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Approaches to the creation of optical temperature sensors based on Bragg structures for biomedical research

The proposed structural implementation of an optoelectronic device for determining tissue microcirculation and body temperature allows miniaturizing a fiber sensor, providing monitoring, diagnostics and screening of the state of tissue microcirculation in various optical modes with high accuracy and reliability, ensuring portability, mobility, access to hard-to-reach areas of biological tissue. Adaptive conditions for diagnosing the state of microcirculation are provided by the amplitude-pulse mode of operation of a laser source of optical radiation based on a seven-layer heterostructure, which allows combining radiation of different wavelengths and changing the intensity of light. Flows, which in its case allows studying different types of biological tissues using a set of radiation modes, as well as providing physiotherapeutic effects. Local temperature control using a fiber optic channel with a formed Bragg grating in the studied area allows you to obtain more complete and complex information about the level of tissue microcirculation and the state of biological tissue without increasing the size of the sensitive part of the optical sensor.

The possibility of using optical transducers based on Bragg fiber gratings as optical sensors for measuring temperature in different parts of the human body has been demonstrated. The possibility of using optical transducers based on Bragg fiber gratings as sensors embedded in composite materials for measuring and monitoring temperature fields has been demonstrated.

Keywords: *optical fiber sensors; Bragg gratings; biomedical diagnostics; tissue microcirculation; temperature sensors.*

Introduction. Currently, methods for controlling optical radiation are widely used in various fields of science and technology. Due to this, it is possible to change the following parameters of a light wave: frequency, amplitude, polarization phase, and direction of propagation.

The use of temperature sensors based on Bragg gratings fiber-optic is one of the main methods for measurement of pressure temperature, and other physical characteristics, including for sensors for biomedical research. The main advantages of such optical sensors are small size, high sensitivity, the ability to operate without electricity, insensitivity to electromagnetic interference and the ability to combine sensors into distributed systems to determine temperature fields [1]. Optic fiber sensors can be placed inside a material or glued to its sensor surface [2, 3]. Then it becomes possible to place fiber optic sensors in a composite material, which creates an intelligent structure.

There are several types of optic fiber sensors that can be built into a structure. As a result of the interaction of a physical quantity with an optical fiber, the light propagating in it changes. In this case, information about the measured quantity appears in the optical fiber. This category includes polarimetric sensors [4], interferometric sensors and sensors with Bragg gratings.

Analysis of the latest achievements. This work is devoted to measuring temperature using sensors based on Bragg gratings with a constant period. With the help of well-known optic fiber sensors with Bragg gratings, it is possible to carry out various measurements of physical characteristics and parameters. For example, this type of sensor can be used to measure strain [5, 6], pressure [8], temperature [7], magnetic and electric fields, etc. refractive index, and its distribution [12, 14].

Sensors with a Bragg grating have a number of advantages over sensors of other types. The most important advantages include [15–18]: weight and small size; frequency nature of the output signal; sensitive, accuracy; sensitive to temperature changes; the appearance of duality in the optical fiber as a result of external forces; relatively expensive measuring systems [19, 20].

Method and technology for implementing optical sensors based on Bragg gratings. Using FBGs, it is possible to measure a physical quantity where the tasks of measuring the spatial distribution of this quantity often arise. For this purpose, various structures have been developed that allow multiplexing of sensitive elements, including those located in the same light guide.

Such schemes include: spectral multiplexing of channels; use of optical switches that connect one or another sensitive element to the measurement system; combined schemes that include several principles of channel multiplexing; space-time multiplexing, in which the response from each of the gratings is recorded at different points in time.

Each cell of the Bragg grating reflects a small part of the radiation transmitted through the optical fiber. For a wavelength 2 times greater than the grating period, the reflected rays are added in phase [16]. The result is a reflected light signal with a narrow spectral band. The wavelength reflected by the grating is called the Bragg wavelength, and it depends on the temperature and tension of the fiber [16]. When an optical fiber is affected (temperature, pressure, etc.), the refractive index and the distance between the waves and grating cells change, and of a different length are reflected from it. The required characteristics (pressure, temperature, etc.) are determined by the change in the value of reflected wavelength [16].

The aim of the work is to demonstrate the possibility of determining the temperature of various areas of the human body by analyzing the effect of temperature on the optical parameters of the oblique Bragg grating and analyzing the possibility of using it as a fiber temperature sensor.

Method and technology for implementing optical sensors based on Bragg gratings. Using FBGs, it is possible to measure a physical quantity where the tasks of measuring the spatial distribution of this quantity often arise. For this purpose, various structures have been developed that allow multiplexing of sensitive elements, including those located in the same light guide. Such schemes include: spectral multiplexing of channels and combined schemes that include several principles of channel multiplexing.

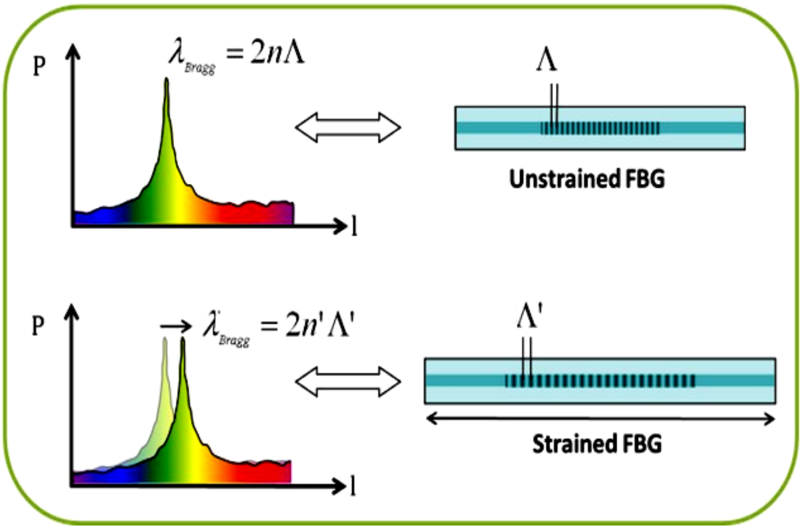


Fig. 1. Features of operation of direct fiber Bragg gratings [16]

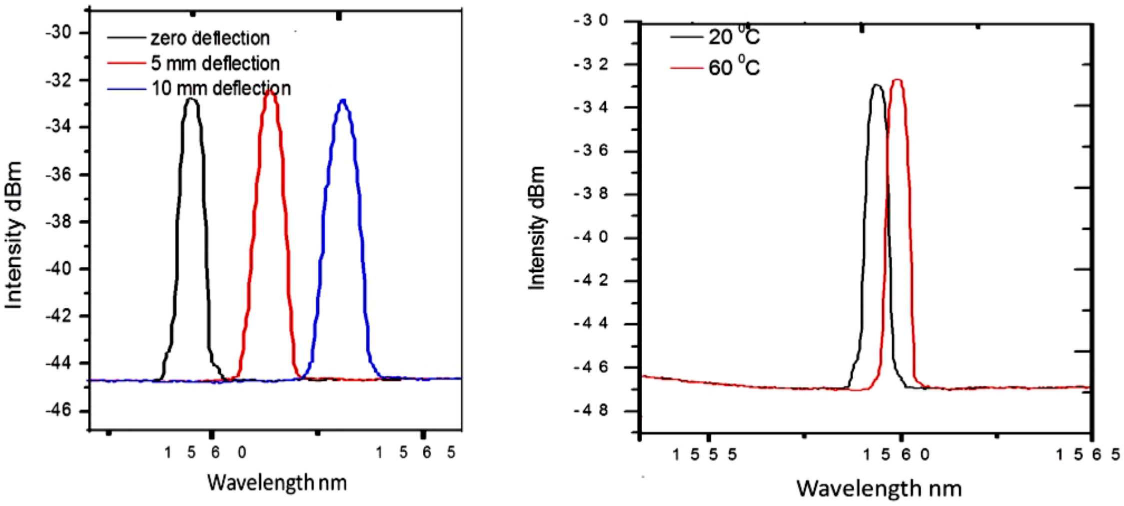
Each cell of the Bragg grating reflects a small part of the radiation transmitted through the optical fiber (Fig. 1). For a wavelength 2 times greater than the grating period, the reflected rays are added in phase [16]. The result is a reflected light signal with a narrow spectral band. The wavelength reflected by the grating is called the Bragg wavelength, and it depends on the temperature and tension of the fiber [16].

The sensitivity of temperature of the Bragg wavelength arises from the change in grating pitch due to the thermal expansion of the optical fiber sensor and the change in refractive value due to the thermo-optic effect. Equation (1) can also be written as [3, 16]:

$$T = (\alpha_0 + \beta_0) \cdot \lambda_B \cdot \Delta T, \quad (1)$$

where α_0 is the coefficient of thermal expansion (CTE) of the fiber and β_0 is the change in the refractive value of the optic fiber with temperature, respectively value. The typical sensitivity of temperature of FBGs at 1550 nm is ~11.6 pm/°C. Thus, based on these unique characteristics of TFBGs, simultaneous discrimination between mechanical disturbances and temperature can be achieved [14, 16]. Other authors have reported various methods to compensate for the cross-sensitivity effects between strain and temperature [7, 8, 10, 11].

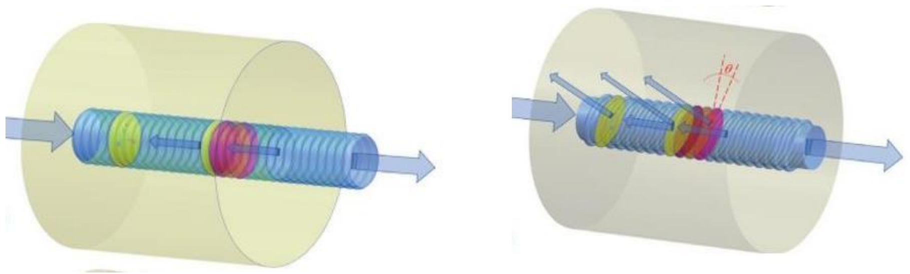
Values of temperature acting in different directions within a composite structure can be measured using multiplexed fiber sensor [17]. In addition, the temperature distribution in region of body can be measured using an FBG recorded in a highly birefringent microstructured fiber (Fig. 2).



(a) (b)

Fig. 2. Temperature distribution in a composite material

Figure 3 shows a schematic comparison of light transfer in a straight and oblique grating. It is evident that in oblique gratings, part of the light is emitted as cloak modes. The radiation intensity depends on the grating tilt angle and the modulation depth, which is affected by the laser beam parameters [23]. Taking into account the features of the structures under study, it is obvious that when writing Bragg gratings with different tilt angles relative to the cross-section of the optical fiber, the modulation of the refractive index in the optical fiber can be represented for the selected tilt as in Figure 3.



a) *b)*

Fig. 3. Schematic representation [23]: a) straight BG; b) oblique BG

Modeling of Bragg Grating Spectra with Variable Technical Parameters. Figure 4 shows the spectral characteristics obtained by numerical modeling. For this, a system of equations of conjugate modes was used, which was solved numerically using the TMM (Transfer Matrix Method). Figure 4 Characteristics were modeled using the Transfer Matrix Method. FBG structure length = 10 mm.

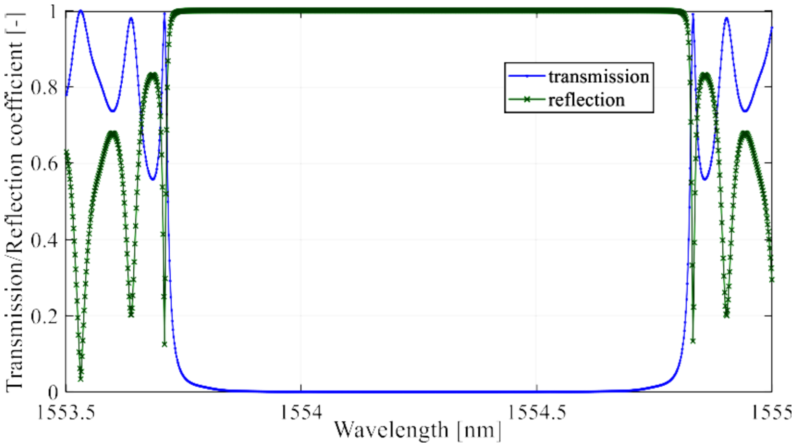


Fig. 4. Spectral characteristics obtained by numerical modeling

Figure 5 shows the reflection and transmission features of a 10 mm long structure with a refractive index modulation value of δn = 0.001. The characteristic shift and strong broadening of the half-width of the main transmission and reflection peak of the grating are typical. Structures manufactured in laboratories, as a rule, have a change in the refractive value modulation in the range from 0.0005 to 0.00001. Therefore, Figure 5 collects the transmission spectra of 10 mm long structures with δn values.

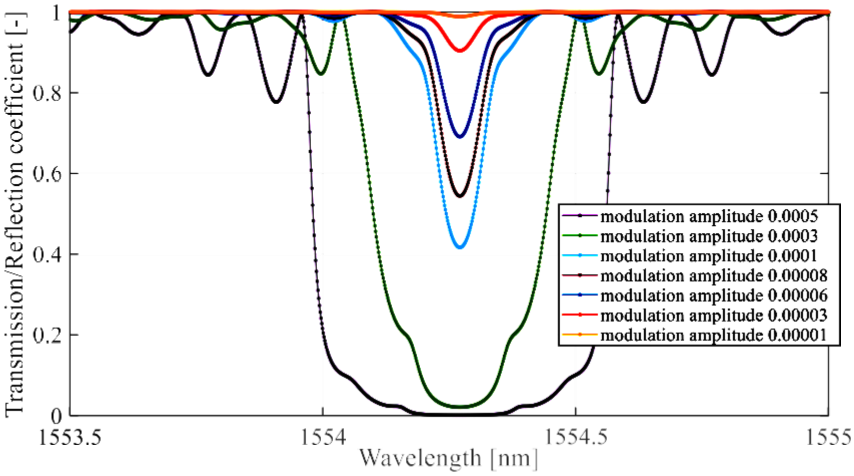


Fig. 5. Reflection and transmission features of a 10 mm long structure

Structural implementation of a fiber sensor based on Bragg gratings. Figure 6 shows a structural block diagram of a biomedical device for determining tissue microcirculation and temperature of a human area with an optical fiber sensor based on Bragg gratings.

The device consists of a laser fiber-optic sensor 1, which consists of a source of laser optical radiation based on a seven-layer heterostructure 2, a Y-shaped fiber-optic splitter 3 with input and output fiber-optic channels, which are connected into one common optical channel with a formed Bragg grating 4, designed for transforming optical radiation, measuring local temperature, directing optical radiation to biological tissue 5 and receiving the intensity of the light flux reflected from it, a photo detector 6, sensitive in a wide spectral range, an amplifier 7, an analog-to-digital converter 8, an optical spectrum analyzer 9, a computer 10, which consists of a microcontroller 11, a graphic liquid crystal display 12, a slot for an SD memory card 13, a power supply 14.

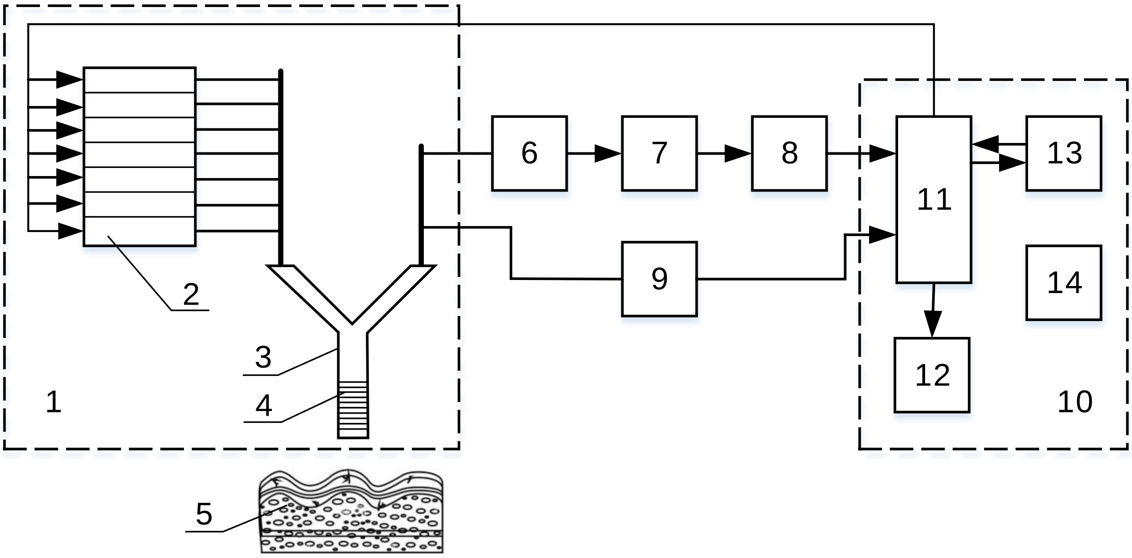


Fig. 6. Biomedical device for determining tissue microcirculation and temperature

The device works as follows. After turning on the power supply 14, which supplies electricity to all the blocks of the device, the computer blocks 10 are reset, in particular the microcontroller 11 is reset to the zero state, the graphic liquid crystal display 12 is loaded and displays the readiness of the device for operation. According to the device operation program, which is set using the microcontroller 11, a pulse-width modulated signal is supplied to its control output, which activates the laser optical radiation source based on the seven-layer heterostructure 2, and the duration and intensity of activation of each layer, corresponding to different wavelengths of optical radiation, can be adjusted independently.

In addition, the optical radiation coming from the input channel of the Y-shaped fiber-optic splitter 3 is transformed and reflected on the formed Bragg grating 4 and through the output channel of the Y-shaped fiber-optic splitter 3 enters the optical spectrum analyzer 9, designed to measure the local temperature in the study area. Temperature measurement using the formed Bragg grating 4 in a common optical channel is based on the phenomenon of changing the Bragg wavelength depending on the temperature change. This change is associated with the thermo-optic effect and the change in the period of the Bragg grating in the optical fiber due to thermal expansion. The Bragg grating reflects optical radiation of a certain wavelength λB, which is directly proportional to the refractive index of the optical fiber core and the grating period, both of which change with temperature. The output of the fiber-optic channel with the formed Bragg grating 4 is connected to the input of the optical spectrum analyzer 9, which determines the Bragg wavelength λB for the radiation reflected from the biological tissue and transmits this information to the second information input of the microcontroller 11. The tissue temperature T is calculated with high accuracy by the formula 2:

$$T = T_0 + \frac{\lambda_B - \lambda_0}{S_T}, \tag{2}$$

where T_0 – is the initial temperature during calibration;

λ_B – and λ_0 are the current and initial (at T_0) Bragg wavelengths, respectively;

S_T – is the sensitivity of temperature of the Bragg grating.

When using a fiber-optic channel with a formed Bragg grating 4 for temperature measurement, it is necessary to perform an initial calibration of the sensor. The initial temperature T_0 during calibration was taken to be 35 °C. A calibration curve was determined showing the dependence of the shift of the Bragg wavelength $\lambda_B - \lambda_0$ on the temperature of the biological tissue sample 5 based on the Bragg shift of the radiation intensity spectrum.

Conclusions and prospects for further research. The proposed structural implementation of the device allows for miniaturization of the sensor, provides monitoring, diagnostics and screening of the state of tissue microcirculation in various optical modes with high accuracy and reliability, ensuring portability, mobility, access to hard-to-reach areas of biological tissue. Adaptive conditions for diagnosing the state of microcirculation are provided due to the amplitude-pulse mode of operation of the laser optical radiation source based on the seven-layer heterostructure 2, which makes it possible to combine radiation of different wavelengths and change the intensities of light fluxes, and this, in turn, allows for research of different types of biological tissues using a set of irradiation modes, as well as providing physiotherapeutic effects. Local temperature control using a fiber-optic channel with a formed Bragg grating in the studied area allows for more complete and complex information about the level of tissue microcirculation and the state of biological tissue without increasing the size of the sensitive part of the optical sensor.

The applicability of optical transducers based on Bragg fiber gratings as optical sensors for temperature measurement in various areas of the human body has been demonstrated. The applicability of optical transducers based on Bragg fiber gratings as sensors embedded in composite materials for measuring and monitoring temperature fields is demonstrated.

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Підходи до створення оптичних температурних сенсорів на основі структури Брега для біомедичних досліджень

Запропонована структурна реалізація оптико-електронного пристрою для визначення тканинної мікроциркуляції та температури тіла дозволяє мініатюризувати волоконний сенсор, забезпечує моніторинг, діагностику та скринінг стану тканинної мікроциркуляції в різних оптичних режимах з високою точністю та надійністю, забезпечуючи портативність, мобільність, доступ до важкодоступних ділянок біологічної тканини. Адаптивні умови для діагностики стану мікроциркуляції забезпечуються за рахунок амплітудно-імпульсного режиму роботи лазерного джерела оптичного випромінювання на основі семишарової гетероструктури, що дозволяє комбінувати випромінювання різних довжин хвиль і змінювати інтенсивність потоків світла, що своєю чергою дозволяє досліджувати різні типи біологічних тканин із застосуванням набору режимів опромінення, а також забезпечувати фізіотерапевтичний вплив. Локальний контроль температури за допомогою оптоволоконного каналу зі сформованою бреггівською решіткою в досліджуваній зоні дозволяє отримати більш повну та комплексну інформацію про рівень тканинної мікроциркуляції та стан біологічної тканини без збільшення розміру чутливої частини оптичного датчика. Продемонстровано можливість застосування оптичних перетворювачів на основі бреггівських волоконних граток як оптичних датчиків для вимірювання температури в різних областях тіла людини. Продемонстровано можливість застосування оптичних перетворювачів на основі бреггівських волоконних граток як датчиків, вбудованих у композитні матеріали, для вимірювання та моніторингу температурних полів.

Ключові слова: оптичні волоконні сенсори; брегівські гратки; біомедична діагностика; тканинна мікроциркуляція; температурні сенсори.

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