49Design of Low *1/f* Noise Folded Cascode Operational Amplifier by Using Chopper Stabilization Technique

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Abstract

Biological signals have low voltage and low frequency. Very low noise, high gain, fast speed and stable amplifier are necessary to process these signals. Unfortunately, *1/f* noise found at below 1 kHz is unavoidable problem if the amplifier is built by CMOS process. To overcome this problem, CMOS is folded and then cascaded. In order to reduce *1/f* noise, chopper stabilization technique is implemented. The circuit were evaluated by using HSPICE simulation with 0.6 μm CMOS process. Using this technique, *1/f* noise can be reduced 46.55 dB in average.

Keywords: Biological Signals, Folded Cascode Operational Amplifier, Chopper Stabilization Technique, *1/f* Noise

1. INTRODUCTION

Biological signals are used to operate medical and health care system. This kind of signals are very weak (low amplitude) and very low frequency[1)]. Figure 1 shows the range of biological signal voltages and frequencies. In order to acquire, record, and analyze in next processes, this signals have to be amplified.

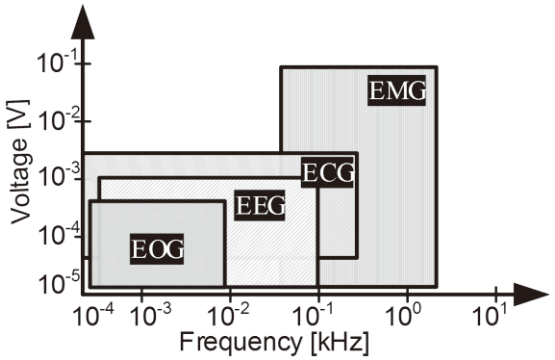

Fig. 1. Range of Biological Signals.

Many integrated Operational Amplifiers (Op-Amps) build with CMOS technology. Two stage Op-Amp is commonly used due to its DC gain and the wide swing at low supply voltages. Furthermore, to meet the requirement for modern technologies, the high gain becomes one of crucial parameters to be a suitable Op-Amp. Combining the cascode and folded CMOS into Op-Amp achieves requirement mentioned before, even gives bigger swing in output. Further, pole at folded cascode is closer to origin than the other cascode technique, telescopic cascode. As a result, this circuit works more stable, however it is followed by several things, such as high power dissipation and lot of noises[2)].

One of big problems from the present noises is *1/f* noise or known as flicker noise, spread over in semiconductor devices especially MOSFET. This noise randomly shows up at low frequency, and it will limit the biological signal to be detected[3)]. However, using power spectral density distribution of *1/f* noise, it can be characterized in $S(f) = 1/f^{\alpha}$ behavior where α's value in range 0.7-1.3 typically[4)].

Meanwhile, this *1/f* noise has a connection to the other noises as shown in Figure 2. It means that reducing *1/f* noise will affect the reduction of the other noises. The junction between *1/f* noise and white noise is named as f_{knee}. In another reference, this f_{knee} connects to thermal noise[2)].

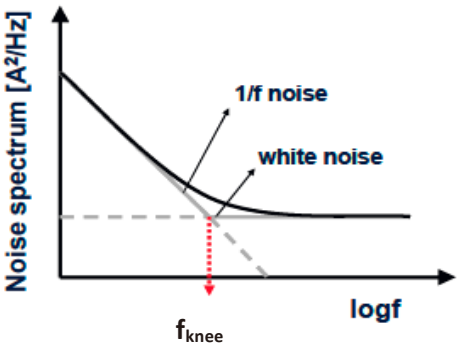

Fig. 2. Spectrum of Noises.

Chopper Stabilization Technique is one of prominent technique to reduce *1/f* noise. Using this technique, *1/f* noise is modulated into high frequency, demodulated after got amplified and separated from biological signal using low pass filter.

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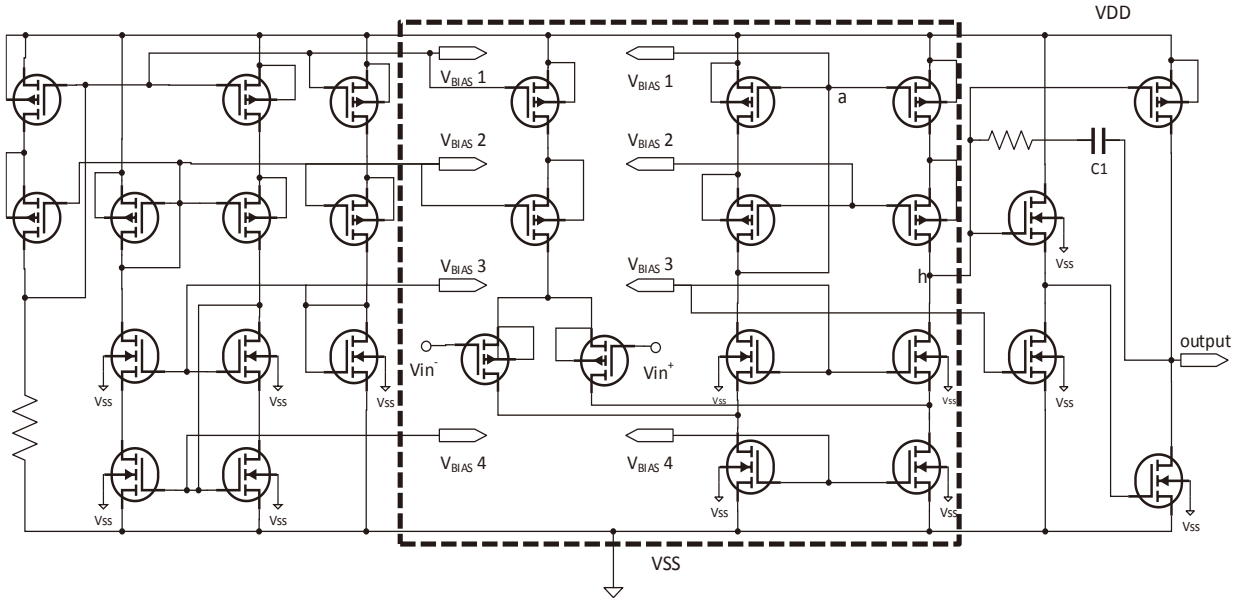

Note :
—— : folded cascode differential amplifier

Fig. 3. Schematic of circuit.

In the past, we designed the instrumentation amplifier which consists of Fully Balanced Differential Difference Amplifier (FBDDA) and Differential Difference Amplifier (DDA) with Chopper Stabilization Technique (CST)[5]. However, our past circuit, CST was applied to the FBDDA only. Therefore, *1/f* noise and offset voltage of DDA cannot be reduced. In order to overcome this problem, we try to apply CST to DDA which can be realized with Folded Cascode Operational Amplifier.

2. FOLDED CASCODE OPERATIONAL AMPLIFIER

Folded cascode operational amplifier (see the dotted line in Figure 3) is one of the stable Op-Amps and widely used. However, this circuit does not have wide output range and drivability of loads due to the high gain of the folded cascade Op-Amp that is only can be achieved by very high output impedance. In order to overcome this problem, two stage Op-Amp, which consists of folded cascode circuit and common-drain circuit or class AB common-source circuit, is obtained.

In this research, we employed two stage Op-Amp consists of folded cascode circuit and class AB common-source circuit with level shift circuit in order to achieve the very high gain and drivability, as shown in Figure 3. The circuit of the left side in Figure 3 is the bias circuit for the folded cascade circuit. Since this Op-Amp is two stage operational amplifier, the phase compensation is necessary. Therefore, we add the phase compensation circuit which is capacitor and resistor as shown in Figure 3.

However, this Op-Amp (Figure 3) suffers with *1/f* noise. In this research, we apply the CST to this Op-Amp.

3. PROPOSED CIRCUIT

1/f noise is known as well spread in the semiconductor devices. MOS transistor suffers higher in this situation than the other semiconductor devices. Unlike all of another noises, *1/f* noise cannot be predicted easily. However, it can be modeled like Equation 1 and 2

$$\overline{V_{n,1/f}^2} = \frac{K_F}{CoxWL} \cdot \frac{1}{f} \quad (1)$$

$$\overline{I_{n,1/f}^2} = \frac{K_F}{CoxWL} \cdot \frac{1}{f} \cdot gm^2 \quad (2)$$

where K_F is constant of process and has value in order of 10^{-25} V^2F.

Equation 1 and 2 are the approximation of *1/f* noise without another noises contribution. When thermal noise is included, total noises can be rewritten as Equation 3.

$$\overline{I_{noise,tot}^2} = 4kT\frac{2}{3}gm + \frac{K}{C_{ox}WL} \cdot \frac{1}{f} \cdot gm^2 \quad (3)$$

However, in this research, thermal noise and the others can be neglected. Focus is given on *1/f* noise only because we try the low frequency signal such as biological signals.

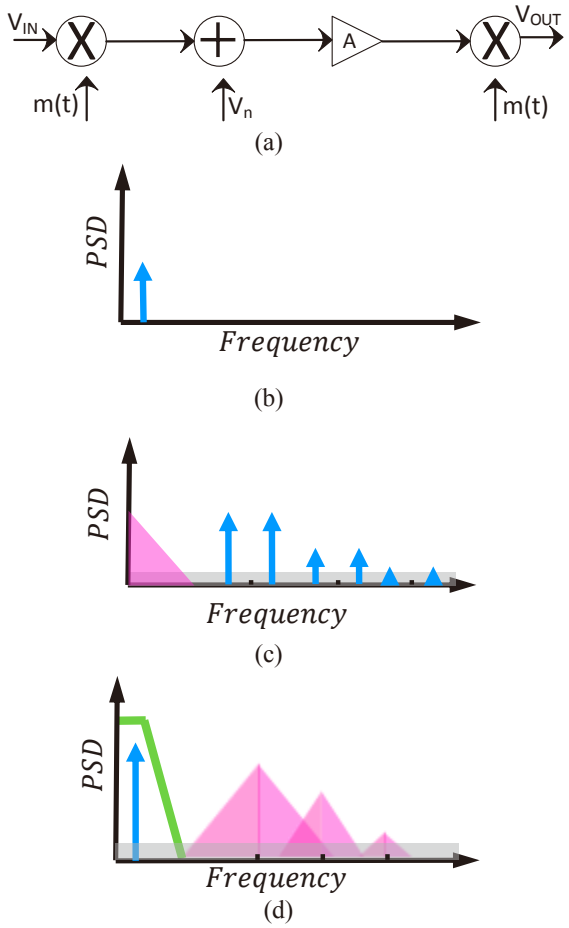

Fig. 4 (a). General Chopper Scheme, (b) Input signal is added, (c) Input signal is modulated and noise signal is inserted, (d) Noise signal is modulated and input signal is demodulated.

The effect of *1/f* noise or noted as V_n, can be minimized using CST. The process of CST is shown in Figure 4 (a-d). In Figure 4 (a), input and output signal are given name as V_{IN} and V_{OUT} respectively. V_{IN} enters switches for the first CST, which is controlled by $m(t)$ and V_{IN} is modulated to the high frequency band. V_n is added to this modulated signal. After that this signal is amplified and lastly, this modulated signal is demodulated by the second $m(t)$.

Stand for figure 4 (b) to (d) is explanation of the processes through graphics. V_{IN} and V_n can be separated by using this system. First V_{IN} (Figure 4 b) is modulated by the first CST. V_n is added and both of them are amplified by A (Figure 4 c). However, as shown in Figure 4 (d) while V_{IN} is demodulated by second CST, the different process is applied onto V_n. CST modulates V_n to higher frequency. The line between V_{IN} and V_n is filter region to remove modulated V_n completely.

Figure 5 shows the proposed system which consists of the Op-Amp from Figure 3, switches for CST and Gm-C low pass filter.

Figure 6 is the folded cascode circuit with CSTs which is employed in this research. Namely we used the circuit shown in Figure 6 instead of the folded cascode circuit shown in Figure 3 (dotted line). The switches for chopper 1 and chopper 2 are implemented as shown in Figure 7 and 8, respectively.

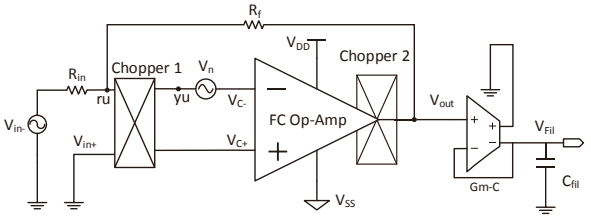

Fig. 5. Proposed System.

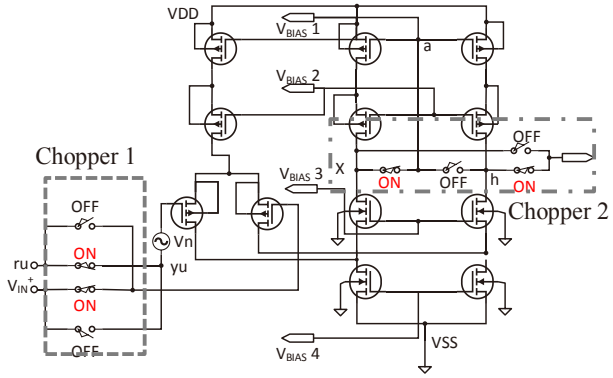

Fig. 6. Schematic of choppers and amplifier.

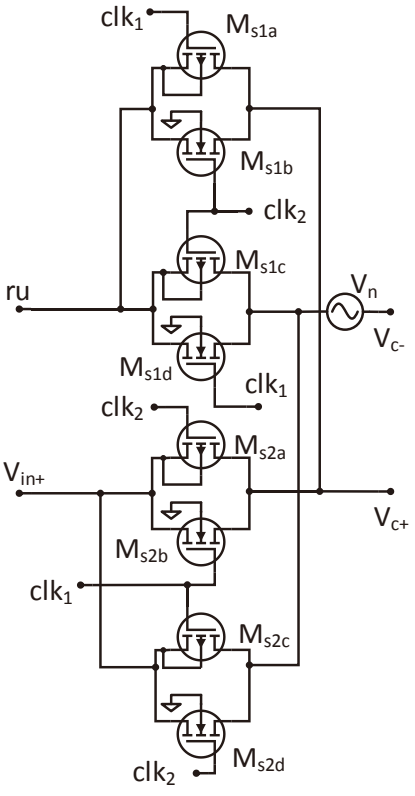

Fig. 7. Schematic of chopper 1.

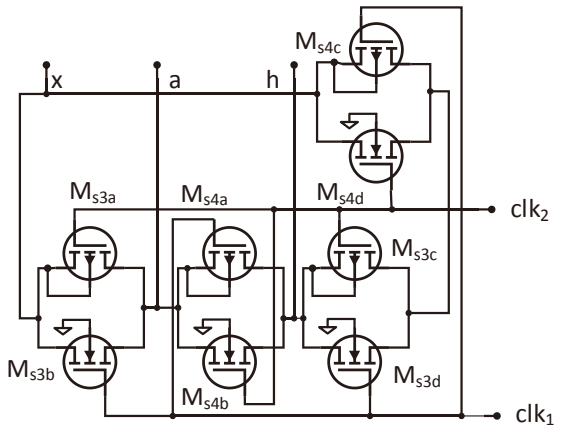

Fig. 8. Schematic of chopper 2.

From the above explanation, the output voltage can be given by Equation 4.

$$V_{out} = \left(-\frac{R_F}{R_{IN}} \right) \{ V_{in} \sin(\omega_{in} t) + V_n g(t) \} \quad (4)$$

where g(t) is the clocks of CST and has a function like shown in Equation 5.

$$g(t) = \frac{2}{\pi} \sum_{n=1}^{\infty} \frac{1}{2n-1} \sin\{(2n-1)\omega_c t\} \quad (5)$$

V_{OUT} has both of input signal and modulated noise. To remove noise influences, Low Pass Filter (LPF) is necessary added. As mentioned in Figure 5, continuous time based on transconductors and capacitor filter (Gm-C LPF) is used. In order to remove V_n, the order of Gm-C LPF and its cut-off frequency should be tuned. These values are depending on the frequencies of V_{IN} and CLK.

4. SIMULATION RESULTS

The proposed circuit was evaluated by using HSPICE with 0.6 µm CMOS process. The simulation conditions was listed in Table 1.

Table 1. Simulation Conditions

Item	Value
V_{DD}	2.5 V
V_{SS}	-2.5 V
Amplitude of V_{IN}	5 mV
Frequency of V_{IN}	100 Hz
Frequency of CLKs	1 kHz, 4 kHz, 10 kHz
Frequency of LPF	350 Hz
R_F	9 kΩ
R_{IN}	1 kΩ

As shown in Table 1, V_{IN} set in 5mV amplitude with 100 Hz of frequency because general biological signals are very weak and low frequencies (even below 1 kHz).

HSPICE does not have a function of transient analysis with noise. Therefore, we employed three sinusoidal signals in order to represent of *1/f* noise. The sinusoidal signal frequencies set on 20 Hz, 40 Hz and 60 Hz and their amplitude were 0.1V, 0.01V, and 0.001V respectively.

In order to evaluate the effectiveness of the proposed circuit, we compared between the proposed circuit and folded cascode operational amplifier without CST.

Figure 9 shown the FFT results of the proposed circuit (with CST) and the conventional circuit (without CST). This figure explained if the proposed circuit could drastically reduce V_n (three sinusoidal signals). For example, this reduction of 20Hz reached 2586.5 times or 70.47 dB in calculation of FFT analysis. The concrete values of V_n were listed in Table 2. From these results, we could find the effectiveness of the proposed circuit.

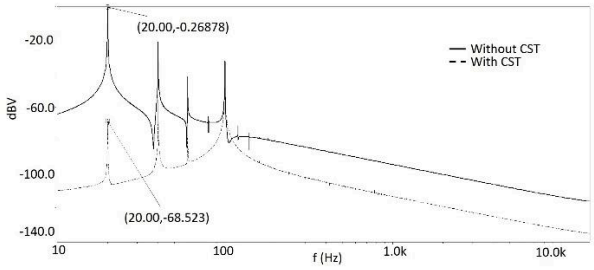

Fig. 9. Comparison FFT results of without and with CST.

Table 2. Simulation comparison of non-chopper and chopper implementation

	Without CST	With CST
V_n *at 20 Hz*	-0.269 dBV	-68.523 dBV
V_n *at 40 Hz*	-20.775 dBV	-56.076 dBV
V_n *at 60 Hz*	-41.172 dBV	-70.629 dBV
V_{IN}	-31.315 dBV	-30.866 dBV

Next, we confirmed the influence of the frequency of CLK in the proposed circuit. The chosen frequencies were 1 kHz, 4 kHz, and 10 kHz. The comparison results of FFT analysis were shown in Figures 10, 11 and 12.

Figure 10 gave information that V_n was already modulated to higher frequency band and could be removed by using LPF. However, we still could find very small V_n (*the remaining of* V_n). The remaining of V_n had larger magnitude alongside the increase of chopping frequency as shown in Figure 10.

Figure 11 shown the enlargement of the low frequency area of Figure 10. For same frequency (i.e. 40 Hz) differences of the remaining of V_n on 1 kHz and 10 kHz reached 14.75 times or 25.59 dB.

Figure 12 showed the output voltage after Gm-C LPF. From the results, we could find low noise floor when chopping frequency of CST was high. In addition, modulated V_n, which was moved into around chopping frequency, was smoothly removed in higher chopping frequency.

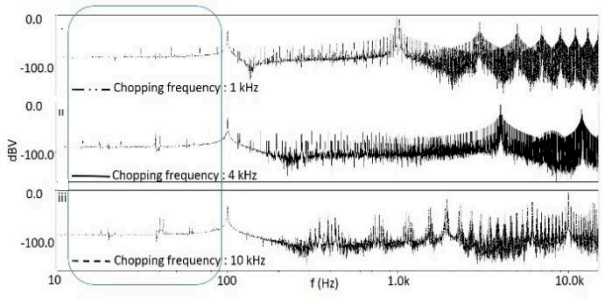

Fig. 10. The output of folded cascode Op-Amp CST implementation (Top: 1 kHz, Middle: 4 kHz, Bottom: 10 kHz)

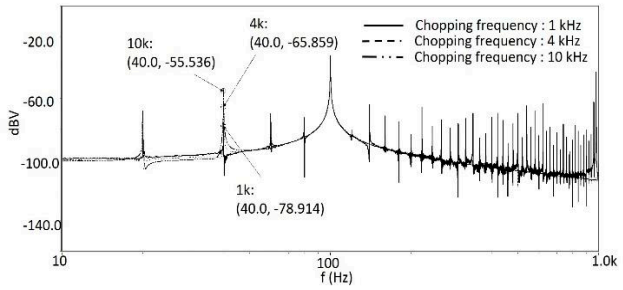

Fig. 11. Comparison of the remaining *1/f* noises.

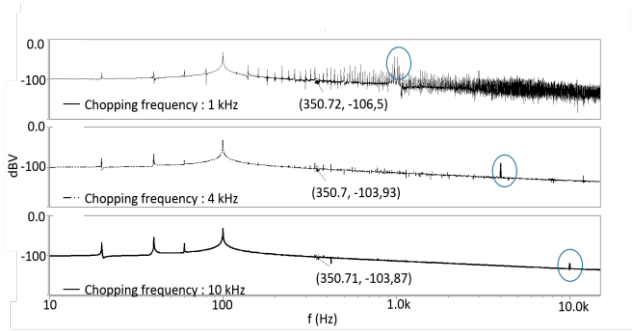

Fig. 12. The filter output of folded cascode Op-Amp CST implementation (Top: 1 kHz, Middle: 4 kHz, Bottom: 10 kHz).

If we compared the simulation results (1 kHz, 4 kHz and 10 kHz), the performance in the case of 4 kHz was better, because the remaining of V_n was small and remaining noise in high frequency band was smooth. Therefore, we focus on the signals on each node in the case of 4 kHz chopping frequency.

Figure 13 shown the process of FFT analysis under 4 kHz chopping frequency. The amplification was 9 times in theory and removing V_n.

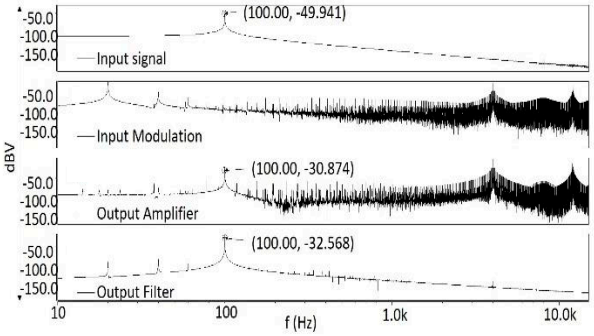

Fig. 13. FFT simulation results of *1/f* noise reduction process under 4 kHz chopping frequency (Top: input signal, Second: modulated signal, Third: output of amplifier, Bottom: output of LPF).

From Figure 13, the magnitude of V_{IN} was -49.49 dBV and the modulated signal moved into $(f_{clock} \pm f_{input})$ and left the remaining of V_n. Next, the signal was amplified 9 times by the amplifier. Finally, the noise of the high frequency band could be cut by LPF and we could get smooth characteristics in high frequency band. It almost completely removed the modulated *1/f* noise. However, the amplification was also reduced around 8.29 dB.

5. CONCLUSION

In this paper, design of low *1/f* noise folded cascode operational amplifier by using chopper stabilization technique has been proposed. Using this design, the *1/f* noise can be reduced drastically. The average of this reduction is 44.337 dBV or 164.767 times. Furthermore, the remaining *1/f* noise is reduced along with reduction of chopping frequencies.

The actual chip fabrication and its evaluation are future work.

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