Medical control of a pulse wave fiber optic sensors

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Abstract. The modern level of development of systems of measurement, processing and data transmission promote creation of optical multiple parameter medical diagnostic systems. One of intensively developed directions is creation of fiber-optical diagnostic systems on the basis of fiber optic sensors. Fiber optic sensors are characterized by high sensitivity to mechanical oscillations of a surface of a body of the patient under power influence of a blood flow. This property creates premises for design miniature, steady against noises, safe sensors of micromovements. Their fixing on a body of the patient allows to reveal a number of the vital parameters characterizing normal and critical condition of the patient. Results of a research of fiber optic sensors of pressure on the basis of standard single-mode optical SMF-28 fiber are presented in article. The principle of operation of sensors consists in use of physical properties of the fiber - the impact which had in some pressure point on throughput characteristic. The purpose of the real work is the research of a possibility of use of fiber optic sensors of the tunnel, flexural and microflexural types on Bragg's grid for control of a pulse wave providing more exact determination of parameters of a pulse wave. The offered monitoring systems of a status of patients on the basis of fiber optic sensors in medicine are very perspective.

1. Introduction
Weak energy of pulse fluctuations creates difficulties for reproduction of vibration amplitude and conversion of their values to units of arterial blood pressure. An important point is transfers of an undistorted form and phase frequency characteristics of the pulse wave representing energy of distribution of a flow of blood up to an artery.

As practice shows, the existing pressure sensors expected measurement range from zero to 300 mm Hg. have low sensitivity of conversion, essential nonlinearity of conversion function, are subject to influence of x-ray and electromagnetic radiations and also big mass and dimensional characteristics. There is no possibility of positioning of the sensor on the surface of a body of the person, at the same time there is a need of leading of dimensional hoses that significantly complicates their construction. Besides, sensors are sources of electromagnetic impact on the patient.

Accuracy of representation of the haemodynamic parameters based on processing of amplitude time characteristics depends on reliability of a form of reproduction of a pulse wave. First of all it is connected with assessment of systolic and diastolic components of pressure, the parameters characterizing elasticity and rigidity of arteries, productivity of work of heart [1-4].

Semiconductor sensors now in use possess the big errors leading to significant distortion of true values of the evaluated haemodynamic parameters and also are not capable to perform trebuyemy functions when performing the magnetic resonance imaging (MRI), the nuclear magnetic resonance (NMR), positron emission tomography (PET).

From the analysis of the available arsenal of the sensor equipment functioning with the low pressure range at impact of the x-ray and electromagnetic influences which were widely adopted not
only in the equipment, but also in medicine, fiber optic sensors which are convenient in operation in wearable systems with the minimum inconveniences in the systems of continuous monitoring.

The developments of fiber optic sensors connected with determination of heart rate, breath, body temperature are known [5, 6]. Advanced developments of the similar sensors which are built in clothes elements, the bed or a medical chair which are not demanding additional actions for training of the patient for monitoring [7, 8].

Prospects of creation of monitoring systems of a cardiovascular system using pressure fiber optic sensors on Bragg's grid, tunnel, flexural and microflexural types are offered [9-24].

The purpose of the real work is the research of a possibility of use of fiber-optical sensors of parameters of a pulse wave on Bragg's lattices, the tunnel, flexural and microflexural types providing more exact determination of parameters of a pulse wave.

2. Methods of researches
Distinctive feature of the offered technique of assessment of haemo dynamic parameters is the combination of a liquid cuff to the fiber-optical sensors (FOS) for perception of micromovements of a surface of tissues of forearm, a wrist, an anklebone or a phalanx of a finger when passing the pulse wave formed by warm reductions.

The layout of sensors and main units of a system is shown in figure 1.

![Figure 1. Layout scheme of sensors and structure of main units.](image)

On the patient's body on the lower and top parts of hands and legs cuffs M\text{mn}, M\text{mv}, M\text{rn} and M\text{rv} with pressure sensors located on them are fixed. The provided layout of hydrocuffs allows to determine on the basis of the analysis of a form of a pulse wave of value of systolic, diastolic pressure on a hand and a leg, and taking into account time of its distribution and the measured distances between sensors as well the speed of a pulse wave \( \upsilon \). It is in addition possible to define the ankle-shoulder index (ASI) - one of key parameters of assessment of a condition of a cardiovascular system [27].
For perception of micromovements of a surface of tissues of forearm, a wrist or a phalanx of a finger when passing the pulse wave created by warm reductions it is offered to use the pressure fiber optic sensors (FOSP) which will be located near arteries.

3. Results of researches
In tunnel FOSP modulation of power of a flow of optical radiation happens owing to rapprochement (under the influence of pressure) two environments in one of which the flow of optical radiation, extends to the distance commensurable with the wavelength (about 1 µm). One of possible constructions of tunnel PFOS is given in figure 2.

![Figure 2](image)

**Figure 2.** Construction of the tunnel PFOS. 1 – optical fiber cable; 2 – fixer; 3 – tip; 4 – case; 5 – optical fiber which part is contracted into a flat spiral; 6, 10 – adjustment screws; 7 – an opening with a stub for pressure control in a submembrane cavity; 8 – membrane; 9 – flat wafer; 11 – hard reference drive; 12 – cover.

The sensor consists of optical fiber (5) and the flat wafer (9) attached to a membrane (8) [14]. The reflecting cover is removed from a certain section of optical fiber (5). This section of optical fiber is contracted into a flat spiral and located under a plate (9). The last is made of material which has an index of refraction more, than the index of refraction of material of a core of optical fiber. At rapprochement of a plate (9) and optical fiber (5) under the influence of pressure a part of a flow of optical radiation «flows» from optical fiber (5) in a plate (9).

In the PFOS on the basis of curved optical fibers modulation of power of a flow of optical radiation is caused by change of bend radius of optical fiber which depends on applied pressure [14, 17].

The PFOS on the basis of microcurved optical fibers (in some works they are called «microflexural PFOS») are characterized by the fact that in them modulation of power of a flow of optical radiation happens at its distribution on optical fiber which owing to influence of pressure is exposed to several microbends. At the same time the radius of each of microbends is commensurable with a diameter of the used optical fiber [18, 19].

For increase in sensitivity of conversion of the fiber-optical transformer of microflexural type it is offered to use an intermediate element between fiber and the element perceiving pressure in the form of two metal rods (figure 3) [20].

Pressure from the perceiving element (1) is transmitted through metal cores (2) with a diameter of 1 mm, under optical fiber (5) there is an elastic rubber lining (3). When rendering influence there is a considerable falling of level of an optical signal that it is connected with violation of a condition of full internal reflection and effluence from fiber of extra aperture beams.
By way of illustration in figure 4 the fragment of a design of FOSP in which for creation of microbends of optical fiber (5) a set of cylindrical rollers (2) and (4) is used is shown.

Figure 3. The scheme of the measuring transducer of the fiber optic sensor on the basis of microcurved optical fiber. 1 – detector; 2 – metal rods; 3 – elastic rubber lining; 4 – basis; 5 – microcurved optical fiber.

The last are squeezed by the deformer (1) made in the form of two gear plates. One of deformer is not mobile, another – moves at a deflection of the perceiving element (3). Optical fiber (5) is surrounded with elastic substance (6) which index of refraction is more, than the index of refraction of a cover of optical fiber.

Sensors are exposed to the deformation caused by concentration of tension which value is correlated with pressure attached to the bearing element.

Figure 4. A sensor design fragment on the basis of microcurved optical fiber. 1 – deformer; 2, 4 – cylindrical rollers; 3 – a membrane with the rigid center; 5 – microcurved optical fiber; 6 – elastic substance.

The main lack of the above-considered fiber optic sensors of pressure is a low sensitivity of conversion of an optical signal in a measurement zone, insufficient for measurement of parameters of arterial blood pressure. For increase in sensitivity of conversion the quantity of rounds of optical fiber in a measurement zone increases. Fiber optic sensors on the basis of FBG (fiber Bragg grating) are considered as the most perspective [21]. They will usually transform the measured value to shift of the central wavelength of the spectral response. Their application in the equipment is limited a number of factors:
- according to conversion function their signal output bears information on two physical quantities at once: «deformation temperature», «a bend temperature» therefore additional measures are taken for
division of the different measured values, for example, is added to the scheme the second bregovksy grid used as reference (compensatory), respectively significantly increases system complexity \cite{22};

- for secondary information processing interrogator by means of which bregovksy grids are polled are used. They are under construction on the basis of optical analyzers of a range or optical filters: the scanning filter of Fabri-Perot, the combined space filter on the basis of diffraction grating and the CCD-camera, or the optical narrowband filter with the spectral characteristic of a slope depending on wavelength \cite{23}. Interrogators are difficult in production, also expensive devices are bulky.

These shortcomings are less essential to medicine. So, if blood-groove parameters are measured, then it is possible to consider that temperature has the constant value equal to the body temperature of the patient, and dimensions and cost of interrogators are comparable with dimensions of other diagnostic equipment.

Let’s stop on classical FBG.

Profile of a range of reflection of FBG depending on length of FBG L and a detune $\delta$ \cite{24}:

$$R = \frac{\sinh^2 kL \sqrt{1-(\delta/k)^2}}{\cosh^2 kL \sqrt{1-(\delta/k)^2}-(\delta/k)^2},$$  \hspace{1cm} (1)

$k$ – coefficient of communication of the falling and reflected wave, $\delta/k$ – a relative detune who for a bregovksy lattice with the period $\Lambda$ makes:

$$\frac{\delta}{k} = \left( \frac{2\pi n_{\text{EFF}}}{\lambda} \right) - \frac{\pi}{\lambda},$$  \hspace{1cm} (2)

$\lambda$ - length of an optical wave.

For demonstration of changes of a range of a fiber bregovksy grid in work \cite{24} the dependence of reflection coefficient $R$ for its different lengths is presented to $L$. The effective index of index of refraction for a fundamental mode of $n_{\text{EFF}} = 1.5$. The grid period $\Lambda$ was selected so that the central wavelength of reflection of FBG was 1500 nanometers. During computational modeling values of length of a grid of $L$ in the range (2 … 5) mm, $kL=0.38$ were set. On the basis of data retrieveds the conclusion is drawn that to reduction of length of a grid of Bragg there is a decrease in reflection coefficient and broadening of a profile. Taking into account these results for the developed sensor of a pulse wave the grid 5 mm long of Bragg was selected.

The simplified design of the measuring converter of pressure of a blood-groove on the basis of FBG differing in hypersensibility of transformation of parameters of a blood-groove to change of parameters of an output signal is given in figure 5.

Figure 5. The simplified design of the measuring converter of a blood-groove The simplified design of the measuring converter of a blood-groove on the basis of FBG.
The fiber-optical measuring transducer (FOMT) contains optical fiber with Bragg's grid as a detector. The detector is executed in the form of an elastic membrane on which internal surface in the center by means of the gluing structure inertial weight is located (for example, in the form of a glass sphere or a parallelepiped). Over inertial weight optical fiber with FBG is fixed. Section of optical fiber with FBG is located between the inertial weight and the sensor housing in hover.

The power influence of a pulse wave changing with acceleration of an is transferred to the cup fixed on the patient's body along a y axis, further to the inertial mass of \( m \). \( F_y = ma_y \), last under the influence of force, will fluctuate concerning the neutral situation along a y axis (figure 6) [24].

Fluctuations of inertial weight will cause deformation of optical fiber. At the same time section of a grid of FBG stretches (is extended). Deformation of optical fiber leads to proportional change of the reflected light wavelength in Bragg's grid from power influence, that is bears information on parameters of a pulse wave.

![Figure 6](image)

**Figure 6.** Geometrical model of vertical fluctuation of optical fiber with Bragg's lattice and inertial weight.

The flowchart of the developed monitoring system using fiber optic sensors is submitted in figure 7.

![Figure 7](image)

**Figure 7.** Flowchart of a fiber optical system of condition monitoring of a cardiovascular system of the patient.

For measurement of parameters of a blood flow the lasing source generates the continuous radiation which via the beam splitter arrives on sensing optical fiber and through it on the FOMT on an FBG.
The response from the FOMT through the sensing optical fiber, the first and second output of the beam splitter bringing optical fiber arrives on a detector in which its amplitude is registered. The acquired information comes to the controller in which pressure of a blood flow proportional to pressure created by a pulse wave in an artery under a cup (figure 8) is determined by the received values of amplitude.

Figure 8. The diagram of a pulse wave received from the output of the sensor on the basis of the fiber-optical vibrotransformer.

4. Conclusion

Fiber optic sensors are characterized by high sensitivity to mechanical oscillations of a surface of a body of the patient under power influence of a blood flow. This property creates premises for design miniature, steady against noises, safe sensors of micromovements.

The offered monitoring systems of a status of patients on the basis of fiber optic sensors in medicine are very perspective.

Fixing of pulse waves on extremities of the patient allows to determine the haemodynamic parameters characterizing a status of heart and vessels with a high accuracy.

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