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A New Linear Low-gm OTA with DC Current Control

Fujihiko MATSUMOTO, Shota MATSUO, Takeshi OHBUCHI, Ryuji YASUGI
Department of Applied Physics, National Defense Academy of Japan
1-10-20, Hashirimizu, Yokosuka, Kanagawa, 239-8686, Japan
E-mail : matsugen@nda.ac.jp

Abstract: In this paper, a new linear low-g_m OTA is proposed. The proposed OTA operates in weak inversion region. The linearity of a conventional OTA is realized by using an attenuator. However the attenuator should be controlled operating current precisely. A simple structure of the voltage divider is employed by the proposed OTA. Using the simple peripheral circuit, the linearity of the proposed circuit is realized easily. Theoretical optimal value of the operating current ratio to linearize the proposed OTA is obtained from the maximally flat approximation. The validity of the proposed circuit is confirmed by simulation. The linearity and frequency characteristics of the proposed OTA are almost the same as the conventional OTA. The linear low-g_m OTA is realized by the simple peripheral circuit.

Keywords—**Low frequency analog circuit, OTA, Linearity Weak inversion region, Operating Current Control**

1. Introduction

Ultra low-frequency low-power fully-integrated active filters to process biomedical signals are to be embedded in compact and low-power medical devices. Low power technique is essential for long time operation of battery drive devices. For very low frequency such as lower than hundreds Hz, a large capacitance and a large resistance are needed. In active filters, the large resistance can be implemented by a linear low-transconductance (g_m) operational transconductance amplifier (OTA).

Several linear low-g_m OTAs have been proposed to date[1][2]. The OTA employing current division technique can realize very low g_m[1]. However, the transistor related directly to voltage-current conversion is just a mere part of the core circuit, so that the OTA wastes much operating current. The OTA employing signal attenuators also consumes much current because each attenuator is composed of plural OTAs other than the main OTA[2]. The authors have developed linear low-g_m OTAs employing transistors operating in subthreshold region. The OTA with degeneration by transistors operating in triode region has good linearity and low g_m with small current consumption[3][4]. However, the analytic calculation to obtain optimum condition for linearity is quite complicated mathematically, and thus designers must rely on approximation through numerical analysis. The linear OTA based on a hyperbolic sine function does not need degeneration resistance[5]. The defect is that the OTA requires a voltage attenuator with precise coefficients.

This paper proposes a new linear low-g_m OTA. Comparing with the conventional OTAs, the advantages are the simple structure, the simple peripheral circuits, and easiness of design.

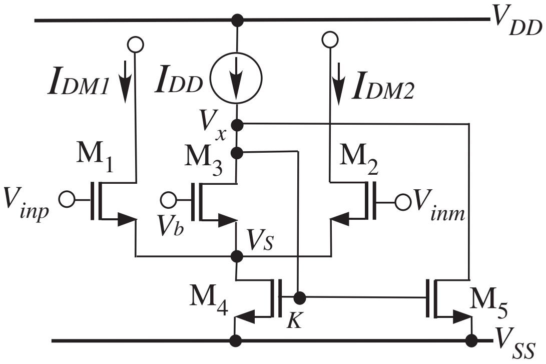

Figure 1. Proposed OTA

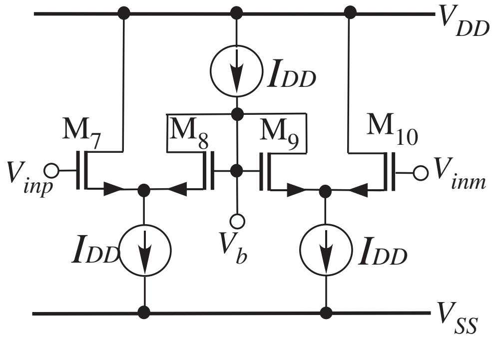

Figure 2. Voltage divider

2. Proposed OTA

The authors have proposed a linear OTA based on a sinh OTA[5]. The transfer function of the sinh OTA is expressed as

$$I_{out} = 2I_{DD}\sinh\left(\frac{v_{in}}{2\eta V_\theta}\right). \tag{1}$$

where I_{DD} is the operating current, η is the subthreshold slope factor, and V_θ is the thermal voltage. From Eq. (1), the output current of the sinh OTA can be controlled easily by tuning DC current. However, the linear input range of the conventional OTA is narrow. The proposed OTA employs a transistor M_5 in order to improve the transfer characteristic of the sinh OTA as shown in Fig. 1. The DC current I_{DD} is controlled by M_5. The proposed OTA can be improved linearity of the transfer characteristics. Assuming that the input voltage is a fully-differential signal, namely

$$V_{inp} = -V_{inm} = \frac{v_{in}}{2}. \tag{2}$$

In Fig. 1, the drain currents I_{DM1}-I_{DM5} of transistors M$_1$-M$_5$ are expressed as

$$I_{DM1} = I_{D0} \exp\left(\frac{v_{in} - 2V_s}{2\eta V_\theta}\right), \tag{3}$$

$$I_{DM2} = I_{D0} \exp\left(\frac{-v_{in} - 2V_s}{2\eta V_\theta}\right), \tag{4}$$

$$I_{DM3} = I_{D0} \exp\left(\frac{V_b - V_s}{\eta V_\theta}\right), \tag{5}$$

$$I_{DM4} = K I_{D0} \exp\left(\frac{V_x - V_{ss}}{\eta V_\theta}\right), \tag{6}$$

$$I_{DM5} = I_{D0} \exp\left(\frac{V_x - V_{ss}}{\eta V_\theta}\right), \tag{7}$$

where I_{D0} is the reverse saturation current, and K is the aspect ratio of M$_4$.

The operating current I_{DD} is expressed as

$$\begin{aligned} I_{DD} &= I_{DM3} + I_{DM5} \qquad (8)\\ &= I_{D0} \exp\left(\frac{-V_s}{\eta V_\theta}\right)\left[\exp\left(\frac{v_{in}}{2\eta V_\theta}\right)\right.\\ &\quad \left. + \exp\left(\frac{-v_{in}}{2\eta V_\theta}\right) + (K+1)\exp\left(\frac{V_b}{\eta V_\theta}\right)\right]. \qquad (9)\end{aligned}$$

The following equation is obtained from Eq. (9)

$$I_{D0} \exp\left(\frac{-V_s}{\eta V_\theta}\right) = \frac{K I_{DD}}{\left[2\cosh\left(\frac{v_{in}}{2\eta V_\theta}\right) + (K+1)\exp\left(\frac{V_b}{\eta V_\theta}\right)\right]}. \tag{10}$$

The output current of the proposed OTA I_{out} is expressed as

$$I_{out} = I_{DM1} - I_{DM2}. \tag{11}$$

Substitution of Eqs. (3), (4), and (10) in Eq. (11) gives

$$I_{out} = \frac{2K I_{DD}\left[\sinh\left(\frac{v_{in}}{2\eta V_\theta}\right)\right]}{\left[2\cosh\left(\frac{v_{in}}{2\eta V_\theta}\right) + (K+1)\exp\left(\frac{V_b}{\eta V_\theta}\right)\right]}. \tag{12}$$

Variables I_{DD} and K are the design parameters. The value of I_{DD} determines the magnitude of g_m, and I_{DD} is to be controlled for tuning. The value of K affects the shape of the characteristic curve. The optimum value for the linear characteristic is obtained from an equation derived by maximally flat approximation[6].

The circuit to determine V_b in the proposed OTA is illustrated in Fig. 2. This circuit is an active voltage divider to generate the average voltage of V_{inp} and V_{inm}. Unlike the conventional OTA[5], the peripheral circuit is simple. Assuming fully differential input, V_b is 0. Substituting $V_b = 0$ in Eq. (12) gives

$$I_{out} = \frac{2K I_{DD}\left[\sinh\left(\frac{v_{in}}{2\eta V_\theta}\right)\right]}{\left[2\cosh\left(\frac{v_{in}}{2\eta V_\theta}\right) + (K+1)\right]}. \tag{13}$$

3. Maximally Flat Approximation

From Eq. (13), the output current of an OTA is expressed as an odd function of v_{in}, and all even derivatives are zero. If the number of parameter variables in the function of the output current is N, the optimum values of the parameters for a linear characteristic are obtained by solving

$$\left.\frac{d^3 I_{out}}{dv_{in}^3}\right|_{v_{in}=0} = \cdots = \left.\frac{d^{(2N+1)} I_{out}}{dv_{in}^{(2N+1)}}\right|_{v_{in}=0} = 0, \tag{14}$$

where N is the number of parameter variables. For the proposed circuit, the parameter variable is only K, and $N = 1$. Consequently, the equation for the linear characteristic is given by

$$\left.\frac{d^3 I_{out}}{dv_{in}^3}\right|_{v_{in}=0} = 0. \tag{15}$$

The third order derivatives of Eq. (13) for $v_{in} = 0$ is expressed as

$$\left.\frac{d^3 I_{out}}{dv_{in}^3}\right|_{v_{in}=0} = \frac{K I_{DD}(K-3)}{4\eta^3 {V_\theta}^3 (K+3)^2}. \tag{16}$$

Solving Eqs.(15) and (16), the solution is obtained as

$$K = 3. \tag{17}$$

The transconductance g_m for $K = 3$ is expressed as

$$g_m = \left.\frac{dI_{out}}{dv_{in}}\right|_{K=3} = \frac{3I_{DD}\left[1 + 2\cosh\left(\frac{v_{in}}{2\eta V_\theta}\right)\right]}{2\eta V_\theta\left[2 + \cosh\left(\frac{v_{in}}{2\eta V_\theta}\right)\right]^2}. \tag{18}$$

Figure 3 illustrates the transconductance characteristics calculating from Eq. (18) by changing K. Figure 3 shows optimum value of K is 3. Figure 3 also shows the linearity of the proposed OTA with change the value of $K = 3$ in the range of ± 5%.

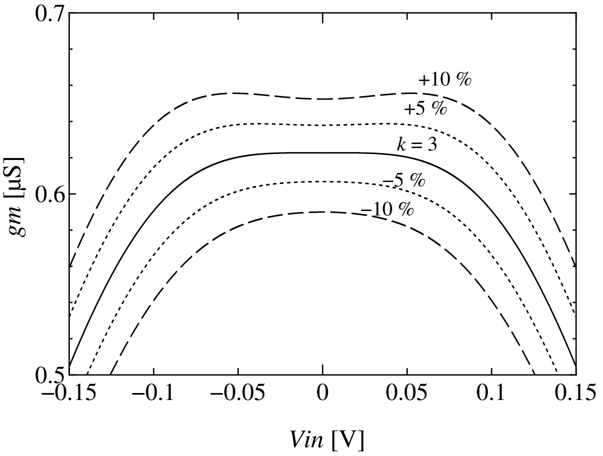

Figure 3. Transconductance characteristics with variety of the aspect ratio K

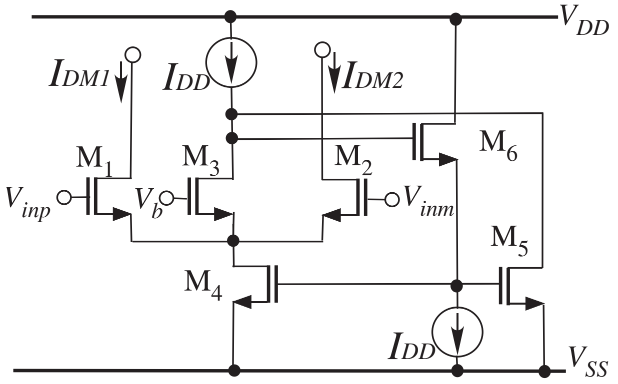

Figure 4. Proposed circuit with level shift circuit

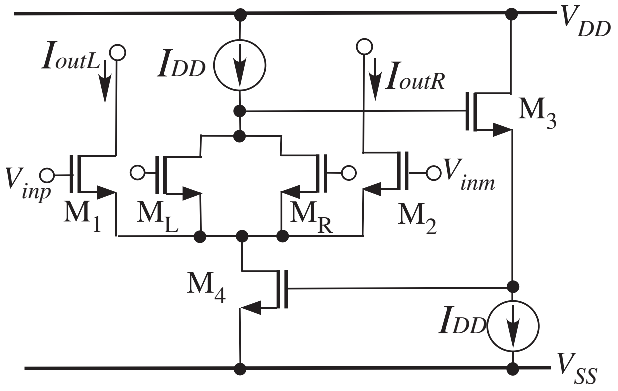

Figure 5. Conventional OTA

4. Simulation

The validity of the proposed circuits is confirmed using simulation software LTspice(Linear Technology). The transistor model used in the simulation is BSIM3 0.18μm process model. The supply voltage is 1.8V. The proposed OTA shown in Fig. 4 employs a level shift circuit to make to M_3 operate in the saturation region. Table 1 shows size of transistors. To reduce the influence of short channel effect, the length and the width of M_3 is double in comparison with M_1(M_2), respectively. Figure 6 shows the transfer characteristics of the proposed OTA with operating current 50nA, 75nA, and 100nA. Figure 7 illustrates the transconductance characteristics of the proposed OTA versus the input voltage with operating current 50nA, 75nA, and 100nA. Figures 6 and 7 show that the proposed OTA has good linearity and its transconductance can be tuned by the current I_{DD}. The characteristics of the proposed OTA is compared with the conventional OTA shown in Fig. 5[5]. The conventional OTA needs a voltage attenuation shown in Fig. 8, where 'a' denotes the attenuation factor of the input signals. The optimal value of the attenuation factor is $a = 1/\sqrt{3}$. In order to realize a=$1/\sqrt{3}$, operating currents should be controlled precisely for linearization. The current consumption of the proposed OTA is compared with that of the conventional OTA shown in Table 2. The current consumption of the proposed OTA is lower than that of the conventional OTA. Figure 9 illustrates the simulated normalized transconductances of the proposed and the conventional OTAs. The solid line denotes the normalized transconductances of the proposed OTA, the dashed line denotes the theoretical normalized transconductances of the conventional OTA. The long-dashed line denotes the normalized transconductances of the proposed OTA. The dash-dotted line denotes the theoretical normalized transconductances of the proposed OTA. In the simulation, the operating current is 50nA. Comparing the theoretical transconductances, it is found that the proposed OTA has slightly wide linear input range. Figure 9 shows that the proposed OTA has narrow linear input range. While the linear input range of the proposed OTA is 147.3mV, the linear input range of the conventional OTA is only 82.9mV. Figure 9 shows that the differences of the characteristics between the simulated characteristics and the theoretical characteristics because of the frequency characteristics because of the secondary effect of the transistors. Figure 10 shows that the frequency characteristics of the proposed OTA does not become worse in comparison with the conventional OTA.

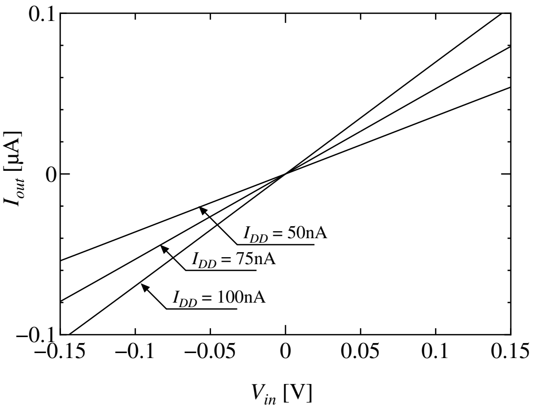

Figure 6. Simulation results of transfer characteristics

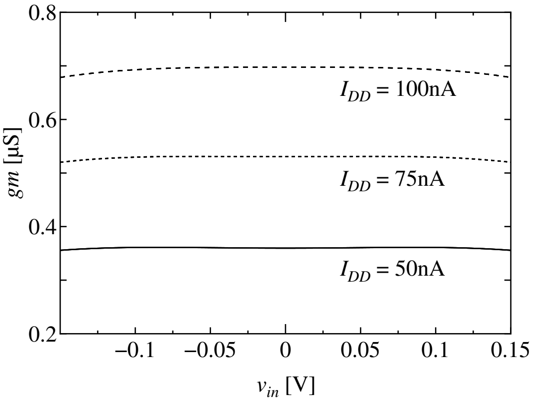

Figure 7. Transconductances

5. Conclusion

This paper has proposed a design of a new linear low-g_m OTA. To implementation of OTA has good linearity, and it

Table 1. Aspect ratio of each transistor

transistors	aspect ratio	transistors	aspect ratio
M_1	$1.8\mu m/1.8\mu m$	M_4	$5.4\mu m/1.8\mu m$
M_2	$1.8\mu m/1.8\mu m$	M_5	$1.8\mu m/1.8\mu m$
M_3	$3.6\mu m/3.6\mu m$	M_6	$1.8\mu m/18\mu m$

Table 2. Consumption current

	Conventional	Proposed
Current consumption of OTA	$3I_{DD}$	$3I_{DD}$
Current consumption of the peripheral circuit	$2.36I_{DD}$	$2I_{DD}$
Total current consumption	$5.36I_{DD}$	$5I_{DD}$

bases operating in the weak inversion region to reduce power consumption. An advantage of the OTA to be noticed is that input signal attenuator with precise coefficient is not necessary. The optimum value of the linearization parameter K is obtained theoretically from maximally flat approximation without relying on numerical analysis. Simulation results show that the linearity of the proposed OTA is about the same as the conventional OTA. However, structure of the proposed OTA is more simple. The future work is the analysis of influence of the short channel effect .

Acknowledgment

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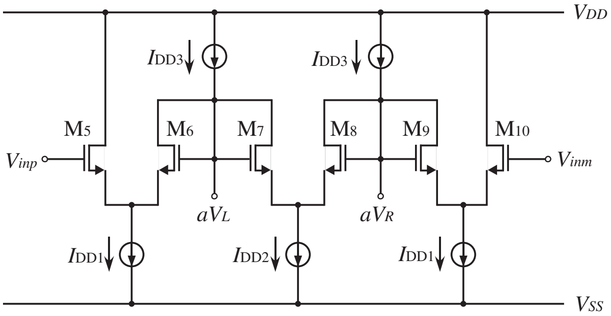

Figure 8. Voltage divider for conventional OTA

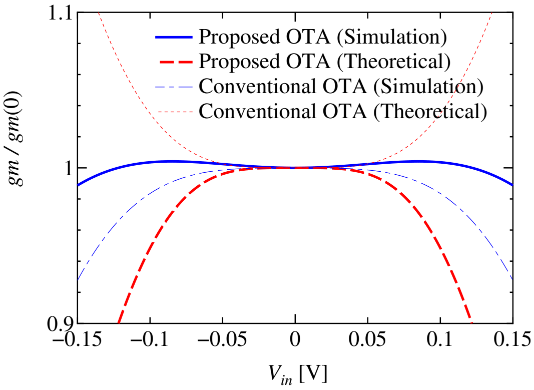

Figure 9. Normalized Transconductances

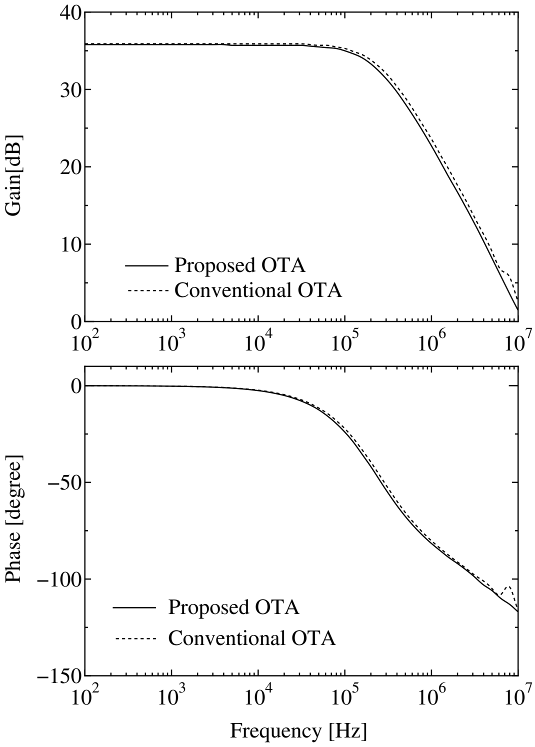

Figure 10. Simulation results of frequency characteristics