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Research and application of biosensors based on tilted fiber Bragg gratings

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Abstract

Fiber sensors based on fiber Bragg gratings (FBG), due to their unique characteristics such as compact size, multiplexing capability, chemical resistance and resistance to electromagnetic fields, have found extensive applications – from monitoring the condition of structures to use in biomedical devices and medical care systems. These sensors are also characterized by high linearity, fast response for real-time monitoring, and increased sensitivity to external influences. These features make fiber sensors extremely attractive for a variety of applications, especially in the field of biomedicine. Fiber sensors based on Tilted fiber Bragg gratings (TFBG) are particularly attractive. TFBG are excellent biosensors used for medical research and diagnostics. These gratings have unique properties that make it possible to create high-precision sensors for biochemical analysis at minimal cost of production and operation. Due to their multi-resonance characteristics, TFBG enable multiparameter sensing and address cross-sensitivity challenges, including temperature sensitivity. TFBG allow you to eliminate cross-sensitivity and measure multiple parameters simultaneously. The article provides a brief overview of the main characteristics, principles of operation, methods of collecting and processing data from sensors, as well as their application in medical equipment and devices.

Keywords: Biosensors, Blood pressure, Body temperature, Fiber sensors, Monitoring, Respiratory rate, Tilted fiber Bragg gratings.

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1. Introduction

The development of fiber-optic technologies has also led to the creation of optical processing devices fully integrated into fiber, which has reduced losses and improved processing quality [1]. One of the key factors contributing to the full integration of fiber-optic technology was the discovery of photosensitive optical fibers. This discovery, made by Hill, et al. [2] led to the creation of the Bragg fiber lattice (FBG). In addition to being widely used in optical communications, FBG have become a key element in fiber-optic sensors due to their versatility in various measurement tasks [3]. Various industries such as aeronautics [4] aerospace industry [5] civil engineering [6-9]. As well as biological monitoring [10] environmental monitoring [11] and pavement monitoring [12] the advantages of this technology have already been evaluated.

Progress in FBG technology has significantly accelerated the development of research and implementation of these sensors in medicine.

Optical fibers were first used in medicine to illuminate internal organs during endoscopic examinations. Over time, this technology has found applications in other fields, including laser therapy and the creation of sensors to monitor key parameters for diagnostic and therapeutic purposes. Despite the fact that fiber-optic sensors appeared more than 40 years ago [13] and have a number of advantages over traditional technologies, their active introduction to the market began only in the last decade due to improvements in optical components and lower production costs [14].

Modern fiber sensors are used to measure various physical and chemical parameters of medical importance [15, 16]. These sensors are classified into two main groups [17]: internal sensors, in which the optical fiber performs the function of a sensing element, and external sensors, where the fiber serves as a medium for transmitting a light signal, the parameters of which (intensity, frequency, phase) are modulated by the measured value. External sensors allow you to place the main components of the system (light source, photodetector) at a distance from the sensor element, which contributes to the creation of miniature and hybrid solutions [18].

The improvement of optical fibers has created new capabilities and advantages of biosensors, such as device miniaturization and the ability to remotely monitor and diagnose in real time. In particular, tilted fiber Bragg gratings (TFBG) are highly sensitive to changes in the refractive index on their surface. TFBG play an important role in chemical and biochemical sensing based on the measurement of changes in the surface refractive index (RI). fiber sensors based on TFBG stand out particularly due to their high sensitivity, high performance, remote monitoring capabilities, biocompatibility, reliability and resistance to electromagnetic interference, and remote operation capabilities. Their small size allows for miniaturization, which makes these sensors ideal for medical applications [19-21]. The introduction of such devices into the healthcare system can significantly improve the quality of medical care [22, 23]. They are widely used in medical diagnostics [24] clinical research [25] biochemical analysis [26] and biosafety [27]. For example, to monitor glucose levels in diabetic patients, fiber-optic biosensors can quickly and accurately track changes in glucose concentration [28]. In diagnostics, fiber sensors based on TFBG are also used to detect protein reactions, which makes them indispensable for tracking various diseases [29]. Fiber sensors based on TFBG are highly sensitive and flexible devices that are widely used in robotic manipulators due to their ability to measure mechanical and physical quantities with high accuracy.

Fiber sensors based on TFBG also find many applications in the field of rehabilitation, especially in exoskeletons used to restore motor functions in patients. These sensors have unique properties that make them ideal for use in exoskeletons, devices designed to support and enhance human movement. Using them in exoskeletons for patient rehabilitation opens up new opportunities for improving the quality of life of people with disabilities [30]. Their high sensitivity, flexibility, resistance to interference, and miniaturization make them ideal for use in such devices. The introduction of TFBG sensors into rehabilitation exoskeletons improves the accuracy of movement control, safety and personalization of rehabilitation, which ultimately contributes to faster recovery and reduces the risk of repeated injuries.

Fiber sensors based on TFBG are becoming an important tool for monitoring the patient's physiological parameters during magnetic resonance imaging (MRI). Currently, MRI has become the main diagnostic method in many fields of medicine due to its ability to provide high-quality images of soft tissues without the use of ionizing radiation [31]. However, the MRI diagnostic process also places high demands on patient safety and comfort, especially for those at risk, such as children, the elderly, and patients with implanted pacemakers.

This article examines fiber-optic sensors based on TFBG and their applications in the medical field. The main focus is on the key characteristics of these sensors, their manufacturing technologies, as well as specific medical applications, including the development of biomechanical devices, monitoring of vital signs such as body temperature, respiratory rate, blood pressure, as well as the development of respiratory monitors and biosensor systems. The scientific significance of the work lies in the creation of a new modification of biosensors based on TFBG, which are distinguished by high sensitivity to biological markers (proteins, DNA, and other molecules). These sensors operate on the principle of analyzing changes in the light characteristics in an optical fiber, providing faster and more accurate measurements compared to traditional methods, as well as the ability to simultaneously determine several diagnostically significant parameters. The practical value of the development is reflected in a wide range of potential applications: from early disease diagnosis and continuous patient monitoring in clinical practice to food quality control and environmental monitoring. The compact size, high operational speed, and reliability of these sensors allow them to be used both in stationary laboratory settings and as part of portable diagnostic systems, opening new prospects for personalized medicine, industrial control, and field research.

2. Research Methodology

2.1. Fabrication and Features of Biosensors Based on Tilted Fiber Bragg Gratings (TFBG).

In recent decades, FBG have gained significant popularity in medical applications. Numerous research efforts have focused on developing biosensors that would be user-friendly, cost-effective to manufacture, capable of real-time measurements, and able to simultaneously detect various components, antibodies, and viruses. An FBG is an optical device created by modulating the refractive index of an optical fiber's core.

For biosensor applications, it is crucial to enable interaction between light within the optical fiber and the surrounding environment. This requirement is successfully implemented using tilted fiber Bragg gratings (TFBG). TFBG have proven effective as biosensors due to their high refractometric sensitivity. Further sensitivity enhancement is achieved by combining TFBG with surface plasmon resonance (SPR) effects, which occur when a thin metallic layer is deposited on the fiber surface. The SPR phenomenon enables sensors to determine the effective refractive index of plasmons and detect its variations.

TFBG is a type of fiber grid made from standard single–mode fiber in which the grids are inserted into the core at an oblique angle. The most common way to create a lattice is to irradiate an optical fiber with ultraviolet radiation with a periodic intensity distribution. The following methods are used for this purpose: the phase mask method, the interferometric method. In this paper, special attention is paid to the phase mask method. The advantage of the phase mask technology lies in its high adaptability in the production of Bragg fiber gratings, as it allows the creation of gratings with a periodicity independent of the angle of inclination. This makes the technology more convenient to meet the actual requirements of the application. There are two ways to tilt a phase mask: The first is the sequential rotation of the phase mask and fiber around an axis perpendicular to the laser beam, while the phase mask and fiber remain parallel; The second method involves holding the fiber and the phase mask perpendicular to the incident laser beam, but rotating the phase mask around the axis of the laser beam itself.

The essence of the phase mask method is the direct irradiation of an optical fiber through a diffractive optical element. After the radiation passes through the mask, interference of rays of diffraction orders ± 1 occurs, which forms a periodic distribution of the intensity of UV radiation. A standard SMF-28 telecommunication optical fiber was used for recording, to improve the photosensitivity of the fiber, it was previously subjected to a storage process in an airtight hydrogen container for 10 days, and the operating wavelength in the spectral range is 1510-1620 nm and an excimer laser with a wavelength of 193 nm is used. During recording, the phase mask was tilted by 10° relative to the fiber axis, and the spectrum of the resulting TFBG was monitored using an optical spectrum analyzer (AQ-6315B from ANDO).

Figure 1 shows the scheme, the principle of operation of TFBG and the comparative structure of homogeneous FBG and TFBG [32].

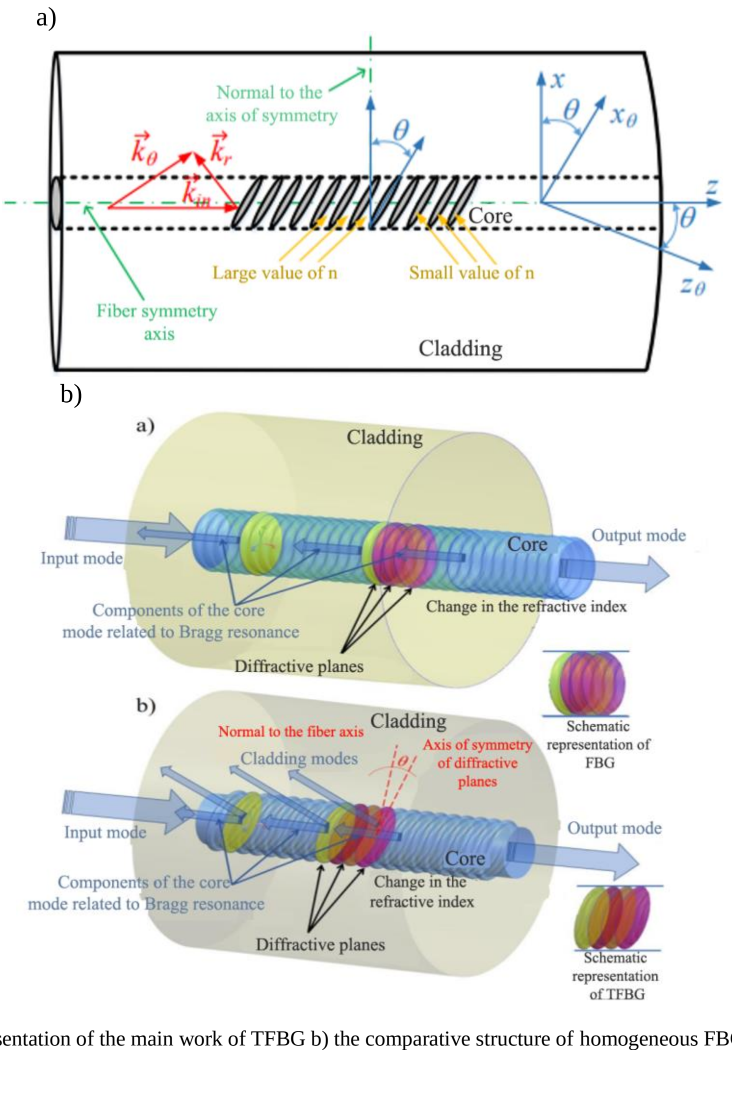

Figure 1.
a) Schematic representation of the main work of TFBG b) the comparative structure of homogeneous FBG and TFBG.

TFBG spectra are measured in a transmission system, since shell modes that are transferred from the core to the shell due to an oblique change in the refractive index are not observed in the reflection spectrum due to their rapid attenuation due to the high attenuation coefficient in the shell. These shell modes propagate in the opposite direction relative to the light in the core, result experiencing complete internal reflection at the boundary between the shell and the environment. Their effective refractive index depends on the refractive index of the external medium, and as it increases, the modes can switch from the mode of total internal reflection to the leakage mode, which leads to a decrease in their amplitude and broadening in the spectrum. Figure 2 shows the transmission spectra of TFBG.

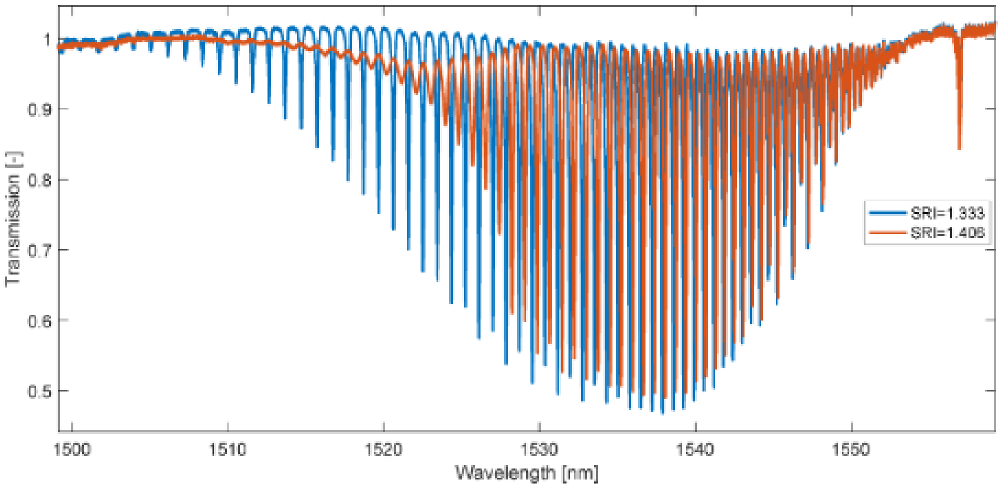

Figure 2.
TFBG transmission spectra.

As the tilt angle of the TFBG increases, a gradual expansion of the bandwidth of the shell modes is observed, accompanied by their shift to the short-wavelength region of the spectrum. In this case, the higher shell modes, which are formed in the short-wavelength part of the spectrum, are characterized by a more pronounced spectral separation.

2.2. Applications of Fiber Sensors Based TFBG in the Biomedical Field

Biosensors are analytical devices that convert biological reactions into measurable signals. Biosensors are distinguished: electrochemical, optical and piezoelectric.

Electrochemical biosensors operate on the basis of potentiometric and amperometric principles, detecting changes in charge distribution on the surface of the transducer. In turn, piezoelectric biosensors use transducers that resonate under the influence of an external alternating electric field. Their work is based on measuring changes in the resonant frequency caused by the mass of the crystal and the biological material attached to it.

Optical biosensors are versatile devices for analytical tasks, as they allow for multiplex detection within a single device. Their principle of operation is to measure the optical properties and characteristics of the transducer surface during the interaction of the analyte with the recognition element. Because these sensors detect deformation, temperature, pressure, vibration, curvature, and refractive index of the surrounding material even under strong magnetic and electric fields, they can serve diagnostic purposes in various fields of healthcare, such as biomechanics, cardiology, oncology, neurosurgery, gynecology, very low temperature monitoring, and immunosensory, to name just a few. one of them.

Next, we will consider optical biosensors based on TFBG, which are a promising configuration for the development of highly sensitive sensor systems widely used in medical monitoring due to their high accuracy, stability and the ability to detect biochemical interactions in real time.

Vital signs monitoring covers key physiological parameters, including heart rate, body temperature, respiratory rhythm, blood pressure, and other critical body functions. Each physiological parameter has diagnostic significance in monitoring and detecting pathological conditions. In clinical practice, basic vital signs include body temperature, respiratory rate and pattern, electrocardiographic data (ECD), and blood pressure levels. The introduction of fiber sensors based on TFBG can improve the accuracy and reliability of monitoring these parameters. As well as miniaturization and immunity to electromagnetic interference, fiber sensors based TFBG are promising for use in magnetic resonance imaging (MRI) applications, where they avoid the use of bulky equipment and minimize patient discomfort.

Body temperature monitoring. Body temperature is one of the key parameters that make it possible to assess the state of the body in real time [33]. Constant monitoring of body temperature is crucial for timely diagnosis of diseases, monitoring the course of treatment, and making emergency medical decisions, which can save a patient's life in critical situations [34]. Its deviations from the norm (about 37°C) upward (hyperthermia) or downward (hypothermia) signal possible disorders in the functioning of organs and systems [35]. Significant fluctuations (±3.5°C) are especially dangerous, which can lead to serious consequences, up to death [36]. Therefore, accurate temperature monitoring is important for early diagnosis and timely treatment [37].

Clinical studies demonstrate that TFBG sensors are capable of measuring body temperature in the range from 35 to 41°C with an accuracy of ±0.1°C [38] which fully meets the requirements of medical monitoring. The high resolution of these sensors, reaching 81.5% [39] makes them especially valuable for detecting the early stages of fever or hypothermia [40]. In addition, TFBG-based fiber sensors have exceptional long-term stability of readings [41] which is critically important for continuous monitoring in intensive care units [42].

A special feature of TFBG technology is the possibility of creating multiplex systems where several sensors are located on one fiber [43] which allows simultaneous monitoring of temperature at different points of the body [44]. This is especially important when monitoring patients with burns or during hyperthermic therapy [45] when it is necessary to monitor the temperature distribution over a large area [46].

Respiratory tract monitoring. The demand for monitoring respiratory parameters is growing in various fields, while respiratory rate (RR), or the number of breaths per minute (beats/min), is considered one of the most important indicators. RR reflects human pulmonary ventilation, and in adults at rest, its normal values range from 12 to 20 beats/min. Respiratory monitoring helps to assess the state of health in clinical practice [47] at work [48] and during sports activities [49].

Clinical studies confirm that RR is a valuable vital indicator that can signal early signs of deterioration [50]. For example, it is used to predict cardiac arrest, assess the severity of acute myocardial infarction [51] and make decisions about admission to intensive care. In addition, RR serves as a marker for detecting serious pathologies, including sleep apnea [52] postoperative respiratory failure [53] and sudden infant death syndrome [54]. Changes in RR are also associated with a number of diseases, such as diabetic ketoacidosis, intoxication, shock, pain, sepsis, allergic reactions, and dehydration [55]. The respiratory rate can serve as an effective tool for monitoring the condition of employees during work. Special wearable devices that monitor RR have been developed for workers experiencing high psychophysiological stress [56]. Studies confirm that this indicator helps to assess cognitive load, emotional stress, exposure to adverse environmental conditions, as well as pain and discomfort [57]. In addition, RR is a sensitive indicator of workload, which is especially important for specialists performing complex tasks, pilots, military personnel, and surgeons [58]. The indicator is also closely related to body temperature, which makes it useful for detecting heat stress in workers in hot workshops or, for example, in firefighters [59]. Compared to traditional metrics (oxygen consumption, lactate level, heart rate), RR more accurately reflects the level of physical activity. It is particularly sensitive to changes in activity intensity, which is typical for interval exercises and team sports such as football or basketball [49]. RR monitoring is also important in a medical context: for example, its changes may indicate shortness of breath during physical activity [60] or serve as a marker of exercise tolerance in patients with chronic obstructive pulmonary disease [61].

Blood pressure monitoring. Continuous monitoring of blood pressure is important for the prevention of cardiovascular diseases such as hypertension [62]. Hypertension has always been one of the common chronic diseases that pose a threat to human health [63]. The traditional method of measuring blood pressure involves the use of a compression cuff, which is fixed on the patient's shoulder [64]. During the procedure, the cuff is inflated with air, creating the external pressure necessary for temporary compression of the artery and subsequent determination of blood pressure [65]. However, this approach has a significant drawback – mechanical compression of tissues during the measurement process causes discomfort and a feeling of tightness in patients, which can negatively affect the accuracy of the results obtained and overall comfort during diagnosis [66].

A special feature of sensors based FBG is their ability to provide highly sensitive detection of pulse fluctuations in real time [67]. An important advantage of this technology is the independence of measurements from such factors as pigmentation of the skin and their moisture level [68]. The use of broadband ASE light sources with increased output power makes it possible to effectively solve the problem of low signal-to-noise ratio, which is typical for traditional photoplethysmographic techniques [69].

The principle of operation of FBG is based on the selective reflection of a certain wavelength when broadband light radiation passes through them, while the rest of the spectrum continues to propagate through the fiber [70]. The analysis of changes in the characteristics of the reflected light signal makes it possible to determine various physical parameters with high accuracy, including temperature changes and mechanical deformations [71].

The physiological mechanism of pulse wave formation is associated with the spread of blood pressure through arterial vessels, which causes cyclic deformational changes in surface tissues [72]. Fixation of the sensor based FBG in the pulsation zone (for example, in the region of the radial or carotid artery) makes it possible to register even minimal mechanical vibrations that cause a corresponding shift of the Bragg wavelength [73]. An accurate analysis of these changes makes it possible to determine the main parameters of cardiac activity: the frequency of contractions, amplitude characteristics, and pulse wave shape [74].

Sensors based TFBG for robotic microsurgery. The use of sensors based FBG in biomechanics and rehabilitation remains a relatively new area, and the potential for widespread adoption requires further study [75, 76]. Possible applications include measuring mechanical stresses in bone tissue [77] analyzing pressure distribution in musculoskeletal structures [78] assessing intervertebral disc deformity [79] monitoring respiratory movements of the chest wall [42] studying pressure distribution in areas of human contact with technical devices [80] and analyzing biomechanical functions ligaments and tendons [81] as well as studying the dynamics of the interaction of body segments during walking [82]. In addition, FBG can be used in dental biomechanics to assess loads in the maxillary system [83].

Modern robotic surgery is a revolutionary trend at the intersection of medical science and precision engineering, offering fundamentally new opportunities for performing complex surgical interventions [84]. Unlike traditional surgical approaches, the latest generation of robotic systems combine unprecedented spatial accuracy, enhanced freedom of manipulation, and minimally invasive access, which together can significantly improve the clinical outcomes of surgical interventions [85]. Fiber sensors based on TFBG, which set new standards of accuracy in surgical and rehabilitation practice [86]. Their principle of operation is based on detecting changes in the spectral characteristics of shell modes, providing unprecedented sensitivity to mechanical influences (with a resolution of up to 1 nm/m) while maintaining a linear response over an extremely wide measurement range [87].

In addition to biomechanical monitoring, sensors based TFBG can be used to diagnose the technical condition of the exoskeleton itself, including the assessment of mechanical stresses in its structural elements, which is especially important during long-term operation [88]. Their resistance to electromagnetic interference and compact dimensions make them ideal for integration into medical devices where reliability and accuracy are the determining factors [89]. They are used for rehabilitation of patients after stroke [90] spinal cord injuries [91] or age-related disorders of the musculoskeletal system [92]. For example, in systems designed to restore walking, they allow precise dosing of the mechanical load on the lower extremities, minimizing the risk of joint overload [93]. In the exoskeletons of the upper extremities, TFBG-based sensors provide control over the smoothness of movements, which is especially important in the rehabilitation of fine motor skills [94]. Clinical studies demonstrate significant improvements in operational performance when using such systems, including a reduction in intraoperative blood loss by 40-60% [95] a reduction in hospitalization time by 30-35% [96] as well as a significant increase in manipulation accuracy [97] which expands the possibilities of minimally invasive surgical approaches.

Fiber sensors for magnetic resonance imaging. In recent decades, the increased demand for medical technologies compatible with magnetic resonance imaging (MRI) has stimulated the development of specialized sensors based on various operating principles [98]. Among them, fiber sensors are of particular interest due to a number of advantages [99].

The high flexibility and small dimensions of optical fibers make it possible to create miniature sensors with metrological parameters such as accuracy, sensitivity, stability and frequency response [100]. These parameters meet the requirements of most medical applications [101]. In addition, immunity to electromagnetic interference and the absence of the need for electrical contact with the patient ensure the safe operation of fiber sensors in conditions of strong magnetic fields, which distinguishes them from traditional electronic analogues [102].

These key characteristics expand the potential of fiber sensors in medicine, making them a promising solution for monitoring physiological parameters during MRI studies [103].

Since its introduction in the 1970s, magnetic resonance imaging (MRI) has significantly exceeded the initial expectations of researchers, taking a key place in clinical imaging [104]. The growing number of MRI examinations and the introduction of new procedures performed under MRI navigation stimulated the development of specialized sensors compatible with magnetic resonance (MR-compatible) [105].

Among such solutions, fiber sensors are of particular interest, since they can be used both to improve the accuracy of surgical interventions [106] and to monitor the condition of patients [107]. Their areas of use include:

- Temperature control during MRI-guided hyperthermic therapy [108];
- Measurement of mechanical parameters (deformations, forces) on surgical instruments, for example, needles during surgical intervention with the support of MRI [109];
- Registration of physiological parameters (heart rate, respiration) [110].

The prospects for using fiber sensors in research protocols are extremely wide, which opens up new opportunities for the development of MRI-compatible diagnostic and therapeutic technologies.

3. Results

Modern medical technologies require the development of highly sensitive multiparametric monitoring systems, where fiber sensors based on TFBG are of particular interest, which, due to their unique geometry and properties, open up new possibilities for simultaneous measurement of pressure and temperature in clinical settings. Unlike traditional FBGs, TFBG exhibit pronounced sensitivity to both axial deformations (pressure) and temperature changes due to excitation of shell modes, making them ideal candidates for medical applications where a compact and multiparameter sensor is required.

In cardiac surgery, such sensors can be integrated into vascular catheters for simultaneous monitoring of blood pressure and blood temperature, and the inclined grid configuration allows for higher sensitivity to mechanical influences compared to conventional FBG, which is critically important for detecting weak pulse waves in patients with heart failure. At the same time, the temperature sensitivity of TFBG, due to the dependence of the effective refractive index on temperature, provides correction of thermal artifacts during pressure measurements, which is especially important during prolonged surgical procedures, when heating the catheter can distort the measurement results.

In neurosurgical applications, miniature sensors based TFBG can be used to monitor intracranial pressure and brain temperature simultaneously, where their advantage lies in the ability to distinguish between mechanical and thermal effects by analyzing spectral reflection characteristics, including not only the Bragg wavelength, but also the amplitude of shell modes that respond differently to pressure and temperature. This allows us to create a multiplex system for continuous monitoring of the condition of patients with traumatic brain injuries, where even small changes in these parameters may indicate the development of dangerous complications.

For oncological applications, in particular radiofrequency ablation of tumors, fiber sensors based on TFBG offer a unique opportunity to monitor not only the temperature in the affected area, but also the resulting interstitial pressure, which helps prevent damage to surrounding healthy tissues. TFBG are particularly valuable in this case due to their ability for spatially distributed measurements along the fiber, which allows obtaining information about the distribution of temperature and pressure along the entire length of the ablation zone, rather than at a single point.

The experimental implementation of such sensors requires careful calibration of their response to pressure and temperature in physiological ranges, which can be achieved using specialized devices that simulate in vivo conditions. At the same time, the key advantage of TFBG is the ability to mathematically separate the contributions of temperature and pressure to the overall sensor response by analyzing spectral characteristics, which eliminates the need for complex hardware solutions for separate measurement of these parameters. Further development in this area includes optimizing the geometry of gratings to achieve maximum sensitivity, developing signal processing algorithms for real-time operation, and creating protective coatings to ensure biocompatibility and long-term stability of sensors in a physiological environment.

Thus, fiber sensors based TFBG represent a promising platform for creating a new generation of medical diagnostic systems that combine high accuracy, multiparametricity and minimal invasiveness, which opens up opportunities for improved monitoring of critically ill patients, intraoperative monitoring and personalized therapy based on comprehensive physiological data.

Next, consider sensors based TFBG that are sensitive to deformation and temperature. This allows them to be used for temperature monitoring, but it also means that it is good practice to combine a temperature sensor with a strain sensor to compensate for the effect of temperature on the strain sensor.

The Bragg grating used in the experiment was 10 mm long. It was made using a phase mask and an ultraviolet laser beam with a wavelength of 193 nm. Optical fiber was previously pumped with hydrogen for 10 days. The central wavelength and reflectivity were 1510-1620 Nm and 90%, respectively. Figure 3 shows the results of measurements of the reflection spectra of the grating for various strain values. It should be noted that the width of the spectral characteristic of the lattice changes as the strain value increases. The width of the spectrum in the absence of interactions is 0.9 nm.

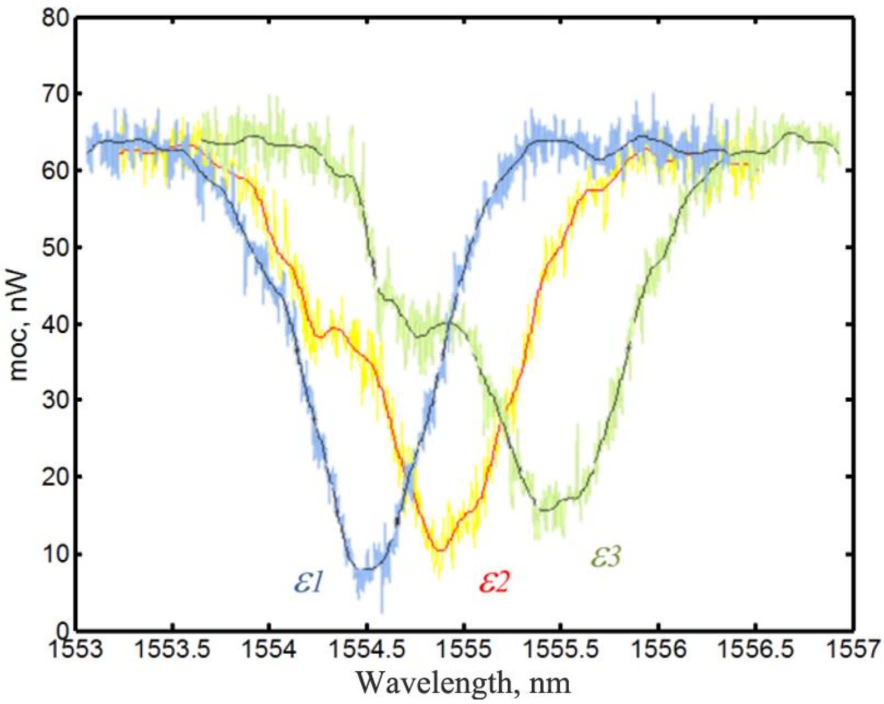

Figure 3.
Transmission characteristics of the proposed sensor at various strain values and constant temperature

The data from the sensor for deformation at constant temperature is shown in Figure 4.

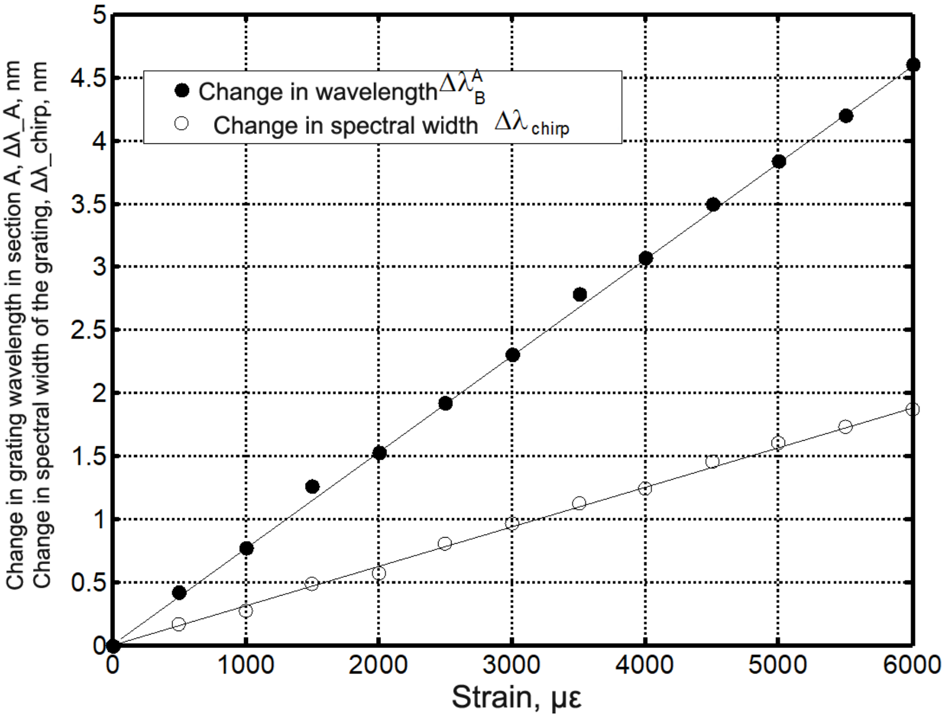

Figure 4.
Measurement results of the sensor's response to deformation, obtained at a constant temperature of 25 C.

Obtaining matrix equations of systems with Bragg gratings for parallel measurement of strain and temperature should begin by recording the dependencies on the Bragg wavelength for a uniform lattice, which takes the following form:

$$\lambda B = 2neff\ \Lambda \tag{1}$$

where neff is the effective refractive index in the core of the fibers on which the grating is written and Λ is the grating period.

The appearance of temperature changes in the ΔT - shaped joint and deformation of the Δε - shaped joint leads to a change in the Bragg wavelength in accordance with the ratio:

$$\Delta\lambda_B = 2\left(\Lambda\frac{\partial n_{eff}}{\partial\varepsilon} + n_{eff}\frac{\partial\Lambda}{\partial\varepsilon}\right)\Delta\varepsilon + 2\left(\Lambda\frac{\partial n_{eff}}{\partial T} + n_{eff}\frac{\partial\Lambda}{\partial T}\right)\Delta T \tag{2}$$

in which T is the lattice temperature, ε - is the relative deformation described by the dependence:

$$\varepsilon = \frac{\Delta l}{l_0}, \tag{3}$$

where l determines the change in the length of the grating, l0 - its initial length.

The sensitivity of the wavelength to deformation is determined, in turn, by the following dependence:

$$K_\varepsilon = \frac{\Delta\lambda_B}{\Delta\varepsilon} = k_\varepsilon \cdot \lambda_B, \tag{4}$$

where kε - the coefficient of relative sensitivity to deformation and is equal to:

$$k_\varepsilon = 1 - p_e, \tag{5}$$

where pe - elasto-optical coefficient describing the change in the refractive index of a fiber during deformation (pe ≈ 0,22).

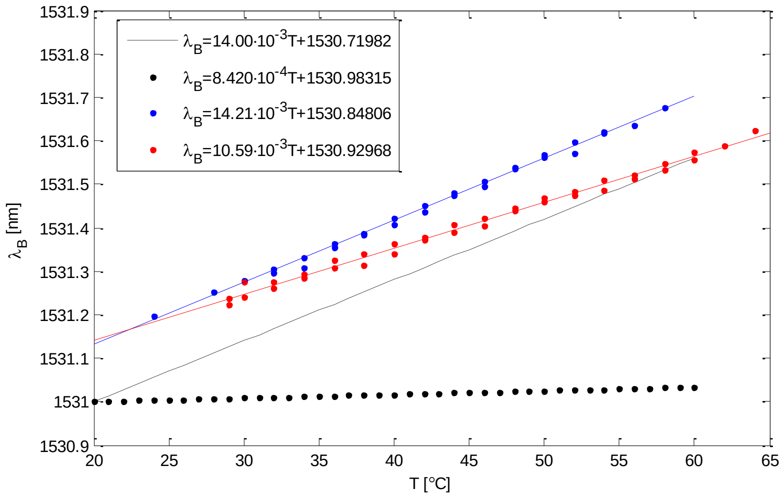

Figure 5.
Dependence of the Bragg wavelength λB on temperature.

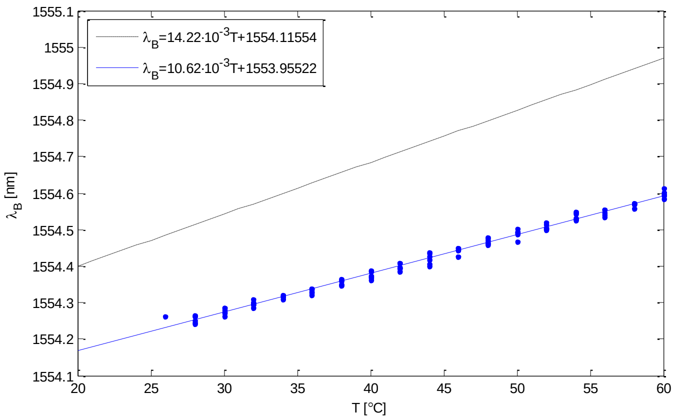

Figure 6.
Dependence of λB = 1554.4 nm on temperature.

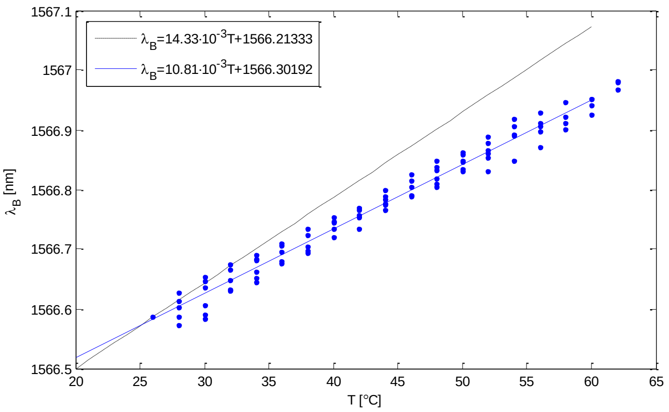

Figure 7.
Dependence of λB = 1566.5 nm on temperature.

It can be seen that the repeatability and reliability of long-term temperature monitoring is ensured by using this type of FBG sensor, capable of measuring temperature with an accuracy of no more than 1 °C for at least one day, and can be easily performed in a reasonable manner within the experimental errors, which were mainly due to instrumental resolution and environmental fluctuations. The excellent stability characteristics of this FBG sensor made it possible to monitor pavement structures in difficult conditions with reasonable accuracy for a very long period of time.

To conclude, it can be noted that the nature of both studied dependences of deformation and temperature turned out to be linear and within the margin of error. This main result of the work is in full accordance with the theoretical as well as practical data available at the moment.

4. Conclusions

In conclusion, the introduction of sensors based FBG into medical monitoring systems has become an important step in the development of healthcare. Numerous studies over the past ten years have confirmed the extensive capabilities and high efficiency of these sensors in various fields of medicine, including monitoring the cardiovascular system, respiration, and biomechanical parameters. Due to their sensitivity, biocompatibility and resistance to electromagnetic interference sensors based FBG are the optimal solution for non-invasive and continuous monitoring of vital signs.

Fiber sensors based on TFBG represent a breakthrough technology in the field of medical diagnostics and monitoring, with a set of unique characteristics. Their special value in medicine is due to their ability to provide high-precision measurements in environments where traditional electronic sensors are ineffective. The key advantages of TFBG for medical applications include their exceptional sensitivity to biomechanical influences, reaching a subnanometer level, which allows even minimal physiological changes to be recorded. Due to the multiresonance nature of TFBG, these sensors are able to simultaneously monitor several parameters - temperature, mechanical stresses and biochemical parameters, which is especially valuable for complex diagnostics.

In clinical practice, temperature is a critically important parameter that is continuously monitored using specialized equipment. This indicator is monitored in all medical institutions, including operating rooms, oncological and intensive care units.

In this regard, the experimental part of the study examined the temperature dependence of the characteristics of a fiber sensor based on TFBG. Thanks to the use of TFBG, the sensors show an equally accurate response to both rising and falling temperatures. A linear relationship is observed between the temperature range (ΔT) and the Bragg wavelength shift. The sensitivity of the sensor is caused by a change in the refractive index of the UVR during temperature fluctuations, which leads to a corresponding shift in the Bragg wavelength.

The most important characteristic of TFBG is their ability to minimize the problem of cross-sensitivity, which traditionally limits the accuracy of fiber-optic measurements. This is achieved due to the unique spectral properties of inclined gratings, which make it possible to clearly differentiate between different types of impacts. In addition, TFBG demonstrate outstanding stability of readings during long-term monitoring, which is critical for monitoring chronic conditions.

The biocompatibility and miniature size of TFBG open up possibilities for their integration into implantable devices and surgical instruments. Their complete immunity to electromagnetic interference makes these sensors ideal for use in MRI diagnostics and other procedures where traditional electronic sensors are not applicable.

TFBG ability to provide distributed measurements with spatial resolution deserves special attention, which makes it possible to create monitoring systems with a high density of measurement points. This characteristic is especially valuable in the development of «smart» surgical instruments and rehabilitation exoskeletons, where accurate mapping of mechanical loads is required.

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