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Precision Photodiode Current Amplifier With Output Signal Scaling Capability

Yurii Dobrovolsky¹ and Yurii Sorokatyi^{2,*}

¹Department of Computer Systems Software, Yuriy Fedkovych Chernivtsi National University, Chernivtsi, Ukraine

²Department of Radiotechnics and Information Security, Yuriy Fedkovych Chernivtsi National University, Chernivtsi, Ukraine

*Corresponding author (E-mail: y.sorokatyi@chnu.edu.ua)

ABSTRACT A precision multi-range photodiode current amplifier with programmable gain scaling and compensation for both offset voltage and dark current is proposed. The relevance of the work lies in the need for accurate measurement of weak optical signals in photometric, spectroscopic, and other optoelectronic systems, where conventional fixed-gain amplifier circuits fail to provide a sufficient dynamic range. The introduction outlines the main limitations of traditional transimpedance amplifiers, particularly their sensitivity to temperature drift and limited adaptability to varying input signals. A literature review is conducted, covering modern solutions aimed at improving the accuracy of photodiode amplifier designs, including commercial systems with zero-adjustment and temperature compensation. The methodology section describes the structural and circuit design of the developed device, which consists of four functional blocks: an input transimpedance stage based on a low-bias-current operational amplifier; a programmable gain module implemented using switchable resistors that provide discrete gain scaling by orders of magnitude; an offset compensation circuit with a stable bias voltage generator; and an output buffer that ensures proper interfacing with a high-resolution analog-to-digital converter. Special attention is given to the implementation of thermally stable dark current compensation by introducing a negative voltage bias, which significantly reduces the drift of the zero-output level. Experimental results demonstrate a high level of precision and stability of the amplifier under varying photodiode current levels. The amplifier's noise characteristics, linearity, and temperature dependence are evaluated. The functionality of the proposed solution is compared to existing commercial alternatives, highlighting advantages in versatility, scalability, and accuracy. Prospects for further development are discussed, including the implementation of automatic gain range control and the reduction of parasitic currents in electronic switches.

KEYWORDS photodiode, operational amplifier, current-to-voltage converter.

I. INTRODUCTION

Photodiodes are widely used for precision measurement of optical radiation intensity in scientific and industrial applications. To convert the photocurrent into a measurable voltage, operational amplifiers in transimpedance configurations are typically used. This approach provides better linearity and bandwidth compared to direct voltage measurement across the photodiode. However, there are challenges related to the limited dynamic measurement range: with a fixed gain factor, it is impossible to accurately measure both very weak and strong optical signals. Additionally, the zero level of the output signal is affected by the photodiode's dark current (the inherent reverse current in the absence of light) and the offset voltage of the operational amplifier, which leads to error and zero drift. Therefore, there is a relevant need to develop a photocurrent amplifier with an extended measurement range (through automatic or programmable gain scaling) and means for compensating the dark current and offset voltage.

The aim of this work is to develop a precision multi-range photodiode current amplifier with a programmable gain coefficient and a compensated zero output offset.

To achieve this goal, the following tasks must be completed:

- analyze existing solutions and literature on photodiode amplifiers;
- develop a schematic diagram of the device and justify the choice of components;
- implement a gain scaling scheme with predetermined amplification factors;
- incorporate offset and dark current compensation units;
- experimentally investigate the amplifier's parameters and compare the results with existing analogs.

II. LITERATURE REVIEW

The issue of expanding the measurement range of photodiode sensors and increasing measurement accuracy is widely covered in the literature. The classical approach involves the use of a transimpedance amplifier (current-to-voltage converter) with a fixed feedback resistor. To increase the dynamic range of the signal, either multi-stage amplification circuits or amplifiers with a programmable gain factor are used. In particular, two approaches are known: the use of an additional programmable amplifier after the transimpedance stage [1], or the implementation of switchable resistors within the transimpedance stage itself [2, 3].

The first approach is simpler to implement but introduces additional noise and error in the second stage. The second approach offers higher accuracy by eliminating the extra stage, but it is associated with

technical difficulties: parasitic capacitance and leakage currents of analog switches can degrade accuracy at the highest gain settings.

In our work, the second approach was chosen, direct gain scaling within the transimpedance stage, as it provides lower errors [4].

There are industrial solutions that are functionally close to the proposed design. For example, Thorlabs [3] produces a series of compact photodiode amplifiers with fixed and switchable gain, as well as with zero-output offset adjustment. These amplifiers feature a Zero Adjust screw for offset compensation.

Another approach involves using a compensating photodiode [2]. The issue of temperature stability of the dark current is also addressed in studies [2, 5, 6]. Dark current has an exponential dependence on temperature, which requires either thermostating or active electronic compensation. In our work, an electronic dark current compensation scheme is implemented by injecting a stabilized +0.1 V offset voltage [5, 7].

Research on high-precision photodetector parameters is also being conducted in Ukraine [6, 8].

III. DEVICE CONSTRUCTION METHOD

The developed photodiode amplifier consists of four main functional blocks, implemented using a quad operational amplifier (U1, which includes amplifiers U1:A through U1:D). A simplified block diagram of the device is shown in Fig. 1. The first block is the input transimpedance amplifier (U1:A), which converts the photocurrent into a proportional voltage. The second block is the signal scaling module (U1:B) with a

programmable gain factor; it includes a set of resistors with different values that are switched using electronic switches to adjust the gain in discrete steps. The third block is the offset voltage generator (U1:C), which applies a small bias voltage (~ 0.1 V) to the input to compensate for the photodiode's dark current. The fourth block is the output buffer (U1:D), which serves as a current amplifier and matches the output to the input of an analog-to-digital converter (ADC).

To ensure stable operation and noise filtering, capacitors C1, C2, and C9 are used in the circuit.

A detailed description of each block's implementation and component selection is provided below.

A. Input transimpedance stage. The photodiode is connected to the inverting input of operational amplifier U1:A (via a connector marked "photodiode" in the schematic). The continuous photocurrent I_{ph} flows through the feedback resistor, creating a voltage drop that the amplifier maintains at the inverting input, thus forming an output voltage of:

$$V_{out1} = -I_{ph} \times R_f. \quad (1)$$

The feedback resistor of U1:A (denoted as R10 in Fig. 1) is chosen to have a relatively high value (10 k Ω) to provide high sensitivity in the first stage. However, the final gain is determined together with the second stage (U1:B), so R10 can be considered the "base" sensitivity of the system. The operational amplifier U1:A is of type AD8574AS (or equivalent), with ultra-low input bias current and low noise, which is crucial for accurate conversion of small photocurrents.

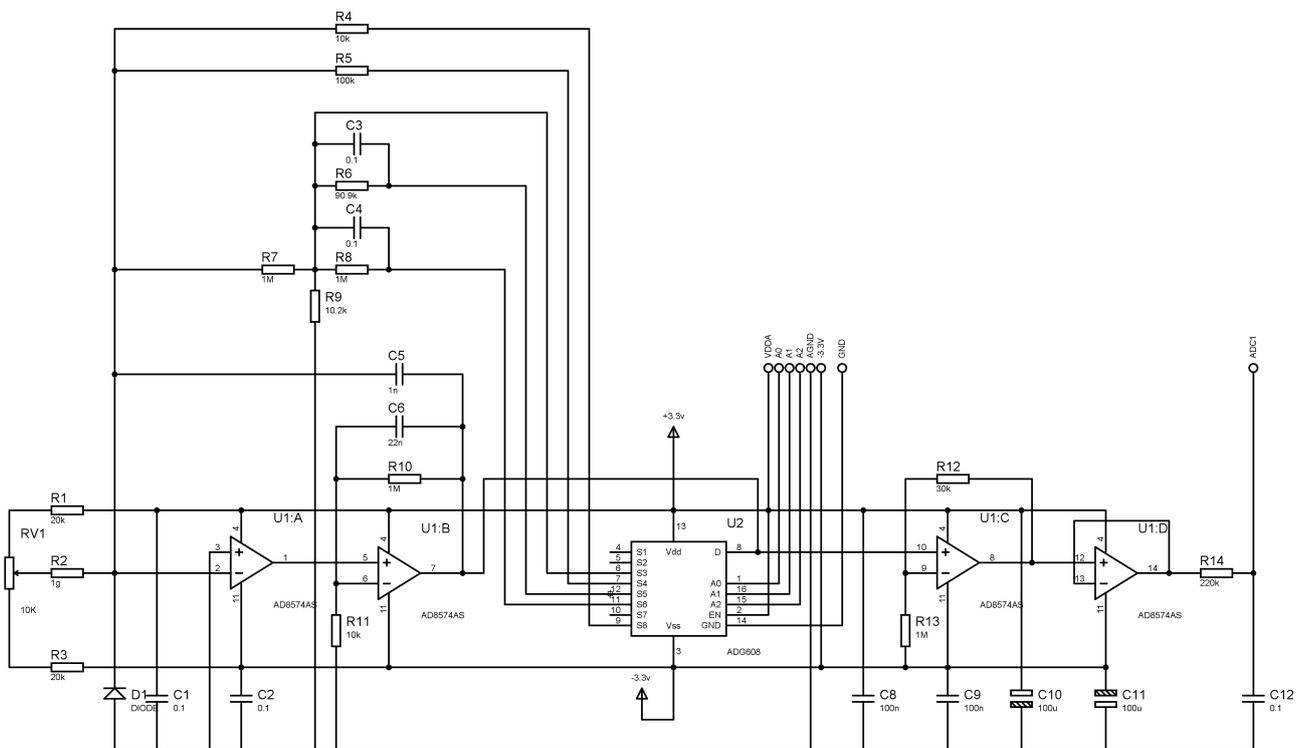


FIG. 1. Schematic diagram of the photodiode amplifier: U1:A – transimpedance input stage; U1:B – programmable gain amplifier; U1:C – offset voltage generator; U1:D – output buffer.

To compensate for DC offset at the output of U1:A, a trimmer potentiometer RV1 is used in the circuit of the non-inverting input. This potentiometer, together with resistors R1 – R3, forms a voltage divider supplying a small adjustable DC voltage to the non-inverting input. By adjusting RV1, the output of U1:A can be set to 0 V in the absence of input signal, effectively correcting the offset of the amplifier. RV1 is adjusted once during device calibration to compensate for the inherent output drift of the op-amp.

To ensure the stability of the transimpedance amplifier in the presence of parasitic capacitance from the photodiode, a compensation capacitor C2 (a few tens of picofarads) is connected in parallel with the feedback resistor. This limits the bandwidth of the stage to the required level (on the order of hundreds of kHz), preventing self-oscillation.

Additionally, a capacitor C1 is installed at the output of U1:A. Together with resistor R9, it forms a low-pass filter that further suppresses high-frequency noise in the first stage.

B. Programmable gain module. The output signal from the first stage, V_{out1} , is fed to the input of the second operational amplifier U1:B, which operates in a voltage amplifier configuration with a variable gain. The negative feedback of U1:B is implemented through a set of resistors R4 – R8, which can be connected in parallel between the output and the inverting input of this amplifier using electronic switches SW1 – SW5. Each resistor has a value approximately 10 times different from the adjacent one (e.g., R4 = 100 k Ω , R5 = 10 k Ω , R6 = 1 k Ω , R7 = 100 Ω , R8 = 10 Ω). By switching these resistors, five gain ranges are implemented, each differing by an order of magnitude ($10\times$). The required range can be selected either manually via switches or automatically via a microcontroller (a control connector for an external controller is provided).

Each of the switches SW1 – SW5 is an analog MOSFET switch selected for low leakage currents (not exceeding a few nanoamperes), to avoid significant errors when operating with the highest resistance (R4).

When none of the switches is closed, only resistor R9 (10 k Ω) remains in the feedback path of U1:B, setting the minimum gain of the second stage. Conversely, when SW1 is closed (R4 = 100 k Ω is connected in parallel with R9), the equivalent feedback resistance increases, and the gain increases approximately $10\times$. Similarly, enabling SW2, SW3, etc., progressively increases the overall gain. Thus, the total adjustable gain range is 10^5 (from 1 to 100,000, if counted from R8 to R4). This discrete scaling allows adapting the amplifier to different input signal levels, ensuring an optimal output voltage range for the ADC in each case (around 0 – 5 V). Importantly, switching gain ranges does not cause significant transients due to the presence of capacitors C1 and C2, which limit the amplifier bandwidth and suppress sharp voltage spikes during switching.

Fig. 2 shows the dependence of the gain of the photocurrent generated by the photodiode using the created amplifier operating as part of the luxmeter. The deviation from linearity is less than 1% and is determined mainly by the linearity of the photodiode.

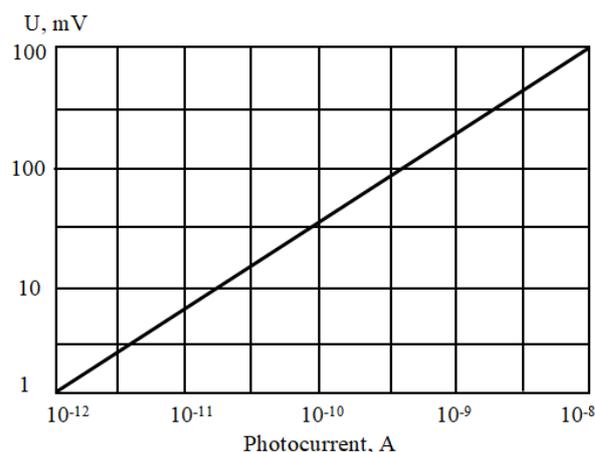


FIG. 2. Dependence of the gain of the photocurrent generated by the photodiode.

C. Offset generation circuit for dark current compensation. The third amplifier, U1:C, is configured as a source of stable low bias voltage applied to the photodiode in reverse polarity relative to its dark current. This circuit essentially compensates the constant reverse current of the photodiode, shifting the operating point of the input stage so that at zero illumination, the output of U1:A approaches zero.

In this design, U1:C operates as an inverting amplifier with a fixed gain. A reference voltage of +0.1 V (from a divider of R12 and R13) is applied to its non-inverting input. As a result, the output of U1:C provides a stable voltage of about –0.1 V (negative relative to the photodiode input), which is injected through resistor R14 into the photodiode circuit.

The value of 0.1 V is experimentally chosen based on the typical dark current of a silicon photodiode and the input bias current of U1:A. This offset causes the dark current to flow in the opposite direction through the photodiode, effectively compensating the device's own reverse current.

A similar principle is used in some industrial amplifiers – e.g., TI solutions introduce ~ 0.1 V on the non-inverting input to neutralize dark current and prevent amplifier saturation.

The adjustment of R12 and R13 is done so that at room temperature and with a dark photodiode, the output of U1:A is zero without further correction via RV1. When temperature changes, the dark current increases, but due to the applied offset voltage, this effect is significantly suppressed.

As a result, the device exhibits high long-term zero stability: even with ambient temperature fluctuations, the output zero level drifts only slightly (within a few millivolts), as confirmed experimentally.

D. Output stage and ADC interface. The final amplifier, U1:D, is configured as a voltage follower (buffer) with capacitive load. It does not alter the signal level (gain ≈ 1), but provides low output impedance for the signal source to the next device. This is important when connecting a high-speed ADC or a long cable, to preserve signal accuracy.

A filtering capacitor C9 (0.1 μ F) is placed at the

output of the buffer to suppress high-frequency noise and stabilize the buffer's operation under load.

As a result, the output voltage V_{out} (labeled "OUT" on the schematic) is ready to be supplied to the input of an external 16- or 24-bit ADC. The output voltage range for each gain setting is selected to maximize the ADC's dynamic range without reaching saturation even at the maximum expected photocurrent.

IV. CONCLUSION

The study presents a precision photodiode current amplifier with programmable output signal scaling. The proposed circuit effectively converts photocurrent into voltage, automatically covering a wide signal range. The use of operational amplifiers with ultra-low input bias current ensures high measurement accuracy down to the picoampere level. The ability to electronically compensate for offset and account for photodiode dark current enhances the device's stability and simplifies calibration. The resulting design is suitable for a wide range of optical measurement systems, including ultraviolet radiometry, fluorescence analyzers, and biomedical sensors. The key advantages of the developed amplifier include:

- wide dynamic range: Five programmable gain sub-ranges cover signal variations of over 10^8 without loss of sensitivity [9];
- high accuracy and linearity: Linearity error does not exceed 0.1 % in each range after calibration; noise floor is approximately 50 pA of equivalent photocurrent;
- stable zero level: Thanks to dark current compensation, the output signal remains close to zero in the absence of light (drift < 0.005 % of full scale);
- IoT system integration: Low power consumption, enhanced reliability, precision, and automatic gain control make the device well-suited for embedded sensing systems requiring stability and long-term durability [10].

AUTHOR CONTRIBUTIONS

Y.S. – development of the amplifier circuit, simulation of amplification stages, formulation of the mathematical model, and construction of experimental plots; Y.D. – methodological guidance, analysis of electrical characteristics and circuit stability, literature review, and editorial revision of the manuscript.

COMPETING INTERESTS

The authors have no competing interests.

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Yurii Dobrovolsky

Doctor of Technical Sciences, Professor of the Department of PZKS. Areas of research interest: Research and development of mathematical models and algorithms for creating reliable software, as well as reliable measuring, medical and environmental equipment.

ORCID ID: 0000-0002-1248-3615



Yurii Sorokatyi

Assistant at the Department of Radio Engineering and Information Protection, Chernivtsi National University. Research interests: silicon-based primary converters for measuring low-intensity optical information signals.

ORCID ID: 0000-0001-9462-775X

Прецизійний підсилювач струму фотодіода з можливістю масштабування вихідного сигналу

Юрій Добровольський¹, Юрій Сорокатий^{2,*}

¹Кафедра програмного забезпечення комп'ютерних систем, Чернівецький національний університет імені Юрія Федьковича, Чернівці, Україна

²Кафедра радіотехніки та інформаційної безпеки, Чернівецький національний університет імені Юрія Федьковича, Чернівці, Україна

*Автор-кореспондент (Електронна адреса: y.sorokatyi@chnu.edu.ua)

АНОТАЦІЯ У роботі запропоновано прецизійний багатодіапазонний підсилювач фотодіодного струму з програмованим масштабуванням коефіцієнта підсилення та схемою компенсації нульового зміщення і темного струму. Актуальність теми зумовлена необхідністю точного вимірювання слабких оптичних сигналів у фотометричних, спектроскопічних та інших оптоелектронних системах, де класичні схеми з фіксованим підсиленням не забезпечують достатнього динамічного діапазону. У вступі розглянуто основні обмеження традиційних трансімпедансних підсилювачів, зокрема чутливість до температурного дрейфу та обмежену адаптивність до змін вхідного сигналу. Проведено огляд сучасних рішень щодо підвищення точності фотодіодних підсилювачів, включаючи промислові схеми з нульовим регулюванням та температурною компенсацією. Методичний розділ містить опис структурної та принципової схем розробленого пристрою, що складається з чотирьох функціональних блоків: вхідного трансімпедансного каскаду на операційному підсилювачі з низьким струмом зміщення; модуля програмованого підсилення з комутованими резисторами, які реалізують дискретне масштабування коефіцієнта підсилення на порядки величини; схеми компенсації нульового зсуву, що включає генератор стабільної зсувної напруги; та вихідного буфера для узгодження з високоточною системою аналого-цифрового перетворювача. Особливу увагу приділено реалізації температурно стабільної компенсації темного струму фотодіода шляхом введення від'ємного зміщення, що дає змогу зменшити дрейф нульового рівня. У результатах експериментальних досліджень продемонстровано високий рівень точності та стабільності підсилювача при різних рівнях фотоструму. Оцінено параметри шуму, лінійність та температурну залежність вихідного сигналу. Порівняно функціональність запропонованої розробки з комерційними аналогами, вказано переваги щодо універсальності, масштабованості та точності. Розглянуто перспективи подальшого вдосконалення, зокрема впровадження автоматичного контролю діапазонів підсилення та зниження впливу паразитних струмів електронних комутаторів.

КЛЮЧОВІ СЛОВА фотодіод, операційний підсилювач, перетворювач струму в напругу.



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