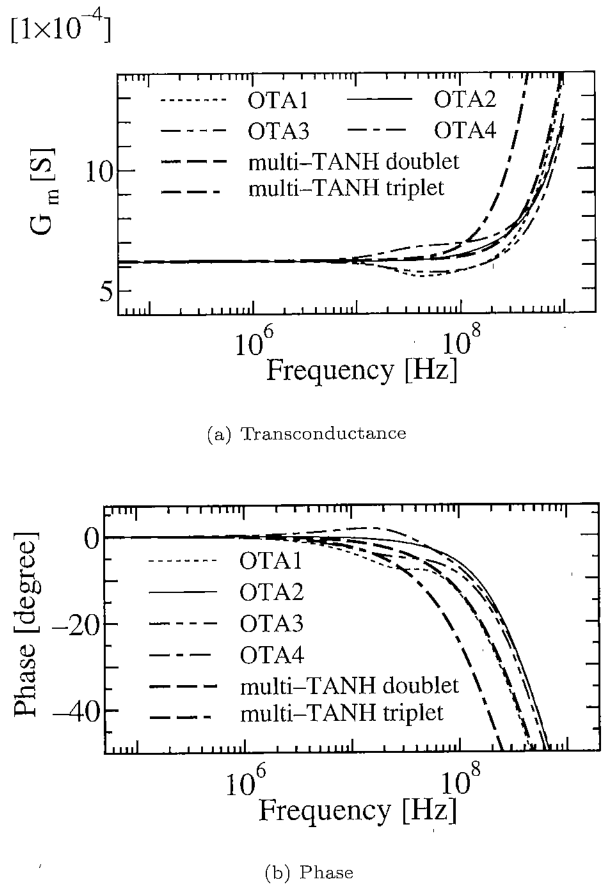


Fig. 13. Frequency responses of the linear OTAs.

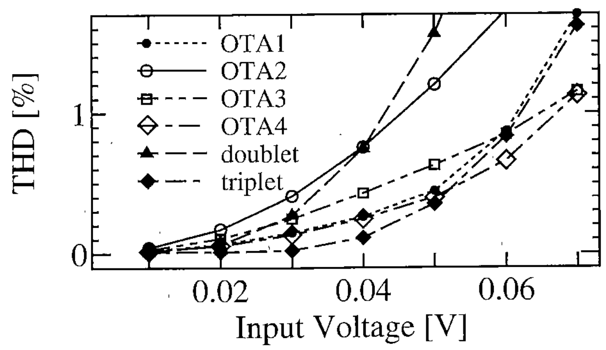


Fig. 14. THD of the OTAs.

ent, the theoretical normalized transconductances of the proposed OTAs are identical. The linear input voltage range of the proposed OTA is wider than that of the multi-TANH doublet and almost the same as that of the multi-TANH triplet. The proposed OTAs have lower power dissipation than the multi-TANH cells.

The SPICE simulation gives the following consequence on four proposed OTAs. The current consumption of OTA1 is the lowest and its linearity is also superior. The high-frequency characteristic of OTA2 is advantaged. Although OTA4 dissipates power, its linearity is the best.

To clarify the reason why there are differences of performance among the OTAs is a subject to be solved in future. Further investigation is also required to expand the linearization technique.

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