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Non-Invasive Experimental Glucometer

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Abstract. The technical implementation of the method for diagnosing blood sugar levels without blood sampling is considered. The structural diagram of the device of the light source and spectrometer is shown. Methods of compensating for the non-uniformity of the spectral characteristics of the receiver of the light flux are presented. The spectra of the studied objects were obtained.

INTRODUCTION

Glucose and metabolites of carbohydrate metabolism play a crucial role in providing energy to body tissues and in cellular respiration. A prolonged increase or decrease in its content leads to serious consequences that threaten human health and life. Therefore, doctors attach great importance to controlling blood glucose levels. Normally, the glucose concentration is maintained in the range from 60 to 100 mg/dl (from 3.3 to 5.5 mmol/l) [1]. Within these limits, the most favorable indicators of the functioning of cells and organs, especially nerve cells and the human brain, are provided. Currently, more than 200 million people in the world have diabetes – an endocrine disease associated with impaired glucose uptake and developing due to absolute or relative (impaired interaction with target cells) insulin hormone deficiency, resulting in hyperglycemia – a persistent increase in blood glucose.

Currently, treatment for diabetes is aimed at eliminating the existing symptoms without eliminating the cause of the disease, since an effective treatment for diabetes has not yet been developed. In order to avoid complications, people with diabetes are forced to adjust their lifestyle and diet, as well as periodically measure the concentration of glucose in the blood. With type 1 diabetes mellitus, blood sampling must be performed several times a day, which, of course, causes inconvenience [1]. A review of the current consumption market shows that despite the active development of science today, like many years ago, the invasive method for determining blood sugar levels is mainly used [2, 3]. All this makes it important to develop a device designed for non-invasive determination of blood glucose.

To solve the problem of developing an experimental sample of a non-invasive glucometer, the most promising solution is the technical implementation of a spectroscopic non-invasive method for monitoring the concentration of glucose in human blood [4–9]. The method consists in analyzing the level of absorption of optical radiation in the near infrared range by glucose. The analysis is carried out by solving a system of linear equations based on the Bouguer-Lambert-Beer law using the Gauss method. To improve accuracy, the authors propose using a mathematical model based on the method of singular decomposition [9].

This article describes the technical implementation of the above method for diagnosing blood sugar levels without blood sampling. The developed device sets the level of light flux in the wavelength range from 700 to 1050 nm, registers it, samples and processes the received data.

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SUBSTANTIATION OF THE SUGGESTED DESIGN

To register the level of optical radiation, it is necessary to convert the light intensity into an electrical signal. A typical solution to this problem is to use a photodetector. The choice of a photodetector is due to the fact that the contribution of the intensity of glucose uptake is very small in relation to other components of biological tissues and is less than 0.2%, therefore it is necessary that the hardware-software module have a large dynamic range. A large dynamic range is provided through the use of a photodetector having a dynamic range of at least 60 dB. To ensure this parameter, the ELIS1024A photodetector was selected, the technical characteristics of which provide more than 70 dB.

The measurements showed that with a signal bandwidth of 30 nm, large errors in the measurement are possible. A more precise definition of the boundaries of the measurement channel is required. This circumstance led to the use of a multi-element photodetector. The width of the sugar-dependent region is 30-40 nm and is uneven in absorption coefficient. The use of a multi-element photodetector having 256 elements solves this problem, which makes it possible to create a correction matrix for each element of the spectrum (pixel). In this regard, it is possible to electronically adjust the channel bandwidth and its exact binding to the desired regions of the world.

The disadvantage of this solution is the uneven spectral sensitivity of the photodetector, which falls 8 times from 700 to 1100 nm. To maintain the dynamic range, it is necessary to use a light source with an inverse spectral characteristic with respect to the photodetector, i.e. the intensity at a wavelength of 1100 should be approximately 10 times greater than 700 nm.

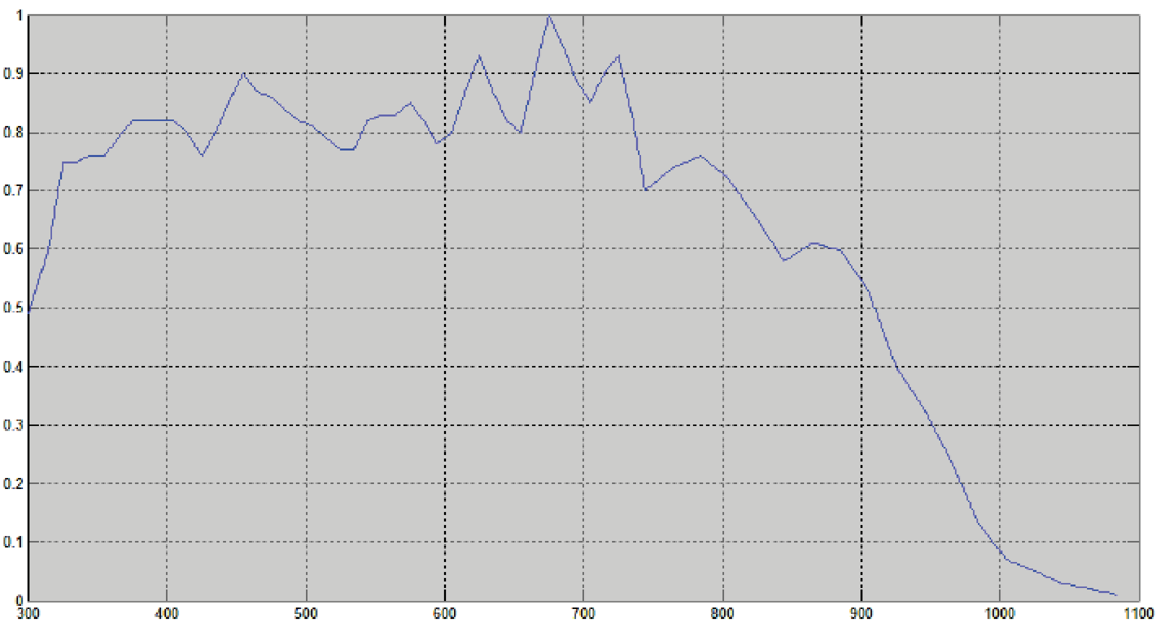

FIGURE 1. Spectral sensitivity of the photodetector depending on the wavelength.

Proceeding from this, a light source module was developed in which light fluxes from LEDs with a given spectrum are added on a diffraction grating. The light source circuit is designed based on the addition of light fluxes of different spectral bands using a diffraction grating. The optimal diffraction grating for a wavelength range from 700 to 1100 nm in terms of the spectral dispersion angle and light curve is a grating of 830 pcs/mm. A diffraction grating with the indicated technical characteristics makes it possible to obtain a spectral dispersion angle of 19 degrees. When using LEDs with a housing of 5 mm, the placement of 8 LEDs is possible at a distance of more than 120 mm from the diffraction grating. The case size will be equal to 80 mm in width. The stability of the parameters is ensured by the power of the stability of the current source with a deviation of 0.05%, which ensures the stability of measurements with a dyne range of more than 70 db.

The advantages of the selected illuminator circuit are its ability to switch bands using an electronic control circuit, as well as control the output power of the source. Given the fact that the stability of the parameters of the optical radiation sources is determined by the stability of the current sources, the power supply circuit of the LEDs is designed based on considerations of minimizing the ripple of the supply voltage. The main objective of the circuit is to control the current through each of the 8 LEDs in the illuminator. You can adjust the amount of current through the LED using a transistor current source, which is a transistor with a load in the collector circuit and a resistor in the emitter circuit, which sets the amount of current through the load. However, such a circuit has low stability due to the influence of the temperature of the transistor on the collector current according to the Ebers-Mall equation:

$$I_c = I_{sat}[exp(U_{be}/U_T) - 1],\ U_T = \frac{kT}{q}, \tag{1}$$

where q is the electron charge, k is the Boltzmann constant, T is the absolute temperature in kelvins.

To compensate for the influence of temperature, it was decided to use an operational amplifier with negative feedback, due to which, by automatically building the voltage on the transistor base, the emitter and collector currents will be kept in the required range of values. The accuracy of establishing the current flowing through the LEDs depends on the gain of the transistor, the spread of the input voltage and the resistance of the resistor. In this regard, a transistor with a large gain h = 250 was chosen, and the resistors were selected with an accuracy of at least 1%.

To adjust the potential on the transistor base switch, a 12-bit AD5328 DAC was used with an external 2.5V reference voltage source. Thanks to this solution, it became possible to independently regulate voltages in 8 channels with a resolution of 2.5V / 4095 = 0.0006V.

Wavelength stability can be ensured by operating in a certain temperature range of the LED crystal. Preventing the temperature of the LED crystal from exceeding the allowable temperature range is achieved thanks to the heat sink structures of the housing and the printed circuit board on which the LED is mounted. This approach allows heat to be removed to the device body, which ensures the crystal does not overheat by more than 5 degrees with respect to the temperature of the medium.

The maximum wavelength shift of the LEDs is 4 nm by 10 degrees with a strip of 50 nm. This is the maximum wavelength shift in the range of about 1000 nm. In other ranges, the maximum temperature shift of the wavelength is 2 – 2.5 times less. This allows you to take measurements after 10 minutes of warming up the device with the necessary accuracy. To control the heating of the light source, a temperature sensor STLM75 was added to the board with accuracy ±0.5°C.

The task of registering changes in the concentration of glucose in the blood requires the use of circuitry solutions aimed at minimizing the level of interference with respect to the input signal. A wide dynamic range and a small amplitude of the useful signal determine the necessity of using an analog-to-digital converter with high bit depth and impose additional requirements on the power source and the reference voltage. In this paper, using the principles of electrical separation of digital and analog ground, replacing switching power supplies with linear voltage stabilizers, and filtering both the supply voltage and the useful signal, we managed to reduce the maximum level of noise signals that impede the processing of an analog signal that carries information about the level of illumination pixel of the ELIS1024 photodetector, up to a value not exceeding 0.07% of the ADC reference voltage.

The analog output of the photodetector is buffered and scaled using an operational amplifier. In order to minimize the signal-to-noise ratio, it was decided to abandon the classical differential amplification circuit on the operational amplifier, since in this case, when choosing a gain, in addition to the useful signal from the output of the photodetector, noise effects will also be amplified. It was decided to use an AD8616 type operational amplifier – a rail-to-rail type amplifier with a low bias voltage (of the order of 60 μV), in an inverse switching circuit with a bias of one of the inputs in order to compensate for the level of dark current.

The microcontroller controls the analog-to-digital converter, collects data and transfers it to the end device - a personal computer. The developed firmware is stored in non-volatile flash memory of the microcontroller unit. Microcontroller programming can be done via JTAG/SWD and USB interfaces. To connect the device modules to each other, the necessary connectors and adapters are displayed on the boards.

The device uses an assembly of 3 lithium-polymer batteries LP503759 3.7V with a capacity of 1200 mAh as a source of electricity. Using the LM1117IMPX linear voltage regulators, the output voltage value from the battery is converted to the operating voltages of the analog and digital parts of the device. To compensate for the instability of the voltage in the digital power line due to the presence of a microcontroller, it uses output integrating RC filters and blocking capacitors. As a reference voltage source of the black level and digital-to-analog converter level shifting circuit, the highly stable low-noise constant voltage source REF192FSZ is used in the current source module.

The measuring part of the experimental non-invasive glucometer (hereinafter referred to as the Clip), made in the form of a clip for the earlobe. The design allows you to install a matching system (collimator) with an SMA905 connector to the output of the light source layout and the spectrometer input, to which the meter can be connected in the form of a clip. Large clip losses are offset by a longer exposure time. If necessary, it is possible to take measurements directly - without using a clip. In this case, adapters are removed from the light source module and the spectrometer module. After that, the user places the test object (for example, earlobe) in the gap between the light source module and the spectrometer module, starts and waits for the measurement to finish. The advantage of this solution is to reduce the level of light loss, and, consequently, the exposure time. The obvious disadvantage is the low ergonomics of this approach.

The digitized and processed data containing information on the level of blood sugar are sent to a personal computer with specialized software installed. The software displays the shape of the absorption spectrum of optical radiation in the studied object, allows you to analyze the level of sugar in the blood and establish the functioning parameters of the experimental sample of a non-invasive glucometer.

Figure 2 shows the structural diagram of the developed device. The developed device consists of two separate modules - a current source and a spectrometer, clips and auxiliary parts (adapters, loops, optical fibers).

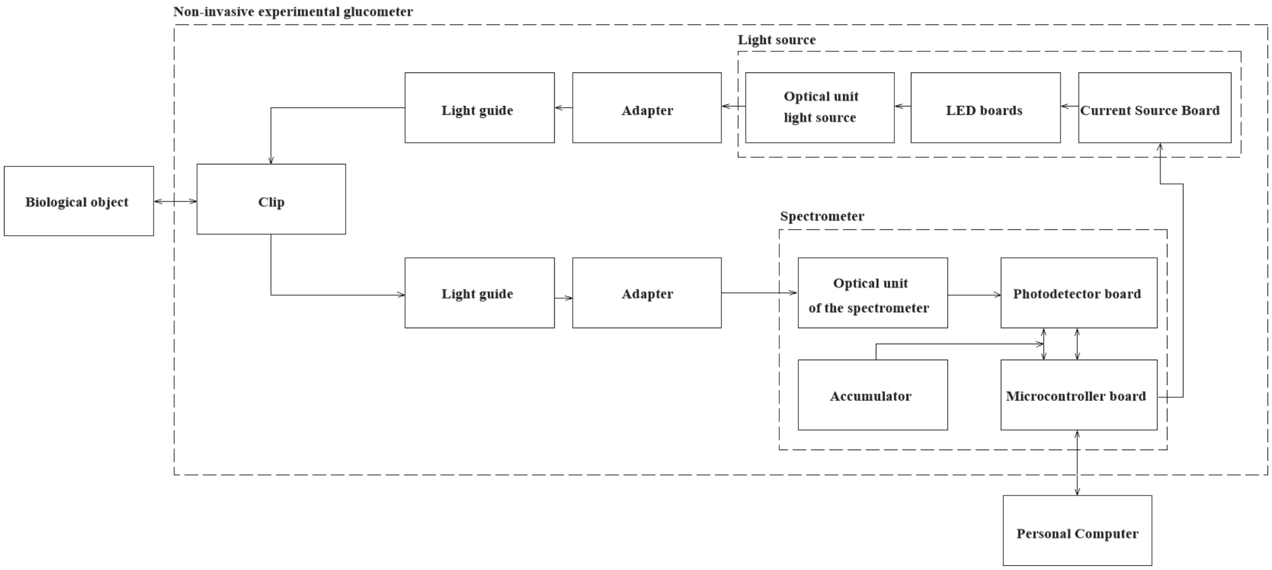

FIGURE 2. Structural diagram of an experimental non-invasive glucometer.

RESULTS

During the work, an experimental non-invasive glucometer was made, the components of which are shown in Fig. 3-5. To manage and process the data received from the device, software was written that was designed to configure and control a non-invasive glucometer and display the data received from it. The software allows you to measure the level of absorption of optical radiation at different wavelengths. Figure 6 shows the result of measuring the transmission of optical radiation through the patient's earlobe. The signal-to-noise ratio obtained during the tests allows testing to determine the concentration of glucose level.

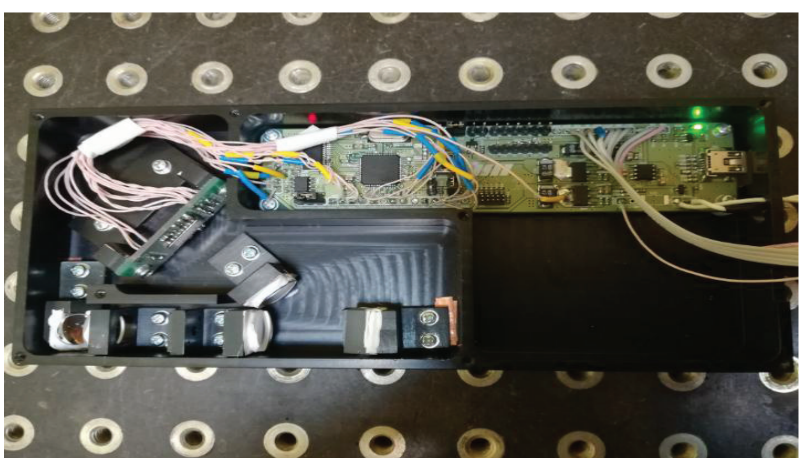

FIGURE 3. Spectrometer module.

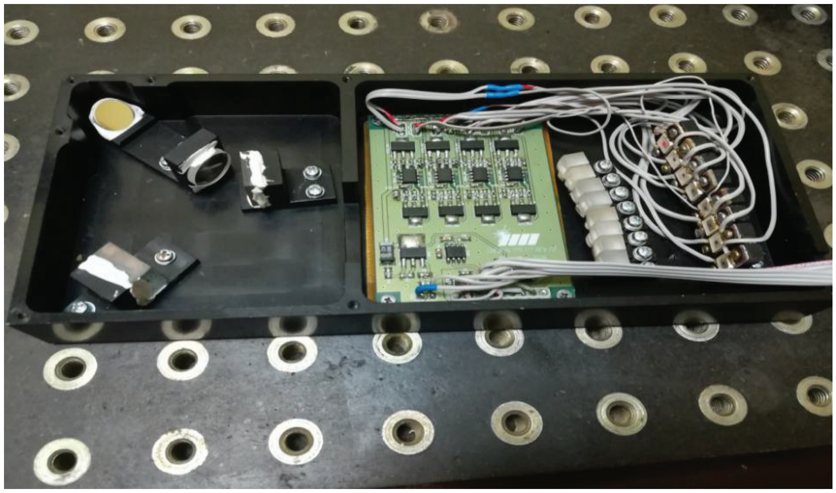

FIGURE 4. Current source module.

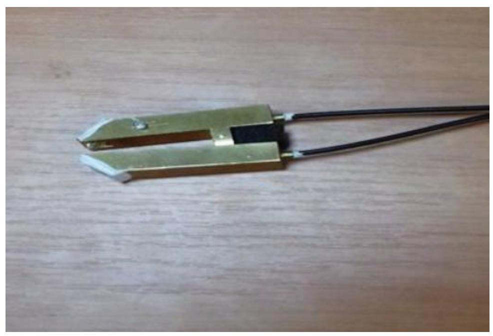

FIGURE 5. The measuring part of the experimental non-invasive glucometer – Clip.

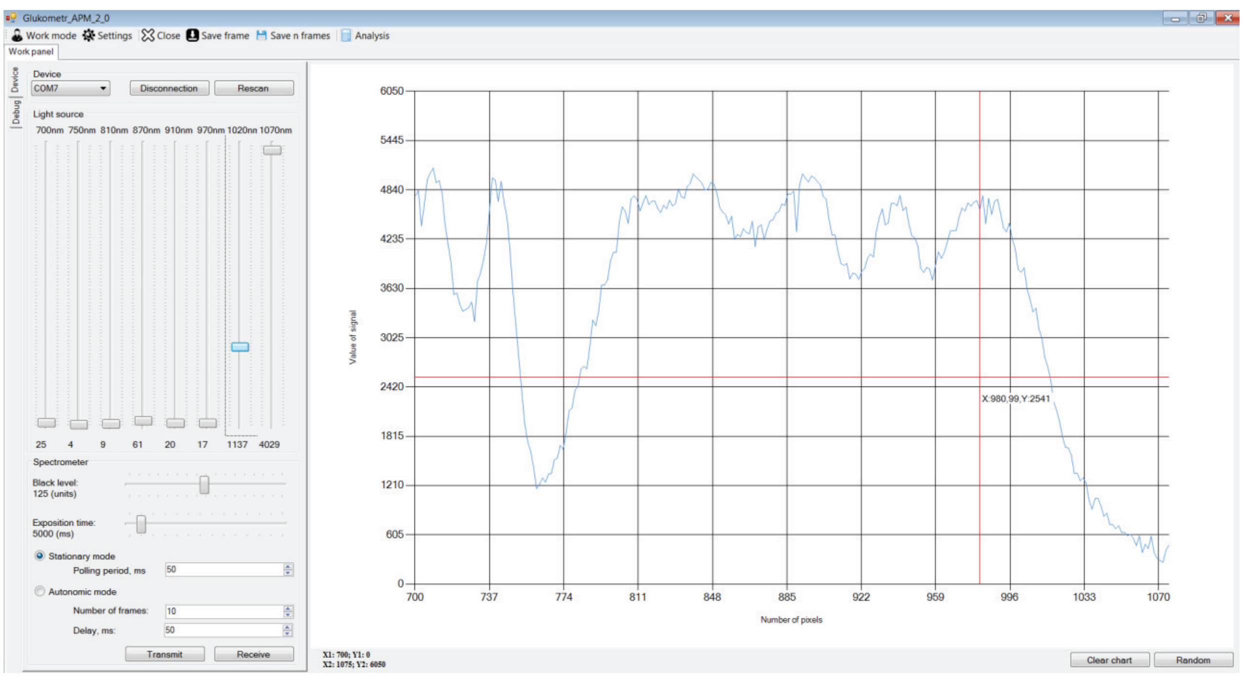

FIGURE 6. Software interface and transmission spectrum of optical radiation through the patient's earlobe.

CONCLUSION

According to the test results, the developed device successfully implements both the task of registering the level of light flux carrying information about the level of glucose concentration in the blood, and the task of processing and transmitting information to a computer. The presented device can be used to diagnose blood sugar levels without blood sampling.

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