완전 차동 Gm-C 필터를 위한 저전압 트랜스컨덕터 설계

論 文
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Design of Low Voltage Transconductor for Fully Differential Gm-C Filter

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Abstract – A fully differential transconductor using the series composite transistor is proposed. Simulation results show that THD is less than 1.2% for the differential input signal of up to $1.5V_{P-P}$ when the input signal frequency is 10MHz. The proposed transconductor is used to design a third-order elliptic Gm-C lowpass filter with 138kHz cutoff frequency for ADSL Tx filter. The design procedure is based on signal flow graph(SFG) of a doubly-terminated LC ladder filter by means of fully differential transconductors and capacitors. The filter is fabricated and measured with a 0.35μm CMOS process.

Key Words : Gm-C filter, Composite transistor, Transconductor, SFG, Elliptic

1. Introduction

Linear transconductors or V-I converters are basic building blocks for analog circuits such as OTAs (Operational Transconductance Amplifier), continuous-time filters, and analog multipliers, etc. The transconductors are also very important in current mode applications. Most of existing transconductors are implemented with MOS transistors because of their high input impedance and compatibility with digital CMOS technology. However, the inherent large threshold voltage of MOS transistors is one main drawback in low voltage applications. Thus, many researches for the improvement of linearity of a CMOS transconductor in low supply voltage have been performed [1][2]. This paper is based on the transconductor reported by [3]. This transconductor has a wide input range. However, from the process point of view, there are some limitations in low voltage applications.[4-6]

In order to resolve these limitations, we propose the low voltage transconductors using the series composite transistor. And then, the fully differential low-pass filter is realized for the application of the proposed transconductor. The simulation and measurement results of the designed filter are included.

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2. Low voltage transconductors

Fig. 1 shows the COMFET(COMposite n-channel MOSFET) transconductor, where V_A and V_B are generated by transistors M1, M5 and M2, M6 respectively, which implement a voltage divider. V_A and V_B must be larger than $V_{Tn}+V_{SS}$ due to a diode-connected transistor M5 and M6, where V_{Tn} is the threshold voltage of NMOS transistor. Also, the minimum voltage of V_1 and V_2 is $2V_{Tn}+V_{SS}$, which is unsuitable for low voltage applications. It is better that the bulks of M1 and M5 (M2 and M6) are directly connected to their sources in order to eliminate the body effect. This is achieved by putting each transistor in a separated well which must be either P-well or twin-well. However, separated wells require large layout areas and cannot be provided in N-well CMOS process.

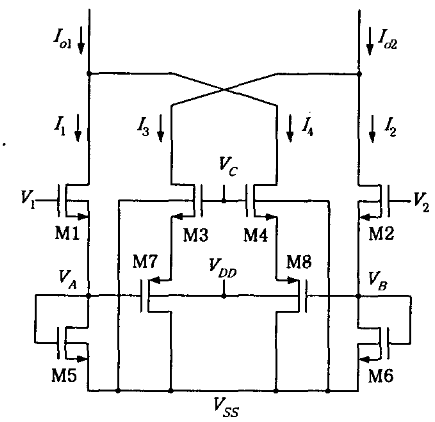


Fig. 1 COMFET transconductor.

To overcome these problems, a new transconductor using the series composite transistor Ma1 and Ma2 (Mb1 and Mb2) is proposed, as shown in Fig. 2.[4] For the series composite, Ma2 and Mb2 are always operating in the triode region, and Ma1 and Mb1 are operating in the saturation region. The bulk of Ma1 and Mb1 are connected to the ground, whose threshold voltage is dependent on the body effect. However, since Ma2 and Mb2 operate in the triode region, the value of V_A (V_B) can be small. Thus, the body effect of Ma1 and Ma2 is eliminated. Note that the minimum voltage of V_1 and V_2 are V_{Tn}. Therefore, the proposed transconductor has extended input range compared to the circuit shown in Fig. 1. Assuming that a fully differential signal is applied to V_1 and V_2, that is, $V_1=V_{cm}+v_{in}/2$ and $V_2=V_{cm}-v_{in}/2$, where V_{cm} is the common mode input voltage and v_{in} is the differential input voltage, the transconductance g_m, is given by

$$g_m = \frac{I_{out}}{v_{in}} = K_n[(1-2K_T)(V_{cm}-V_{Tn})+K_T(V_C-V_{Teq})] \quad (1)$$

which can be tuned by changing the control voltage V_C.

In Fig. 2, the composite transistors have the large equivalent threshold voltage. Moreover, NMOS transistors and PMOS transistors of composite transistors have their bulks connected to the ground and V_{DD}, respectively. Thus, due to the body effect, the equivalent threshold voltage is more increased.

The minimum value of V_C is given by

$$V_C \geq V_{DS2,triode} + V_{Teq} = V_{DS2,triode} + V_{Tn3} + |V_{Tp4}| \quad (2)$$

To resolve this limitation, the transconductor using the low voltage composite transistor is proposed in Fig. 3.

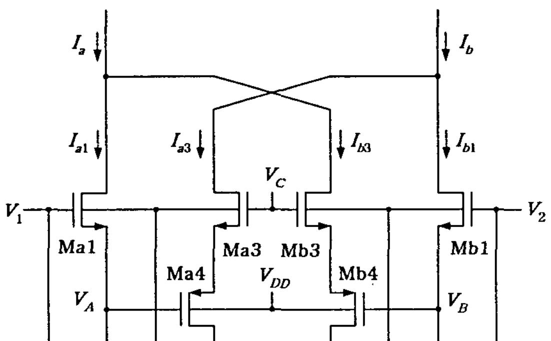


Fig. 2 The proposed transconductor using the series composite transistor.

Ma3, Mb3 and Ma4, Mb4 are a basic CMOS composite transistor. Ma5, Mb5 and I_B form a level shift circuit to reduce the value of the threshold voltage of the composite transistor. The minimum value of V_C is given by

$$V_C \geq V_{DS2,triode} + V_{Teq} = V_{DS2,triode} + |V_{Tp4}| - \sqrt{\frac{2I_B - I_3}{K_{n5}}} \quad (3)$$

where, K_{n5} is the transconductance parameter of diode-connected transistor Ma5 and Mb5.

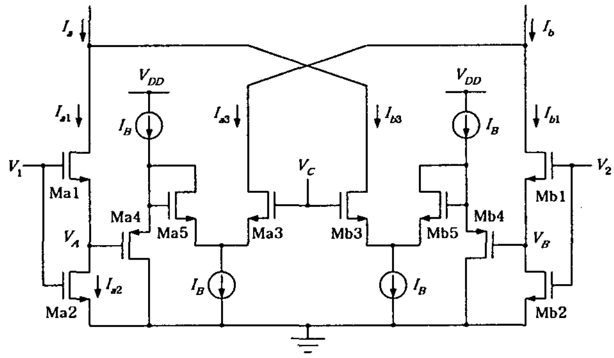
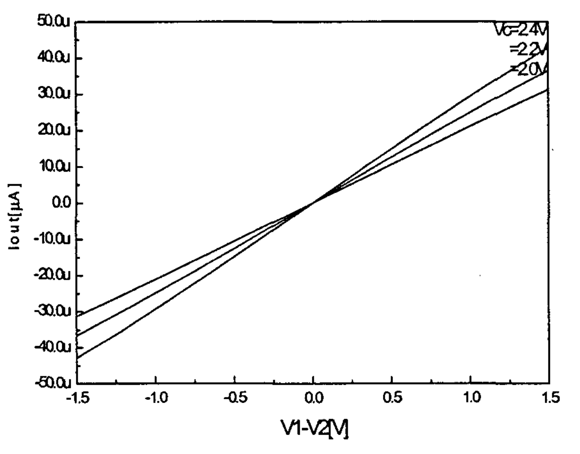


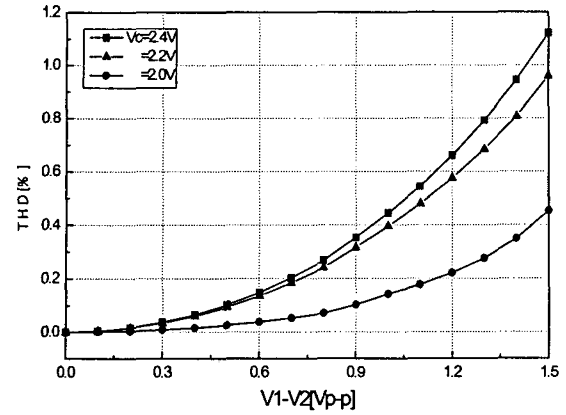
Fig. 3 The proposed transconductor using the low voltage composite transistor.

From Eq.(2) and (3), it is obtained that the proposed transconductor shown in Fig. 3 can operate at a lower voltage supply compared to the transconductor shown in Fig. 2.

The proposed transconductors have simulated by HSPICE using 0.35μm N-well CMOS process with V_{Tn}=0.556V and V_{Tp}=0.601V. Fig. 4(a) shows DC transfer curves for the proposed transconductor of Fig. 2 with V_{DD}=2.5V and different V_C. Fig. 4(b) shows Total Harmonic Distortion(THD) as a function of V_1-V_2. Less than 1.2% THD can be obtained for the differential input signal of up to 1.5V_{P-P} with the input signal frequency of 10MHz.



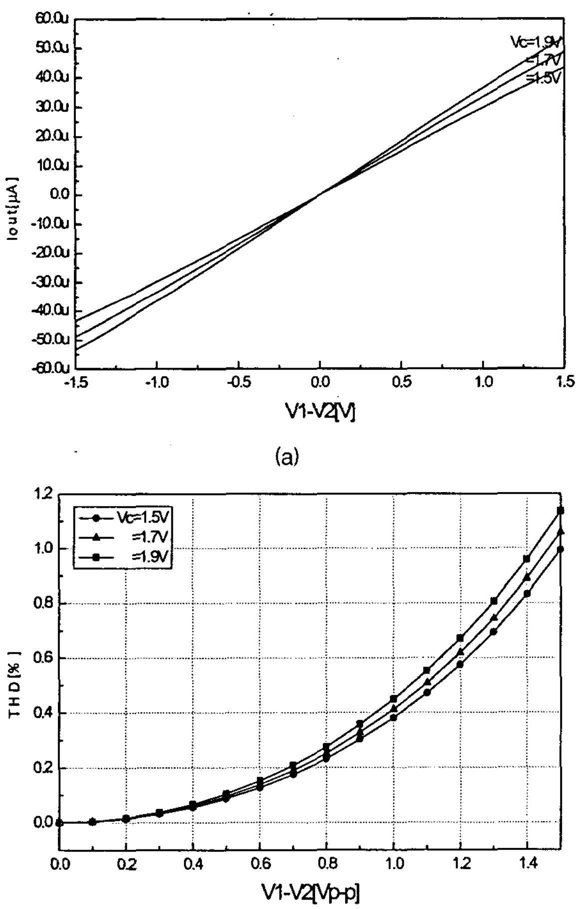
(a)



(b)

Fig. 4 (a) DC transfer curves and (b) THD for the proposed transconductor of Fig. 2.

The proposed transconductor of Fig. 3 is simulated with V_{DD}=2V and I_B=100μA. The DC transfer curves and THD of the proposed transconductor is shown in Fig. 5 with three different V_C. The THD is obtained less than 1.2% for a 10MHz 1.5V_{P-P} input signal.



(b)

Fig. 5 (a) DC transfer curves and (b) THD for the proposed transconductor of Fig. 3.

3. Gm-C filter design

The 3rd-order elliptic Gm-C lowpass filter is designed for ADSL Tx filter. From the doubly-terminated LC ladder network, the fully differential Gm-C filter is obtained through the use of signal flow graph method. The cutoff frequency of Tx lowpass filter is 138kHz with 1 dB passband ripple. Fig. 6 shows the circuit diagram of the final Gm-C filter implementation using the proposed transconductor as shown in Fig. 3. In Fig. 6, the first transconductor of the input stage is connected to compensate the 6dB loss of the doubly-terminated LC ladder network.

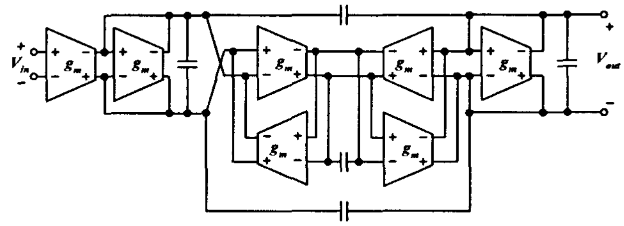


Fig. 6 Elliptic Gm-C lowpass filter.

In Fig. 7, the cutoff frequency of the lowpass filter is changed from 126kHz to 164kHz according to the variations of V_C(1.4V~1.8V). When V_C is 1.5V, the cutoff frequency and DC power consumption of the filter are 138kHz and 11.05mW. The THD is achieved 0.97% for a 100kHz 0.8V_{P-P} input signal.

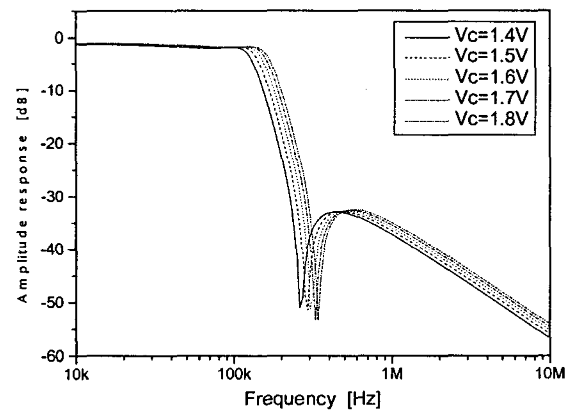


Fig. 7 Simulation results of Gm-C filter.

4. Measurement results

The designed filter was fabricated with a 0.35μm CMOS N-well process. Fig. 8 shows the microphotograph of Gm-C filter. This is a part of the analog front-end chip for ADSL modem, which consists of ADC, DAC, Tx lowpass filter, Rx lowpass filter, and AGCs. Area of the Tx lowpass filter is 305×652μm^2.

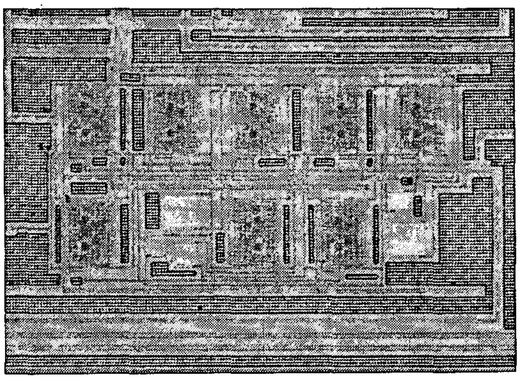


Fig. 8 Microphotograph of Gm-C filter.

The measured frequency response is compared with the simulation result in Fig. 9 by using LabVIEW. Fig. 9 shows that the cutoff frequency satisfies the requirement of ADSL Tx lowpass filter. The single-ended output spectrum for a 40kHz input signal is shown in Fig. 10. The measured THD is 0.45% for a $0.1V_{P-P}$ input.

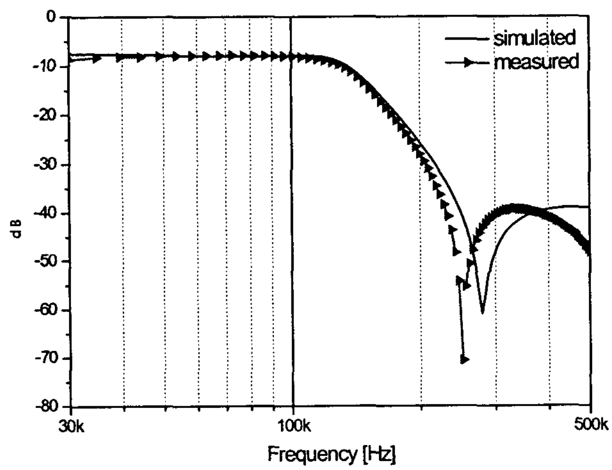


Fig. 9 Frequency response of Gm-C filter.

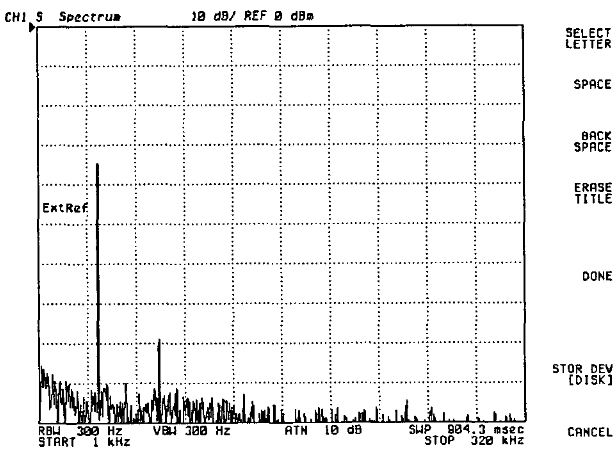


Fig. 10 Output spectrum of Gm-C filter.

5. Conclusion

In this paper, low voltage transconductors using the series composite transistors are presented. The minimum input voltage of the proposed circuits is V_{Tn}, which is suitable for a low supply voltage. The proposed transconductors have ±1.5V input range at 2V supply voltage, and the transconductance can be tuned by V_C. Simulation results show that the THD is obtained less than 1.2% for a 10MHz $1.5V_{P-P}$ input signal. For the application of the proposed transconductor, the fully differential Gm-C filter is designed and fabricated to apply the front-end of ADSL modem. The measured cutoff frequency of the filter is 138kHz when V_C is 1.6V. The proposed transconductors are expected to be useful in low voltage analog circuit applications.

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