A Rail-to-Rail OTA Using Equivalent MOSFETs without Cutoff Region Operating in Triode and Saturation Regions

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Abstract: In this paper, we propose a Rail-to-Rail OTA using equivalent MOSFETs without cutoff region, which operate in triode and saturation regions. The proposed circuit has a merit that its input range is not limited due to voltage drop of current mirrors. The simulation results of the proposed circuit are shown. From the simulation results, the linearity of the proposed circuit is improved when input voltage is from 2V to 3V.

1. Introduction

In analog integrated circuits, as the power supply voltage becomes lower, input voltage range of analog circuit blocks becomes narrow.

As one of the methods to enlarge input range, there is a method using equivalent MOSFETs without cutoff region [1]. An equivalent MOSFET without cutoff region is the MOSFET that operates as if it does not have cutoff region equivalently by using two MOSFETs operating in either saturation or cutoff region alternately. In the references [2], it is reported that input voltage range of an OTA is enlarged to Rail-to-Rail input range by applying this equivalent MOSFETs to the OTA using bias offset technique [3]. But in the case of the conventional Rail-to-Rail OTA [2], its input range is limited due to voltage drop of current mirrors. This causes that the linearity of the conventional circuit is degraded. Besides, the conventional circuit needs to enlarge the aspect ratio(W/L) of current mirrors to derive drain currents from equivalent MOSFETs so much.

This paper shows a Rail-to-Rail OTA that its input range is not limited due to voltage drop of current mirrors and some level shift circuits to realize the proposed circuit. Finally, the performances of the proposed circuit are confirmed by simulation.

2. Conventional Rail-to-Rail OTA

2.1 Equivalent MOSFET without Cutoff region

Two circuits shown in Figure 1(a) and (b) are equivalent MOSFETs without cutoff region reported in [1], [2]. To begin with, we describe the principle of equivalent MOSFET shown in Figure 1(b) because the basic principle of equivalent MOSFETs shown in Figure 1(a) and (b) are the same.

N-channel MOSFETs, N2a and N2b are complementarily operating in either saturation or cutoff regions.

If input voltage range is $0 \le V_{in1} \le V_{tune}+V_{TN}$, N2a is in cutoff region and N2b is in saturation region. In this case, the equivalent drain current I_{D2} is given by

$$\begin{aligned} I_{D2} &= I_{D2a} + I_{D2b} \\ &= K\left(V_{in1} - V_{tune} - V_{TN}\right)^2 \end{aligned} \tag{1}$$

where we assume that N2a and N2b are matched, K is transconductance parameter of N2a and N2b, V_{tune} is level shift voltage realized by the source follower, V_{TN} is n-channel MOSFET's threshold voltage and $V_{TN}+V_{tune}$ is the equivalent threshold voltage. Alternatively, if input voltage range is $V_{TN}+V_{tune} \le V_{in1} \le V_{DD}$, where V_{DD} is power supply voltage, N2a is in saturation region and N2b is in cutoff region. In this case, the equivalent drain current I_{D2} is given by equation (1).

Thus, the circuit in Figure 1(b) always has the drain current of equation (1) for input voltage from ground to power supply voltage.

In the case of Figure 1(a), V_{tune}=0 is applied to equation (1), the equivalent drain current I_{D1} is expressed as

$$\begin{aligned} I_{D1} &= I_{D1a} + I_{D1b} \\ &= K\left(V_{in1} - V_{TN}\right)^2 \end{aligned} \tag{2}$$

In common with Figure 1(b), the circuit in Figure 1(a) also have Rail-to-Rail input range.

2.2 Rail-to-Rail OTA Using Equivalent MOSFETs

An Conventional Rail-to-Rail OTA is constructed by applying two equivalent MOSFETs to the OTA using bias offset technique [3]. The OTA using the bias offset technique is shown in Figure. 2 and conventional Rail-to-Rail OTA is shown in Figure 3.

In Figure 2, the OTA the using bias offset technique is linearized by connecting level shift voltage V_{tune} both gate terminals of N1 and N2 in saturation region and taking difference between each drain currents. If all transistors are in saturation region, the output current I_{out} of the circuit in Figure 2 is defined as difference between drain currents I_{D1}-I_{D2} and I_{D4}-I_{D3}, we have

$$\begin{aligned} I_{out} &= I_{D1} - I_{D2} - (I_{D4} - I_{D3}) \\ &= I_{D1} + I_{D3} - (I_{D2} + I_{D4}) \\ &= 2KV_{tune}(V_{in1} - V_{in2}) \end{aligned} \quad (3)$$

where $2KV_{tune}$ is defined as transconductance (Gm), V_{in1}-V_{in2} is defined as differential input voltage of the OTA.

In Figure 3, the output current I_{out} of the Rail-to-Rail OTA is equal to equation (3), its input range is Rail-to-Rail. Although its input range is Rail-to-Rail, we need a condition that all transistors are in saturation region. In other words, voltage drop of current mirrors P1, P2 is smaller than V_{TN}. If the voltage drop of that is lager than V_{TN}, output current I_{out} is not linear for input voltage of the OTA. To solve this problem, in the next section, we propose a Rail-to-Rail OTA whose input range is independent of voltage drop of the current mirrors.

3. Proposed Rail-to-Rail OTA

We show the basic principle of the proposed OTA in Figure 4. The proposed OTA has a merit that its input range is independent of voltage drop of the current mirrors.

In Figure 4, the voltage between drain terminals of two equivalent MOSFETs is V_{tune}. Because of this voltage V_{tune}, when input voltage V_{in1} is high, N1a, N1b, N2a and N2b are in triode region. As two equivalent MOSFETs are in triode region at one time, drain current I_{D1} and I_{D2} are expressed as

$$I_{D1} = 2K\left[(V_{in1} - V_{TN})V_{DS1} - \frac{1}{2}V_{DS1}^{2}\right] \quad (4)$$

$$I_{D2} = 2K\left[(V_{in1} - V_{tune} - V_{TN})(V_{DS1} - V_{tune}) - \frac{1}{2}(V_{DS1} - V_{tune})^{2}\right] \quad (5)$$

I_{D1}-I_{D2} results in

$$I_{D1} - I_{D2} = 2K\left[(V_{in1} - V_{TN})V_{tune} - \frac{1}{2}V_{tune}^{2}\right] \quad (6)$$

Thus, output current I_{out} is given by

$$\begin{aligned} I_{out} &= I_{D1} - I_{D2} - (I_{D4} - I_{D3}) \\ &= 2KV_{tune}(V_{in1} - V_{in2}) \end{aligned} \quad (7)$$

and linear for input voltage V_{in1}-V_{in2} in the case of that N1a, N1b, N2a and N2b are in not only saturation region but also triode region.

As a result, input range of the proposed Rail-to-Rail OTA is not limited due to voltage drop of current mirrors, the linearity of the proposed circuit is improved moderately. Besides the proposed circuit do not need to enlarge the aspect ratio(W/L) of current mirrors to derive drain currents from equivalent MOSFETs.

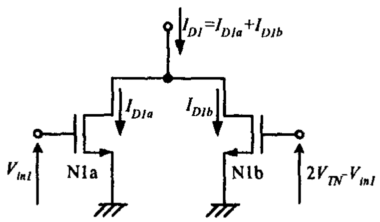

Figure 1(a). Equivalent MOSFET(Type I)

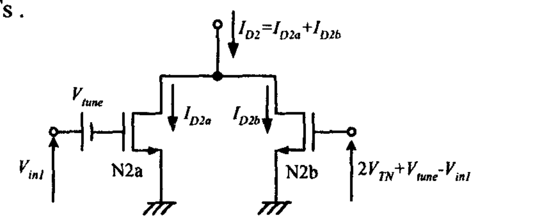

Figure 1(b). Equivalent MOSFET(Type II)

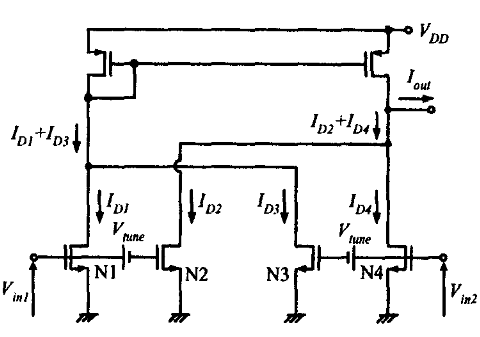

Figure 2. OTA using bias offset technique

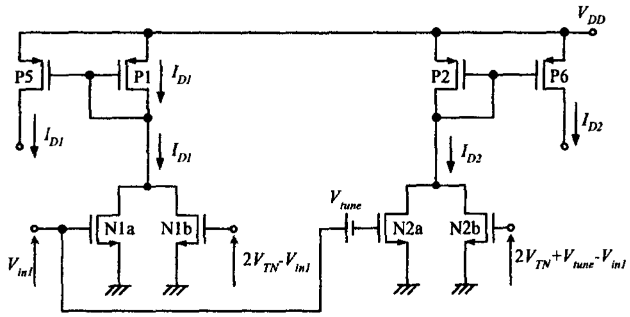

Figure 3.. Half circuit of conventional Rail-to-Rail OTA

Next, we show a circuit structure of the Rail-to-Rail OTA in Figure 5. As shown in Figure 4, voltage difference V_{tune} is needed between drain terminals of equivalent MOSFETs adjoining each other. For that purpose, as shown in Figure 5, we used the Voltage Regulating Circuit composed of Nb, P2, P6 in saturation region and two bias current sources I_b are given as

$$I_b = K_b(V_{tune} - V_{TN})^2 \qquad (8)$$

where K_b is equal to transconductance of Nb, V_{tune} is level shift voltage to regulate transconductance (Gm) of the OTA. In the voltage regulating circuit, bias current I_b is given by equation (8), gate-source voltage V_{GSb} of Nb is written by

$$V_{GSb} = \sqrt{\frac{I_b}{K_b}} + V_{TN} \qquad (9)$$

From the equation (8) and (9), we have $V_{GSb} = V_{tune}$.

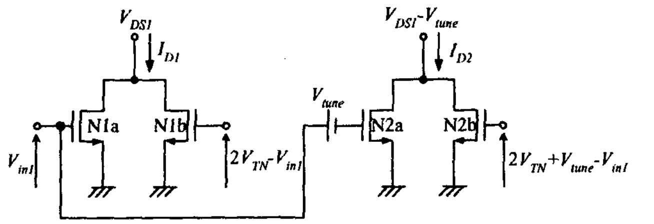

Figure 4. Basic principle of the proposed Rail-to-Rail OTA

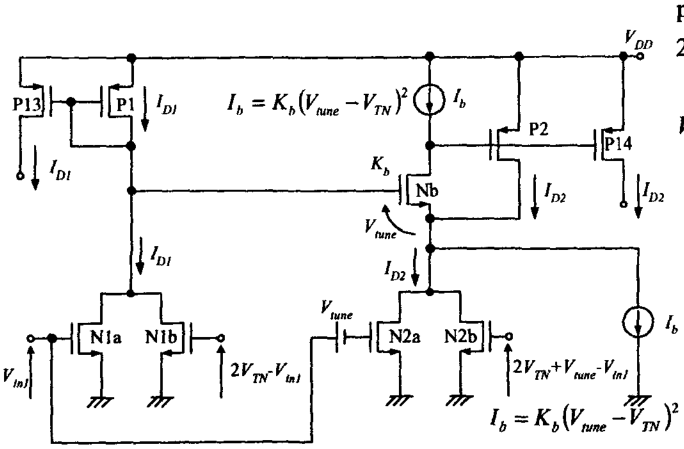

Figure 5. Half circuit of the proposed Rail-to-Rail OTA

4. Level Shift Circuits

To realize the proposed Rail-to-Rail OTA, we use some level shift circuits as shown in Figure 6-8. Figure 6 is a simple source-follower, Figure 7 is a circuit to extract the level shift voltage $2V_{TN}$, reported in reference [4].

In Figure 7, the transconductance parameters of N12 and N13 are at a ratio of 1 to 9. Figure 8 is a example of level shift circuit to output $2V_{TN}$-V_{in1} and $2V_{TN}$+V_{tune}-V_{in1} for input voltage V_{in1}. In the level shift circuits, the value of $2V_{TN}$ is the most effective to the Rail-to-Rail OTA's linearity, so level shift voltage $2V_{TN}$ is decided as precisely as possible.

5. Simulation Results

The performances of the conventional and proposed circuit are confirmed by Spectre simulation with the 0.35μm CMOS process, LEVEL 49 model parameter, threshold voltages of NMOS and PMOS are about V_{TN}=0.51V and $|V_{TP}|$=-0.57 respectively. In the simulation, the bulk-terminals of all transistors are connected to those source terminals, the body effect of all transistors is neglected. Power supply voltage V_{DD} is 3V, Gm controllable voltage V_{tune}=0.55, 0.65 and 0.75V, V_{in2}=1.5V, and V_B=2V.

The dc transfer characteristics are shown in Figure 9 and 10. Compared Figure 9 with Figure 10, the linearity of the proposed circuit is improved in the condition that V_{in1} is from 2V to 3V.

The frequency responses for input bias voltage V_{in1}=1.5V, V_{in2}=1.5V, are shown in Figure 11 and Figure 12.

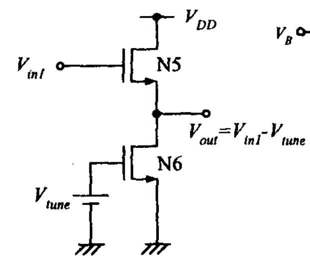

Figure 6. Source-follower

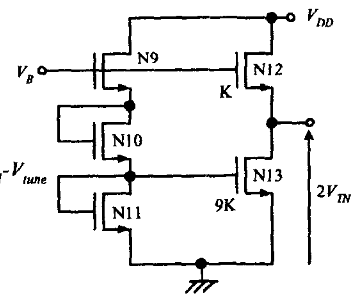

Figure 7. $2V_{TN}$ extractor

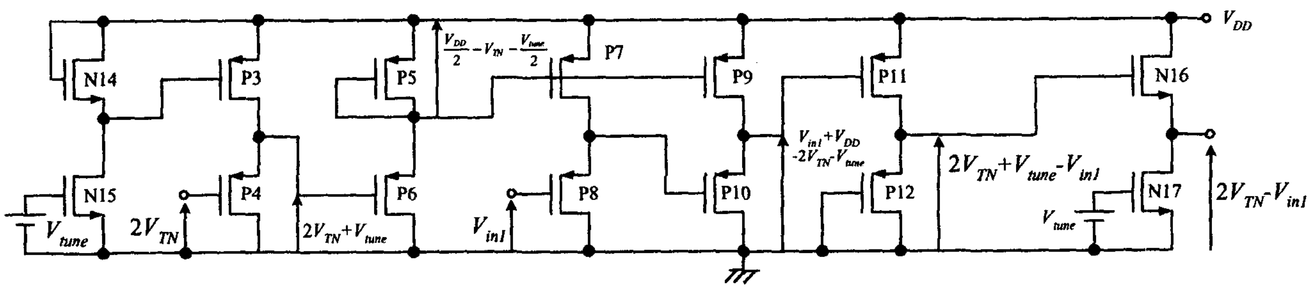

Figure 8. Level shift circuit

Finally, we confirmed Total Harmonic Distortion (THD) of the conventional and the proposed circuits. THD of the conventional circuit is 0.88% and THD of the proposed circuit is 0.46% when V_{tune} is 0.55V, V_{in1}=2.3+0.1sin(2π1kt)V and V_{in2}=2.3V.

6. Conclusions

We have proposed a Rail-to-Rail OTA using equivalent MOSFETs which are operating in saturation and triode region without cutoff region. It is shown that the proposed Rail-to-Rail OTA is not limited due to drop of the current mirrors. From the simulation results, we confirmed that the linearity of the proposed circuit is improved. However, the frequency response of the proposed circuit is not as fine as the conventional that because of use of the voltage regulating circuit using negative-feedback as shown in Figure 5.

References

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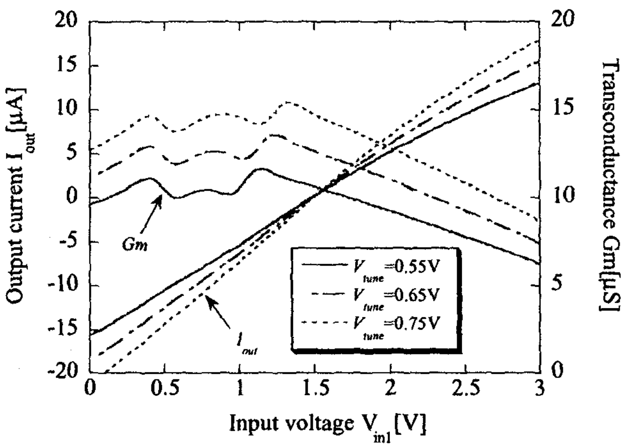

Figure 9. DC transfer characteristics of the conventional Rail-to-Rail OTA

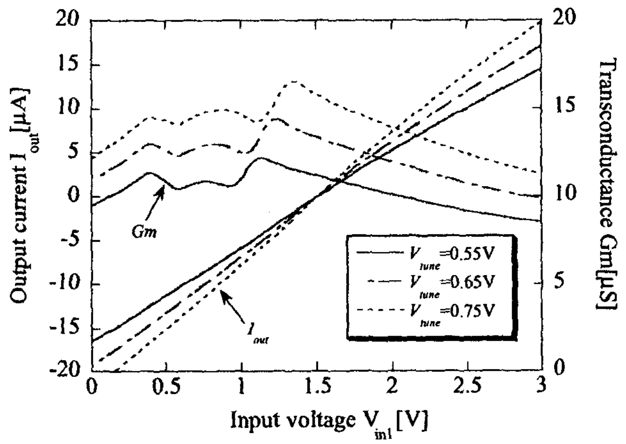

Figure 10. DC transfer characteristics of the proposed Rail-to-Rail OTA

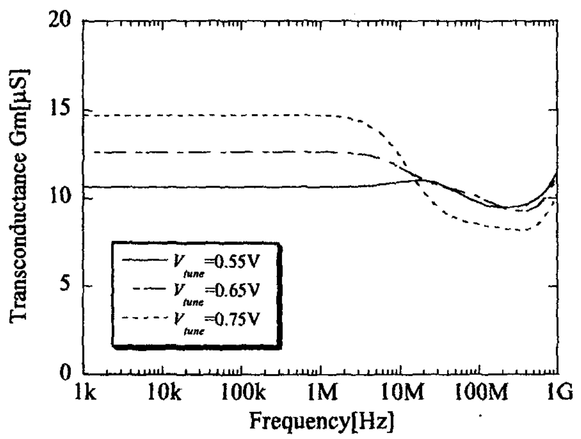

Figure 11. Frequency responses of the conventional Rail-to-Rail OTA

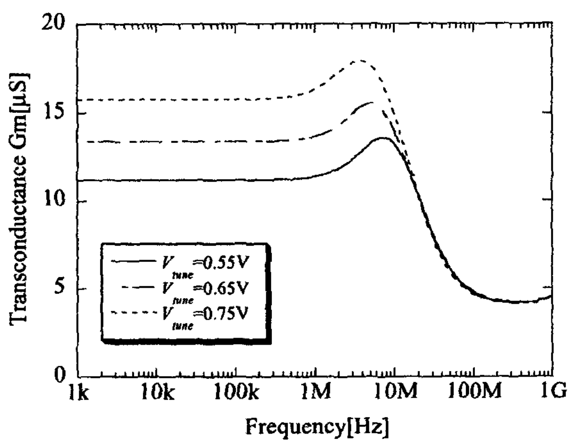

Figure 12. Frequency responses of the proposed Rail-to-Rail OTA