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Modeling of integrated signal converters for biomedical sensor microsystems

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This paper presents the results of computer modeling of the proposed functional-electrical circuit of integrated signal converters (ISC) from photosensitive elements based on CMOS operational amplifiers, which is intended for the construction of an element base of hybrid sensor microsystems for biomedical applications. A feature of this ISC is the regulation and filtering of the constant component amplitude in the amplified signal from the diode photosensitive element in the wave range of 400 - 1040 nm

Computer simulation of the functioning of the device was carried out, the constituent components were determined and their parametric optimization was carried out. The results of experimental studies and computer modeling agree well, which confirms the correct functioning of the proposed signal converter from photosensitive elements. The developed ISC is suitable for creating real devices, both on the basis of discrete components and in an integrated design, as an element of sensor microsystems-on-chip or intelligent sensors.

Keywords: sensor microsystem-on-chip, integrated signal converter, photosensitive element, circuit modeling, operational amplifier, CMOS-structures.

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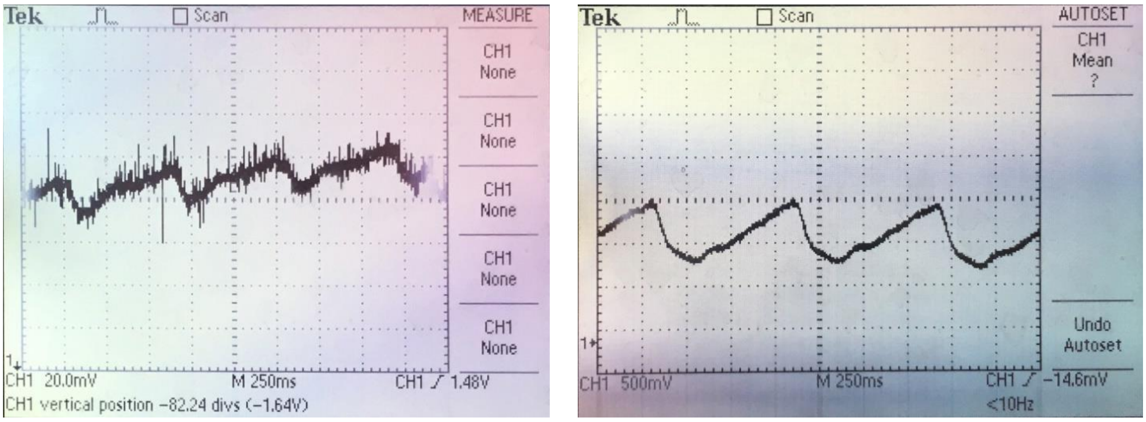
Introduction

In recent years, non-invasive pulse oximetry monitoring methods, using both portable and stationary devices, have been increasingly used [1,2]. The physical principles of photometry for biomedical applications are given in [3,4], which shows the possibility of calculating the ratio of oxygenated and non-oxygenated fractions of hemoglobin in human blood using photoplethysmography methods. In [5-7], attempts were made to use these methods for non-invasive control of hemoglobin and glucose levels in human blood. A prototype of a portable device based on the analysis of optical absorption of light and frequency separation using interference filters is proposed. But the use of only one frequency of 940 nm to determine the level of glucose does not allow obtaining the required accuracy, due to practically the same absorption coefficients of water and glucose at the specified frequency. However, increasing the accuracy of measurements can be achieved by computational methods using spectral analysis in devices for non-invasive blood glucose control [5, 8] and by methods of coordinated filtering of absorption spectra of various blood components, measurement accuracy acceptable for practical use can be achieved.

Important components for the construction of sensor microsystems-on-chip, in particular, for biomedical applications related to the monitoring of such important parameters as the level of glucose in human blood, the blood saturation with oxygen (saturation level), the heart rate (pulse oximetry), the bilirubin level etc., which can be obtained by non-invasive methods – are converters of optical signals from photosensitive sensor elements for different wavelengths. Existing photosensitive sensor elements of this type, when building specific schemes require special transformations of the investigated signals, in particular, amplification of the amplitude of the investigated signals or compensation of their constant component [9]. In addition, there are no domestic devices of the mentioned type in an integral design.

The paper presents the results of the development and



a b

Fig. 1. Oscillogram of the signal from the photo-detector after passing light through the finger (a) and the oscillogram after hardware processing and filtering (b).

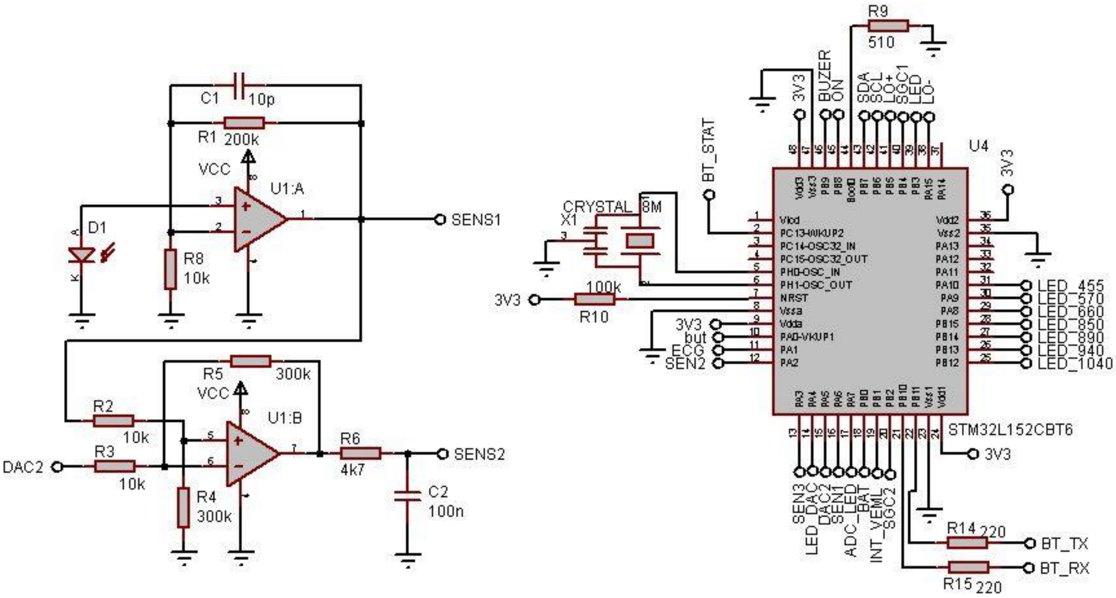


Fig. 2. Functional principle scheme of the signal converter from photosensitive elements for photoplethysmography.

computer modeling of the proposed functional-electrical circuit of integrated signal converters (ISC) from photosensitive elements based on CMOS operational amplifiers, which can be used to build an element base of hybrid sensor microsystems for biomedical and other applications. A feature of the developed ISC scheme is the ability to adjust and filter the constant component amplitude in the amplified isolated information signal from the diode photosensitive element in the wave range of 400-1040 nm.

I. Development of the functional principle scheme of the integrated signal converter (ISC) from photosensitive elements.

The blood pulsation signal from the photodiode obtained from the photodetector is quite weak and very noisy, and also contains a large constant component (Fig. 1,a.) and is not suitable for direct digital-to-analog conversion with sufficient resolution [10,11].

The amplitude of the signal is quite small, less than 2% of the constant component, and high-frequency noise is also present. Also, the value of the constant component is not known in advance, and depends on many factors, such as the thickness and transparency of the translucent tissue, and may change significantly during the measurement process due to human movement. To eliminate the constant component, a differential circuit on the operational amplifier (Fig. 2) is proposed, with the possibility of dynamically changing the level of compensation with the help of a digital-to-analog converter of a microcontroller (DAC). This approach makes it possible to compensate for the constant component of any value, and to pre-amplify the useful signal for expansion over the entire dynamic range of the ADC [12].

After eliminating the constant component, the signal passes through an RC filter to clean it of high-frequency interference and distortions. The SENS1 output is also connected to the ADC channel, which allows adjusting the current of the LED to maintain the signal in the entire ADC range, regardless of the thickness and throughput of bio-tissues. The oscillogram of the signal from the SENS2 output is shown in Fig. 1, b, [9] from which we can see that it can already be digitized with sufficient accuracy for further mathematical processing. This signal is digitized with a frequency of 200 Hz and stored in an array. The pulse wave is investigated at the wavelength of light radiation of 570 nm, for which the absorption capacity of blood is the greatest. For other frequencies, only the normalized amplitude is analyzed to determine saturation and other blood components [9]. The current of the LED is stabilized by the current stabilizer on the OD, and the DAC of the microcontroller is setting (LED_DAC, Fig. 2). The current value is chosen so that the maximum signal at the SENS1 output is close to the upper limit of the ADC operation (2.4 V). In this way, the maximum amplitude of the useful signal is achieved regardless of the thickness and transparency of the bio-tissue.

Since the determination of various parameters of blood requires a light source in a fairly wide range, the photodetector must also have high sensitivity in a wide range of wavelengths from 450 to 1040 nm [8]. It is also possible to implement using several photo receivers with their own signal processing schemes, for example, one in the visible range and one in the infrared. This implementation reduces the bandwidth requirements of the receiver and makes it possible to place the photo-receiver exactly opposite the corresponding LED. To reduce interference and temperature drifts, it is better to place the hardware signal processing circuit on one chip.

II. Modeling and parametric optimization of the integrated signal converter

The proposed electrical schematic circuit for the integrated implementation of the operational amplifier is shown in Fig. 3, the dimensions of *p*- and *n*-channel MOS transistors are shown in table. 1.

The manufacturing technology and design-technological standards for designing the topology are based on a 1.2-micron technological process on *p*-type conductivity substrates for *n*-channel MOS transistors and *n*-type wells for *p*-channel MOS transistors. The OD input stage is built on a differential pair of *n*-channel MOS transistors M18, M19. The start-up circuit is built on transistors M1-M3. Transistors M4-M9 set a constant bias and control all current sources. Transistors M10, M11, M17 set the voltage of the current mirror M12-M15. The output stage is formed on transistors M16, M21.

On the basis of the designed circuit of the operational amplifier and the results of its computer simulation (Fig. 4), the structural and technological parameters (Table 1) were obtained for designing the topology of the integral converter of the multi-channel receiver of

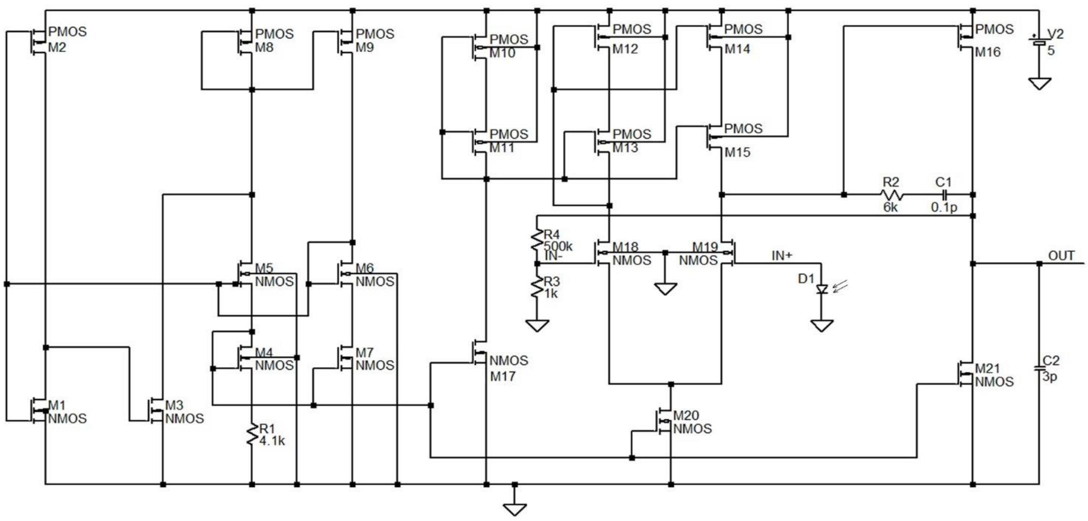
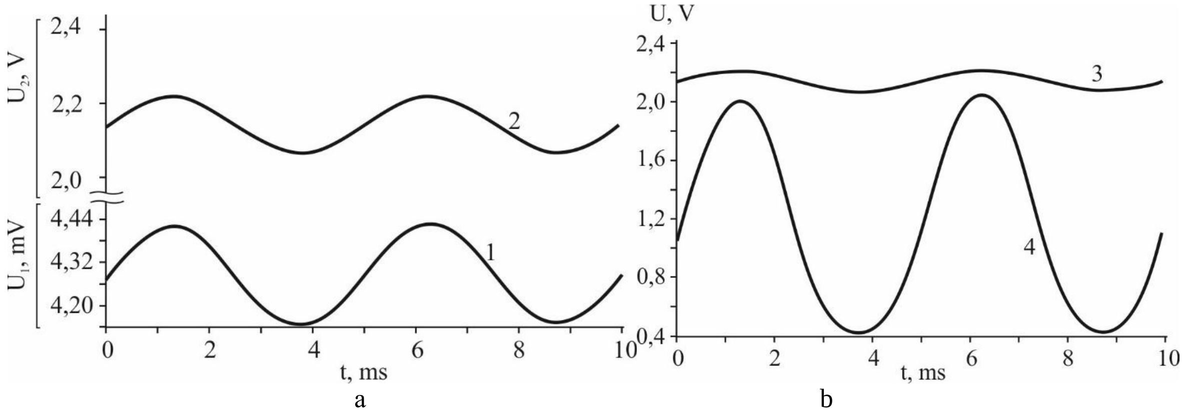


Fig. 3. Part of the electrical schematic circuit of the ISC (one operational amplifier) (the dimensions of the *p*- and *n*-channel MOS transistors are given in Table 1).

Table 1.

Dimensions of *p*- and *n*-channel MOS transistors

Transistor number	Transistor type	Design topological dimensions of channels	
		Length, μm	Width, μm
M1	*n*-MOS	3,2	10
M3	*n*-MOS	20	4
M4	*n*-MOS	4	240
M5, M6, M18, M19	*n*-MOS	4	70
M7, M17, M20	*n*-MOS	4	60
M21	*n*-MOS	4	80
M2	*p*-MOS	16	4
M8, M9, M11, M13б M15	*p*-MOS	4	120
M10, M12б M12	*p*-MOS	4	30
M16	*p*-MOS	4	115



a b

Fig. 4. Timing diagrams of the simulation of the functioning of the ISC in LT SPICE: a – amplification of the output signal of the photo-receiver, b – compensation of the constant component, filtering and amplification of the useful signal over the entire dynamic range of the ADC. 1 – input signal, 2 – SENS1 output, 3 – SENS2 output.

Photoplethysmography signals.

After filtering and selection of the variable component of the signal, the output signal was obtained in the entire range of operation of the ADC with minimal distortion, which preserves the maximum of useful information contained in the photoplethysmography signal.

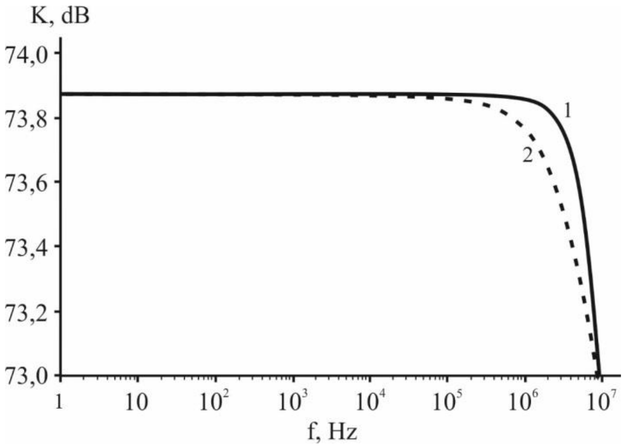


Fig. 5. Amplitude-frequency characteristics of the integral signal converters circuit:
1 – amplitude, 2 – phase.

An amplitude-frequency characteristic was obtained for the developed circuit, which shows the stability of the amplification factor and the signal phase up to frequencies of the order of 10 MHz.

For the practical implementation and further development of the non-invasive photoplethysmograph, its integral implementation is planned, which involves the development and modeling of the layouts, taking into account the influence of integral parasitic elements and connections, structural and technological parameters of integral CMOS-structures, and their layouts features.

Conclusions

A functional electrical circuit and a real prototype of an integral signal converter from diode photosensitive sensor elements in the frequency range from 400 to 1040 nm and operational amplifiers based on discrete components for photoplethysmography have been developed. The results of oscillographic studies of the proposed prototype are presented and computer simulation of its functioning is carried out, the constituent components are determined and their parametric optimization is carried out. The results of both oscillographic studies and computer simulations agree well, which confirms the correct functioning of the proposed signal converter from photosensitive elements.

It is shown that in the proposed functional-electrical circuit of this signal converter, it is possible to eliminate the constant component with a dynamic change in the level of compensation with the help of a digital-to-analog converter of a microcontroller. This makes it possible to compensate for the constant component of any value, and to pre-amplify the useful signal over the entire dynamic range of the ADC.

The obtained results can be the basis for the development of the layouts of the integrated signal converter on CMOS-structures.

The developed integrated signal converter is suitable for creating real devices both on the basis of discrete components and in integrated implementation as an element of sensor microsystems-on-chip or intelligent sensors for biomedical applications.

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Моделювання інтегральних перетворювачів сигналів для біомедичних сенсорних мікросистем

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В роботі наведено результати комп'ютерного моделювання запропонованої функціонально-електричної схеми інтегрального перетворювачів сигналів (ІПС) від фото- чутливих елементів на основі КМОН-операційних підсилювачів, що призначена для побудови елементної бази гібридних сенсорних мікросистем для біомедичних застосувань. Особливістю даного ІПС є регулювання та фільтрація амплітуди постійної складової у підсиленому сигналі від діодного фоточутливого елементу в діапазоні хвиль 400 - 1040 нм. Проведено комп'ютерне моделювання функціонування пристрою, визначено складові компоненти і проведено їх параметричну оптимізацію. Результати експериментальних досліджень і комп'ютерного моделювання добре співпадають, що підтверджує правильність функціонування запропонованого перетворювача сигналів від фоточутливих елементів. Розроблений ІПС є придатним для створення реальних пристроїв, як на основі дискретних компонентів, так і в інтегральному виконанні, як елемент сенсорних мікросистем-на-кристалі або інтелектуальних сенсорів.

Ключові слова: сенсорна мікросистема, інтегральний перетворювач сигналів, фоточутливий елемент, схемотехнічне моделювання, операційний підсилювач, КМОН-структури.