DOI: 10.18721/JCSTCS.14306
УДК 621.375

ZERO-DRIFT OPERATIONAL AMPLIFIERS

A. Assim[1,2], E.V. Balashov[2]

[1] Salahaddin University, Erbil, Iraq;

[2] Peter the Great St. Petersburg Polytechnic University, St. Petersburg, Russian Federation

This article considers the design and implementation of four different zero-drift operational amplifiers with 50 nm technology CMOS and compares their characteristics. The aim is minimizing input offset voltage and flicker noise. Offset voltage is unavoidable in operational amplifiers, because no two transistors can be identical. A small difference in their dimensions (length or width) gives rise to this undesirable effect, the value of offset voltage in common operational amplifiers is less than 10 mV. In this article, two major techniques of dynamic offset cancellation, chopping and auto-zeroing, are considered. The operational amplifier with chopping shows the best result among the four amplifiers.

Keywords: zero-drift operational amplifiers, auto-zeroing, chopper amplifier, offset voltage reduction, CMOS.

Citation: Assim A., Balashov E.V. Zero-drift operational amplifiers. Computing, Telecommunications and Control, 2021, Vol. 14, No. 3, Pp. 64–74. DOI: 10.18721/JCST-CS.14306

ОПЕРАЦИОННЫЕ УСИЛИТЕЛИ С НУЛЕВЫМ ДРЕЙФОМ

А. Ассим[1,2], Е.В. Балашов[2]

[1] Университет им. Салахаддина, Эрбиль, Ирак;

[2] Санкт-Петербургский политехнический университет Петра Великого, Санкт-Петербург, Российская Федерация

Рассмотрена разработка и реализация четырех различных операционных усилителей с нулевым дрейфом с использованием технологии КМОП 50 нм. Целью является минимизация входного напряжения смещения и фликкерного шума. Напряжение смещения неизбежно в операционных усилителях, так как невозможно изготовить два транзистора одинаковых размеров. Небольшая разница в их размерах (длина или ширина) вызывает этот нежелательный эффект, значение напряжения смещения в обычных операционных усилителях меньше 10 мВ. В статье описаны два основных метода: коррекция дрейфа нуля на основе модуляции/демодуляции сигнала и периодическая коррекция дрейфа. Операционный усилитель с техникой коррекции дрейфа нуля на основе модуляции/демодуляции сигнала показал наилучшие результаты среди четырех усилителей.

Ключевые слова: операционные усилители с нулевым дрейфом, периодическая коррекция дрейфа, коррекция дрейфа нуля на основе модуляции и демодуляции сигнала, снижение напряжения смещения, КМОП.

Ссылка при цитировании: Assim A., Balashov E.V. Zero-drift operational amplifiers // Computing, Telecommunications and Control. 2021. Vol. 14. No. 3. Pp. 64–74. DOI: 10.18721/JCSTCS.14306

Introduction

Operational amplifiers are among the most versatile building blocks that are used in many modern analog and digital systems including filters, active rectifiers, current-to-voltage converters, etc. [3–18]. Due to their robust performance and righteous characteristics, they mimic an ideal amplifier, namely high input resistance, low output resistance, high gain, and stability [17]. Like in any other device, getting ideal characteristics in practice is impossible; therefore, tradeoffs must be made between the parameters (noise, linearity, gain, supply voltage, voltage swings, speed, input/output impedance and power dissipation) according to the required application [3]. Indeed, such tradeoffs pose many challenges to the designer, requiring solid knowledge and experience to reach an acceptable compromise.

Offset voltage is a dominant error source for operational amplifiers, especially at low frequencies. It has direct proportionality with flicker noise, hence in this article offset reduction is measured through reduction in flicker noise. Offset voltage exists due to mismatch in transistor sizes. Amplifiers without offset compensation have flicker noise as high as 400 nV/√Hz [1, 2]. There are three major techniques that are commonly used to reduce offset voltage and flicker noise: trimming, auto-zeroing, and chopping. Trimming is done during fabrication to eliminate offset. In order to correct the dimensions of the circuit elements, laser is used. It does not belong to the category of zero-drift operational amplifiers. Because of that, trimming is not considered in this article. Auto-zeroing's principle of operation is based on sampling. The offset voltage is captured in one clock phase (a capacitor is charged to such value, with an opposite polarity) and then subtracted in the next clock phase. Chopping is based on continuous-time modulation. The input signal is modulated by the first chopper to a higher frequency. The offset voltage is added to it, then this signal will be amplified, and the second chopper modulates the offset voltage and demodulates the modulated input signal, hence the offset is converted to a higher frequency. Since the offset voltage undergoes modulation in chopper amplifier, a ripple is observed at the amplifier's output. Both mentioned techniques are dynamic techniques that continuously reduce offset. They also reduce low frequency noise and offset drift as a function of temperature or time, in this paper, auto-zeroing and chopping methods are implemented practically with different architectures. These include a fundamental auto-zeroing amplifier, continuous-time auto-zeroing, chopper amplifier and a combination of chopping and auto-zeroing together.

Fundamental auto-zeroing amplifier

A principal auto-zeroing amplifier is provided in Fig. 1. It consists of an operational amplifier with 5 transistors that act as switches, the differential input signals are given on the input. Clock signals (C1 and C2) are out of phase by 180 degrees. The transistors (M1, M3 and M4) are controlled by clock signal C1, while M0 and M6 transistors are controlled by clock signal C2. The output signal is single-ended, labeled as (Vout). The proposed amplifier operates in the following manner. On the first cycle when the input clock C1 is on (C2 is off), both of the differential inputs (labeled as V– and V+) are shorted. The feedback loop (R0 resistor and transistor M3) is closed and the offset that appears at the output is fed back into the input. Thus, the capacitor (C0 – 5 nF) is charged to the offset voltage value (–10 mV), as shown in Fig. 2. On the other cycle when C2 is on (C1 is off), the amplifier works as usual, meaning that the differential inputs appear at the amplifier's input (they are not shorted). At the same time the capacitor charge compensates the offset voltage, because they are opposite in sign. This will result in zero offset voltage at the input. The capacitor takes around 350.2 μs to charge and begins to compensate the offset voltage.

The fundamental auto-zeroing amplifier isn't suitable for continuous-time applications, therefore, another architecture is introduced below, namely "Continuous-time auto-zeroing".

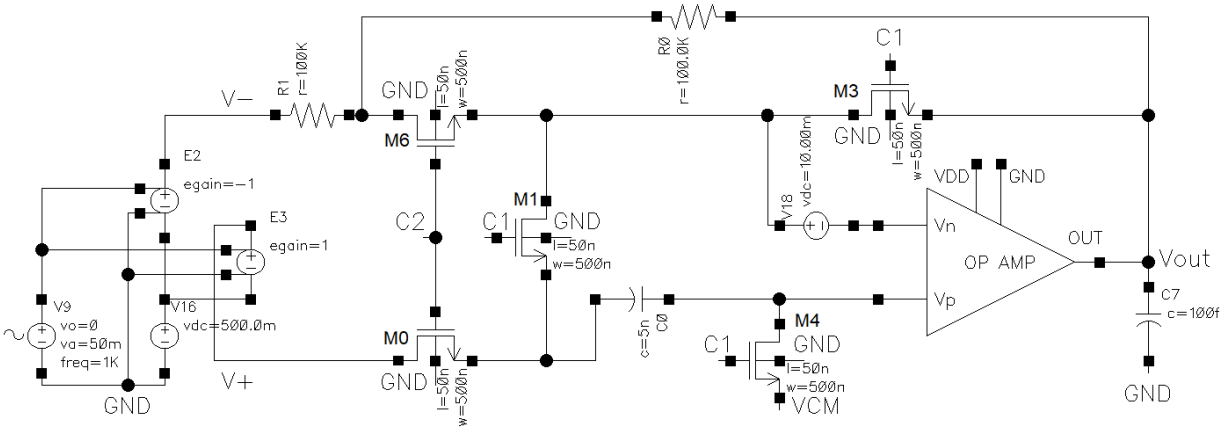

Fig. 1. Amplifier with auto-zeroing

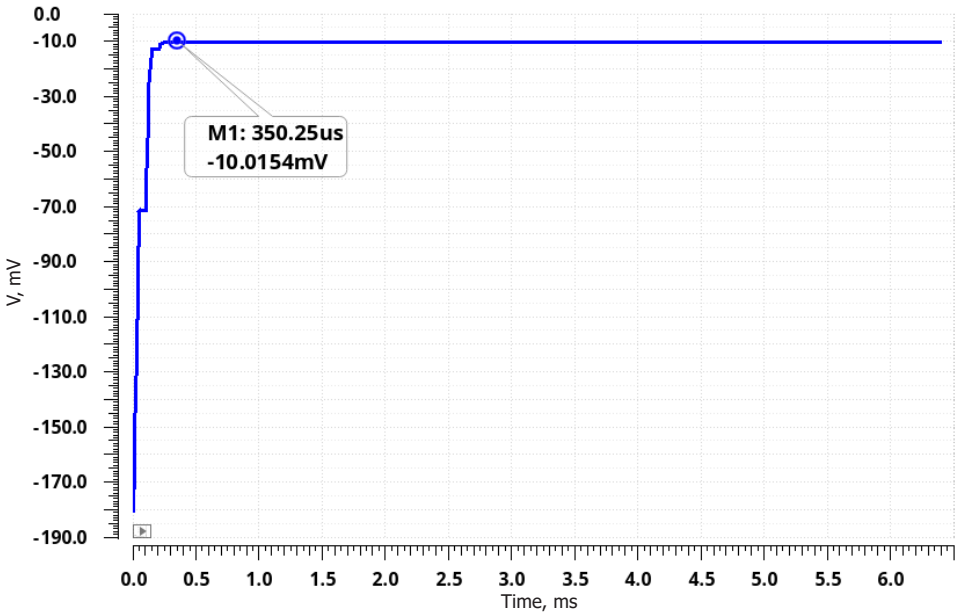

Fig. 2. Voltage on capacitor C0 versus time

Continuous-time auto-zeroing

The fundamental auto-zeroing amplifier was meant to be used in non-continuous applications. Except certain applications, it should not be used, when continuous-time signals are needed, as in voice amplifiers or analog-to-digital converters. A configuration exists that is known as continuous-time auto-zeroing amplifier (CTAZ or ping-pong amplifier). It is a general term that can be used for any amplifier that implements two identical sub-amplifiers with opposite clock pulses to achieve a continuous signal at the output. A realization of such amplifier is given in Fig. 3. It consists of two identical operational amplifiers, 2 feedback resistors (100 kΩ), 5 transistors that are controlled by two out of phase clock signals C1 and C2; the output is a single-ended signal taken from Vout pin. Its working principle can be summarized in two stages. The first stage, when C2 is high (C1 is low), the upper amplifier receives the signal from the differential inputs, amplifies it and feeds it to the output (Vout). The lower amplifier's inputs are shorted and it's in compensation mode. In the next stage, when C2 turns into low (C1 is high), the lower amplifier amplifies

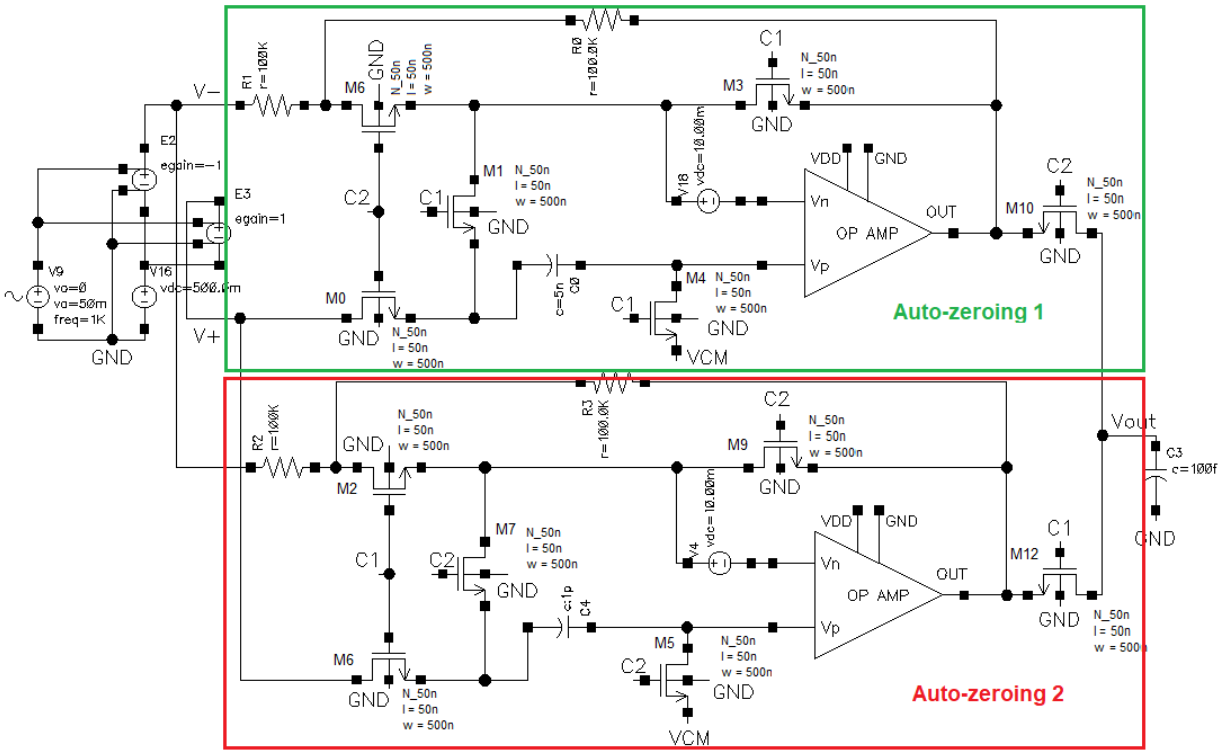

Fig. 3. Continuous-time auto-zeroing amplifier

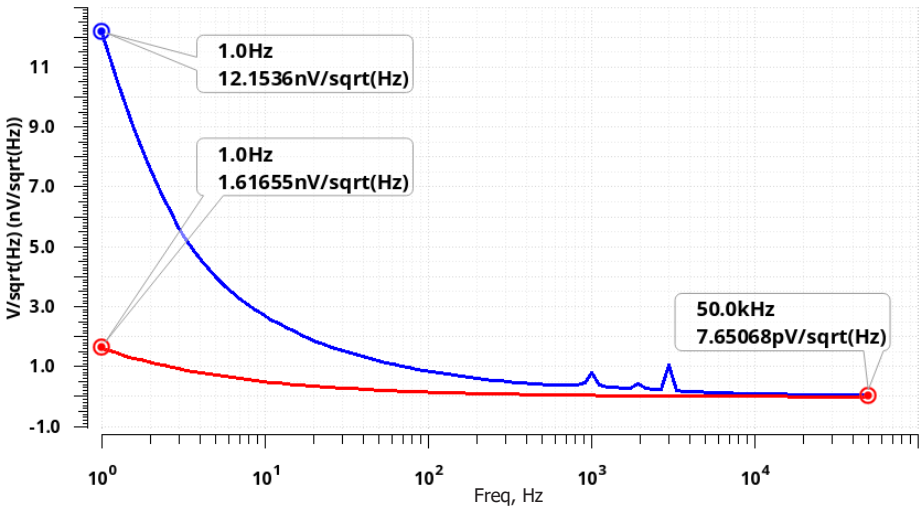

Fig. 4. PSS noise results for circuit in Fig. 3 before and after compensation (blue and red)

the signal, and the output voltage is taken from the lower amplifier . The upper amplifier compensates for offset, this results in a continuous signal at all times at the output. Fig. 4 shows flicker noise reduction.

Besides auto-zeroing, another popular offset reduction technique known as “chopping” exists. It has better flicker-noise reduction characteristics as demonstrated below.

Chopping

Chopping is a major offset-reduction technique. It is widely used to reduce offset voltage [4, 8–11, 20–24]. It is favorable in applications where a continuous-time signal is needed. Unlike auto-zeroing

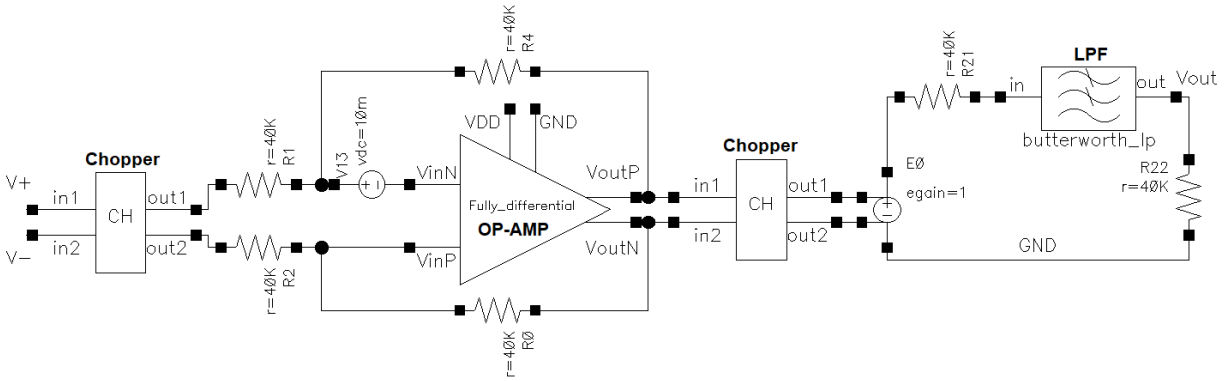

Fig. 5. Chopper amplifier circuit

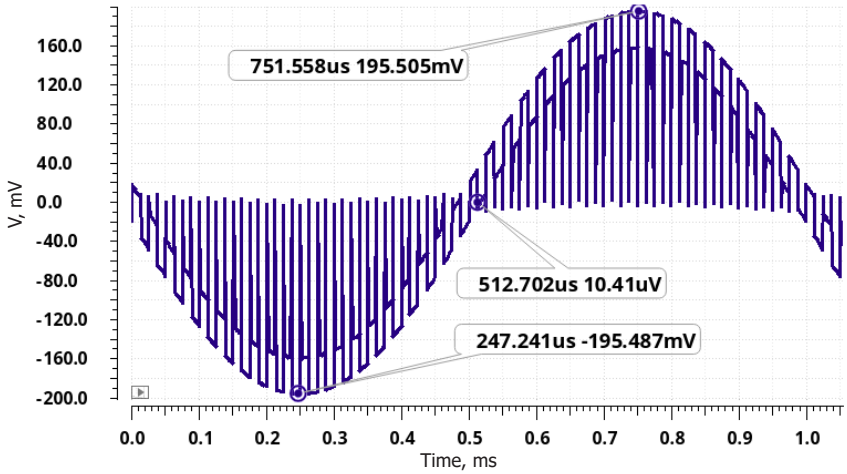

Fig. 6. Chopper amplifier's output signal

amplifiers, chopper amplifiers do not cause noise-folding. This method is based on modulation. The principle of operation is that the voltage Vin goes through the chopper that is driven by a clock at frequency f_{ch}. Hence, it is transformed to a modulated pulse voltage [11, 20–22]. Later, the modulated signal is amplified along with the input offset. The second chopper acts as a demodulator. It demodulates the input signal to a DC voltage, and concurrently modulates the offset to the odd harmonics of clock frequency that will be removed by a low-pass filter [13, 20–24]. In contrast to auto-zeroing, chopper amplifiers do not need any capacitor, they compensate offset voltage using modulation rather than charge compensation. A basic chopper amplifier is presented in Fig. 5. It consists of two modulators (choppers), a fully-differential op-amp, and a Butterworth LPF. As in the previous cases, the value of offset voltage is 10 mV, and it is added as a DC voltage source. The output signal is shown in Fig. 6. The signal looks like a sampled signal due to ripples.

Interestingly, both popular offset-voltage reduction techniques can be used together. This advanced architecture allows us to get the best of each technique.

Chopping & auto-zeroing

A combination of both chopping and auto-zeroing can be used to achieve better noise performance. That is a more sophisticated configuration despite its complexity, because auto-zeroing part gets rid of the voltage ripples caused by chopping, while chopping gets rid of the noise folding problem caused by auto-zeroing. An example of such topology is provided in Fig. 7.

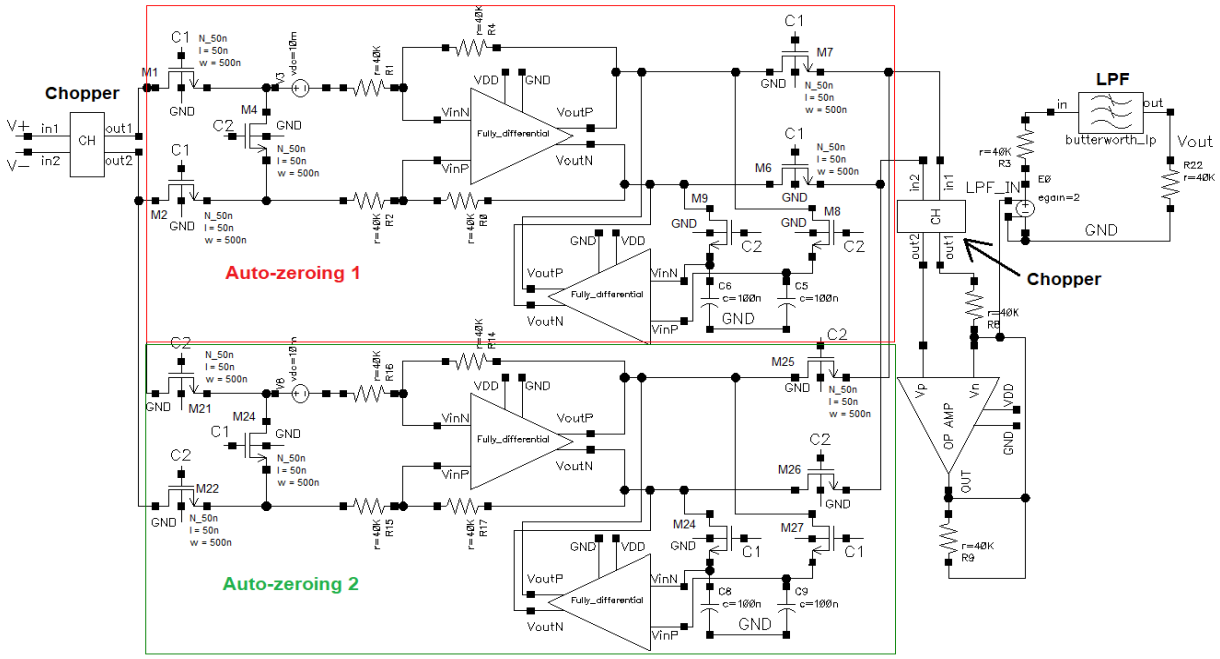

Fig. 7. Schematic of an amplifier using both chopping and auto-zeroing

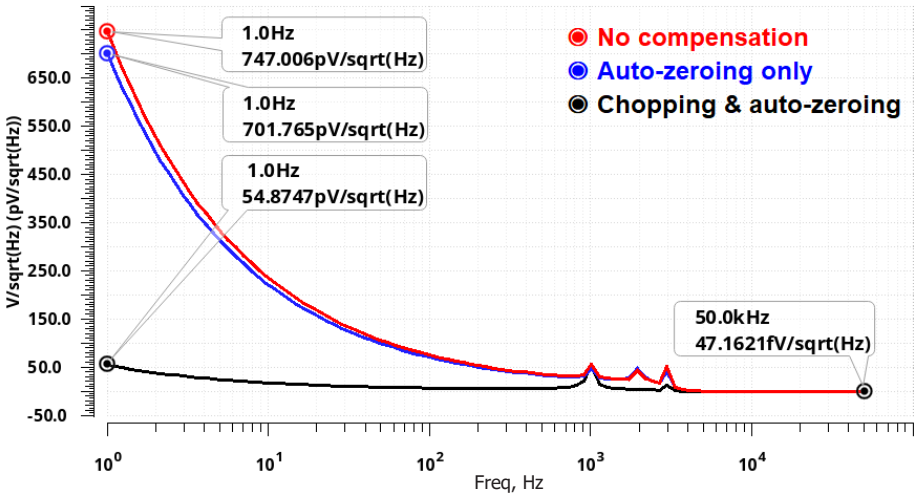

Fig. 8. Schematic of an amplifier using both chopping and auto-zeroing

The circuit consists of two choppers, they are placed at the input and output stages, the first chopper acts as a modulator, while the second chopper acts as a demodulator. Two auto-zeroing amplifiers (they are placed in red and green rectangles) are used between the choppers to further reduce flicker noise and reduce the ripples in the continuous-time signal; their operation can be explained simply by the two-phase nonoverlapping clock signals (C1 and C2). When C1 is one and C2 is zero, the upper auto-zeroing amplifier works in amplification mode while the lower auto-zeroing amplifier compensates the input offset of 10 mV. The feedback loop op-amp senses the voltage difference at the output of the main amplifier, then the capacitors are charged to this value. Later, they are amplified and subtracted from main amplifier's output. In the next clock period (when C1 is zero and C2 is one), the system works in a similar manner.

The lower amplifier operates in amplification mode and the upper amplifier compensates the offset. PSS noise analysis results for the circuit in Fig. 7 are provided in Fig. 8.

Table 1

Input-referred noise PSD, PSRR and CMRR

Configuration	Input-referred noise PSD before compensation, nV/√Hz	Input-referred noise PSD before compensation, nV/√Hz	PSRR, dB	CMRR, dB
Auto-zeroing (AZ)	9.3	2.5	104	98
Continuous-time auto-zeroing	9.4	0.02	103	97
Chopping	337	4.5	116	110
Chopping & auto-zeroing	0.74	0.054	112	106

Table 2

Comparison of the best performing circuit (chopping & auto-zeroing) with previous works

Parameters	This work 2021	[2] 2015	[6] 2016	[7] 2015	[8] 2015	[9] 2017	[11] 2015	[14] 2017	[17] 2011	[20] 2010	[23] 2017
Bandwidth, MHz	47	2.8	10	10.3	3.1	43	0.329	1.5	–	–	30
Bias current, μA	4.6×10^{-5}	420	5×10^{-5}	–	1.5×10^{-5}	–	–	–	175	–	–
Chopping frequency, kHz	20	–	150	10	800	500	500	1	–	10	–
CMOS technology μm	0.05	0.5	0.6	0.045	0.18	0.18	0.028	0.18	0.18	0.18	0.18
CMRR, dB	106.6	123	> 120	–	145	–	70	–	90	–	–
Voltage noise PSD, nV/√Hz	0.05	90	6.5	2.54	6.8	3.5	27	200	15	179	–
Maximum VOS, μV	10.4	90	–	–	–	–	–	–	15	–	1296
PSRR, dB	112.6	–	> 120	–	150	–	68	131	88	–	–
Supply voltage, V	1	5	5.5	1	60	5	0.9	1.8	3.3	1.8	1.2

Results

There are multiple metrics that are commonly mentioned in datasheets to evaluate the performance of operational amplifiers: power supply rejection ratio (PSRR), common-mode rejection ratio (CMRR) and input-referred noise power spectral density. These parameters are provided in Table 1. PSRR and CMRR can be obtained using these formulas:

$$\mathrm{PSRR} = \frac{\Delta V_{DD}}{\Delta V_{OS}}, \tag{1}$$

$$\mathrm{CMRR} = \frac{\Delta V_{CM}}{\Delta V_{OS}}, \quad (2)$$

where V_{CM} is the common-mode voltage; V_{OS} is the offset voltage and V_{DD} is the drain supply voltage (equal to 1 V in the proposed circuits). Additionally, the thermal performance was analyzed, the operational amplifiers work properly in the temperature range of –40 °C to 85 °C.

The results obtained in this work are compared with the existing works in Table 2.

Conclusion

Four zero-drift operational amplifiers were realized and compared. The operational amplifiers were simulated using Cadence Virtuoso software. The Periodic Steady State (PSS) analysis results showed that the proposed techniques are an effective way to reduce the input offset voltage and flicker (1/f) noise. Two operational amplifiers used in this work have a gain-bandwidth product (GBWP) of 47 MHz and 493 MHz, and an open-loop gain of 69.78 dB and 47 dB, respectively. The clock frequency of 20 kHz was chosen for all the circuits. In short, chopper amplifier and continuous-time auto-zeroing amplifier are reducing the flicker noise and input offset voltage more effectively. Chopper amplifier reduces flicker noise from 337 nV/√Hz to 4.5 nV/√Hz, in other words by approximately 7500 %, while continuous-time auto-zeroing amplifier reduces flicker noise from 9.4 nV/√Hz to 0.02 nV/√Hz, that is by 47000 %. But taking into account the simplicity, chopper amplifier is the best configuration. Nevertheless, choosing an operational amplifier for a certain application does not depend only on its flicker noise and offset voltage reduction capability. For instance, in continuous-time applications such as in analog-to-digital converters, continuous-time auto-zeroing must be used, while for amplifying a trigger signal from a sensor, a basic auto-zeroing amplifier can be used despite its humble qualities when compared to other more sophisticated amplifiers.

Acknowledgment

I would like to thank my parents for their never ending support. Special thanks to my dearest friend (Nikolai Kirichenko) for his help throughout my studies in St. Petersburg, Russia. Finally, I want to extend my thanks to the editors of this journal for taking time to review my work.

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Статья поступила в редакцию 26.08.2021.

THE AUTHORS / СВЕДЕНИЯ ОБ АВТОРАХ

Assim Ara Abdulsatar
Ассим Ара Абдулсатар
E-mail: araabdulsattar@gmail.com

Balashov Evgenii V.
Балашов Евгений Владимирович
E-mail: balashov_ev@mail.ru