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ИНЖЕНЕРЛІК ҚҰРЫЛЫМДАРДЫҢ ЖАҒДАЙЫН БАҚЫЛАУ ҮШІН ӘРТҮРЛІ ЗАМАНАУИ ТАЛШЫҚТЫ-ОПТИКАЛЫҚ СЕНСОРЛАРДЫ ЖОБАЛАУ ЖӘНЕ ПАЙДАЛАНУ ТӘЖІРИБЕСІН ТАЛДАУ ЖӘНЕ ЗЕРТТЕУ

АНАЛИЗ И ИССЛЕДОВАНИЕ СУЩЕСТВУЮЩЕГО ОПЫТА ПРОЕКТИРОВАНИЯ И ИСПОЛЬЗОВАНИЯ РАЗЛИЧНЫХ СОВРЕМЕННЫХ ВОЛОКОННО-ОПТИЧЕСКИХ ДАТЧИКОВ ДЛЯ МОНИТОРИНГА СОСТОЯНИЯ ИНЖЕНЕРНЫХ СООРУЖЕНИЙ

ANALYSIS AND STUDY OF THE EXISTING EXPERIENCE IN THE DESIGN AND USE OF VARIOUS MODERN FIBER-OPTIC SENSORS FOR MONITORING THE STATE OF ENGINEERING STRUCTURES

Abstract. *Recently, considerable number of innovative sensor systems, based on fiber-optic sensors was on-stream in mechanical and engineering structures, thanks to their differential advantages, such as small size, light weight, nonsensitivity to electromagnetic interference and corrosion, as well, incorporation possibility. An article herein considered review, study and research of multitude design systems, based on fiber-optic sensors for continuous measurements and assessment of different engineering structures in real time. Aim of survey article herein is to present the summary of basic principles of various fiber-optic sensors operation, innovations in probing area and computational methodologies, developing new fiber-optic sensors, as well, fiber-optic sensors technology practical usage health.*
Keywords: *Optical fiber, fiber Bragg grating, interference methods, photomask method, point-to-point method.*

Аңдатпа. *Соңғы уақытта оптикалық-талшықты сенсорларға негізделген инновациялық сенсорлық жүйелердің едәуір бөлігі шағын мөлшер, жеңіл салмақ электромагниттік кедергілер мен коррозияға* *қарсы тұра алуы, сондай-ақ құрылымдана алуы сияқты артықшылықтарының арқасында механикалық және құрылыс құрылымдарында пайдаланыла бастады. Бұл мақалада әртүрлі инженерлік құрылымдарды үздіксіз өлшеу және нақты уақытта бағалау үшін оптикалық-талшықты сенсорларға негізделген көптеген жобалау жүйелерін шолу, талдау және зерттеу қарастырылған. Осы шолу мақаласының мақсаты-әртүрлі оптикалық-талшықты датчиктер жұмысының негізгі принциптерінің қысқаша мазмұнын, зондтау және есептеу әдістемесі саласындағы инновацияларды, жаңа оптикалық-талшықты датчиктерді құруды, сондай-ақ оптикалық-талшықты датчиктер технологиясын практикалық қолдану жағдайын ұсыну.*

Түйін сөздер: *Оптикалық талшық, талшықты Брагг торы, интерференциялық әдістер, фотошаблон әдісі, «нүкте-нүкте» әдісі. Түйін сөздер, түйін сөздер.*

Аннотация. *В последнее время значительное число инновационных сенсорных систем на основе волоконно-оптических датчиков эксплуатируется в механических и строительных конструкциях, благодаря таким преимуществам этих датчиков, как малые размеры и вес, невосприимчивость к электромагнитным помехам и коррозии, а также возможность их встраивания в систему измерения. Цель данной обзорной статьи – представить краткое изложение основных принципов работы различных волоконно-оптических датчиков и сделать краткий обзор исследований и практических разработок в области мониторинга состояния зданий и инженерных сооружений с применением технологии волоконно-оптических датчиков.*

Ключевые слова: *Оптическое волокно, волоконная брэгговская решетка, интерференционные методы, метод фотошаблона, метод «точка-точка».*

Introduction. Currently, in civil construction field, the health structural monitoring is quickly developing area in engineering disciplines. In engineering and academic communities in the field of monitoring the civil construction systems health exploded within recent two decades [1-3]. For fast technology development the available experience proved, that the probing method has progressive development. Fiber-optic sensors possess a number of unique advantages, such as small size, light weight, nonsensitivity to electromagnetic interference and corrosion, as well, incorporation possibility comparing to conventional mechanical and electrical sensors, and therefore they are used for monitoring engineering and building structures all over the world. The given article will present all-around view, analysis and investigation of current experience of designing and using state of the art fiber-optic sensors for health control.

For the recent two decades there have been conducted plenty of researches, designated to studying the progress of investigations and developments of fiber-optic probing technology, as well fiber-optic sensors usage in monitoring various engineering and building structures.

Ansari offered a concise summary of basic principles, belonging to civil engineering structures monitoring by means of fiber-optic sensors. Measures et al. in the work [4] made a survey on developing structurally-integrated fiber-optic sensors for smart structures. Monitoring system, mainly, consists of four parts: FBG sensor, signal transmission, data collection system and data processing system. In FBG sensors' data collection system the optic probing interrogator unit SM125-500, production of Ministry of internal affairs, USA (Optics Micron, Inc.) represents Fabry-Perot four-way filter with entire spectrum display, as shown on Fig. 2, which is applicable to durable monitoring under severe conditions. Wave length is 1510-1590 nm. Stability and accuracy of the wave length constitutes 1 fs. Working temperature is 0~50 °C. Interrogator can show optical properties with spectral bandwidth of 1-2 GHz/3 dB. Dynamic range is 50 dB, scanning frequency -1 Hz. Fiber SMF28 is covered with acrylate, fiber resolution is 0,25 ± 0,05 nm, a bend radius -25 mm. Bragg grating temperature-sensitivity coefficient is 10,9 pm/°C.

Materials and methods of research. Fiber-optic sensor system consists of light sender unit, receiver, optic fiber, modulating element and signals processing block. One of fiber-optic sensor basic part, optic fiber, usually is made of silica glass or polymer material, which itself can be a sensitive element or can transfer an element from the source to modulator element. When there occurs deformation or construction's temperature change, superficially installed or built-in fiber-optic sensor in the construction expands or contracted. To obtain appropriate fiber structure physical magnitude, fiber-optic sensor modulates the light in compliance with optical beam length change and reflects back the optical signal into analytical block. As it is shown in following sections, fiber-optic sensors can be divided into different types, which are based on probing principle.

Figure 1. View of SM125 optic sensor interrogator's front [5]

Fiber Bragg grating sensors (FBG). To the present day FBG sensor is widely used in civil infrastructure monitoring. It might be considered as fiber-optic sensor type with various refractive indices in the core. According to Brag law, colorless light beam is recorded into FBG sensor and, when the light from broad-band source goes through the grating at certain wavelength, Bragg wavelength is reflected, which is connected with grating period, as it is shown on Fig.1. Bragg wavelength might be expressed as

$$\lambda_B = 2n_{eff}\Lambda \qquad (1)$$

where n_{eff}- effective refractive index and Λ –grating period. Wave length shift changes linearly both with deformation and temperature. When grating part is exposed to external disturbance, the grating period changes and accordingly, changes Bragg wavelength. Bragg wavelength can be obtained as follows

$$\Delta\lambda_B = \lambda_B\{(\alpha + \xi)\Delta T + (1 - p_\varepsilon)\}\Delta\varepsilon \qquad (2)$$

where $\Delta\varepsilon$ – deformation change; ΔT – temperature change; α – thermal-expansion coefficient; ξ– thermal optic factor; p_ε – strain-optic factor.

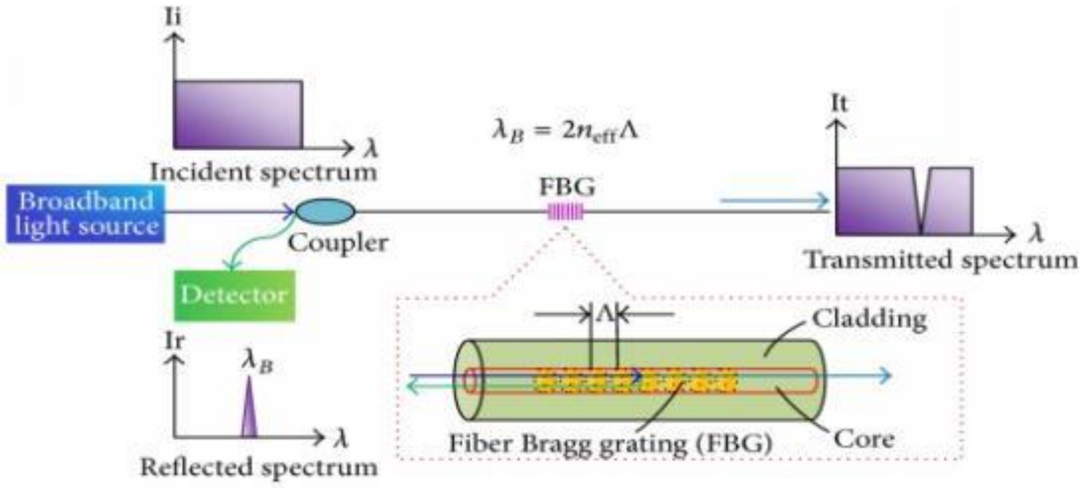


Figure 2. Measurement principle of FBG sensor [6]

Fails detection and localization are critical problems for structures health monitoring. For that, there was offered a plenty of methods to detect damages availability, variations of their dynamic characteristics between undamaged and damaged states. As bigger information volume is localized at higher frequencies, there should be used the sensor systems with adequate spectral bandwidth and resolution.

There have been used fiber Bragg grating sensors with appropriate interrogating system to detect damages in the structure. As preliminary step there have been conducted modal analysis tests in very high frequency range to check the optical devices features to reveal high frequency structural dynamic characteristics.

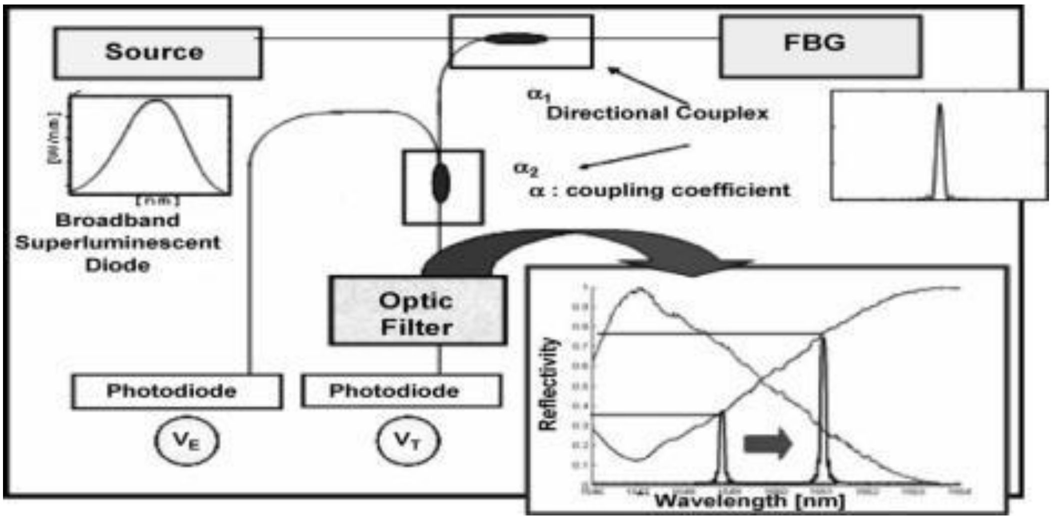
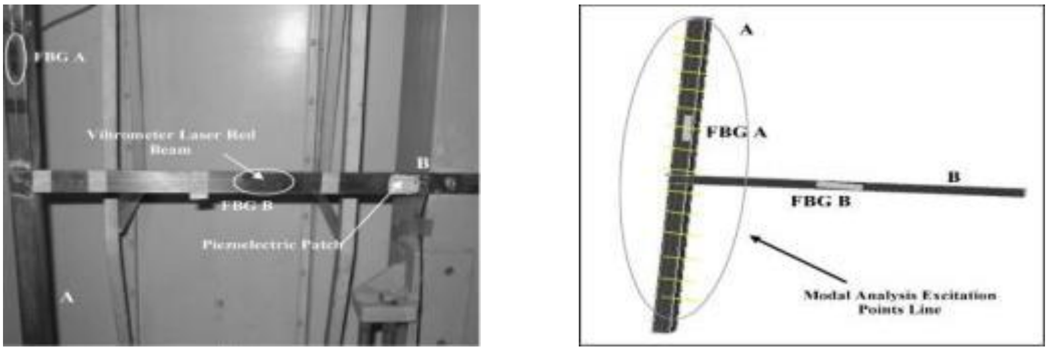


Figure 3. Diagram of optoelectronic installation, used for wide band interrogation and optical filtering [7]

As monitor sensors there have been used laser Doppler vibration sensors and accelerometers, representing up-to-date engineering level in the application area herein.

Experimental results confirm excellent characteristics of fiber Bragg gratings, which are able not only to detect fails, but, as well, differentiate different damages levels.



a) b)

Figure 4. Scheme of being studied mechanical structure a and b – fragment, imaging operated piezoelectric element and vibration sensor beam [8]

Present some outcomes of interdisciplinary research program on FBG sensors with participation of Civil construction school and School of electric engineering and electronics at Nanyan technological university in Singapore. New FBG strain sensors have been developed and used at highway bridges to measure dynamic characteristics, static deformation and temperature. Outcomes of investigations thereof show, that at correct packing FBG sensors can withstand severe conditions, connected with construction environment of civil infrastructure.

Bragg grating is a periodical structure, created with ultraviolet light impact at the picture of fiber sensitized core (Figure 5).

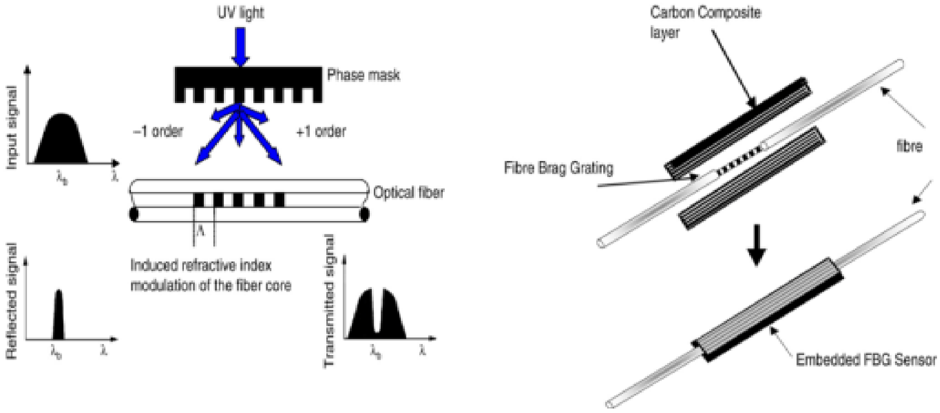


Figure 5. Process of FBG manufacturing [9]

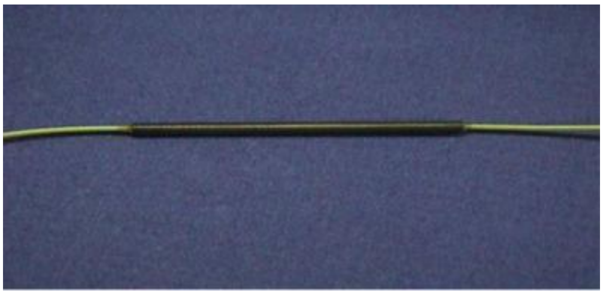


Figure 6. FBG temperature sensor [10]

Temperature sensor consists of FBG sensor, sealed in 35 mm metallic pipe

Figure 7. Strain sensor with temperature compensation [11]

Built-in deformation sensor consists of FBG, clamped between carbon composite material layers (Fig. 7), has the length about 50 mm, 0,5 mm thickness. Sensor's accuracy and sensitivity depend on interrogating optical system. Interrogating optical system function is to detect wavelength shift in reference to external disturbance and unhide measured magnitudes, using the equation (2). Interrogation system, used for measuring deformation, described herein, had sensitivity 1 με and accuracy 5 με, ε-is a unit of measurement for relative strain. It should be noted, that the strain sensor is not protected from temperature fluctuations and, consequently, will denote the deformation due to thermal expansion. The sensor, described in the section 3.3, allows minimize deformations, linked with temperature change.

There has been developed the interrogation system of signals, entering from rotation sensors. Its sensors analysis system most frequently demands capacity reference measurement. It allows obtain measurement higher resolution, comparing to single-channel systems, in which it is impossible to measure based capacity. In case of single channel solutions there is most frequently monitored wavelength shift, corresponding to extreme value, according to spectral characteristics.

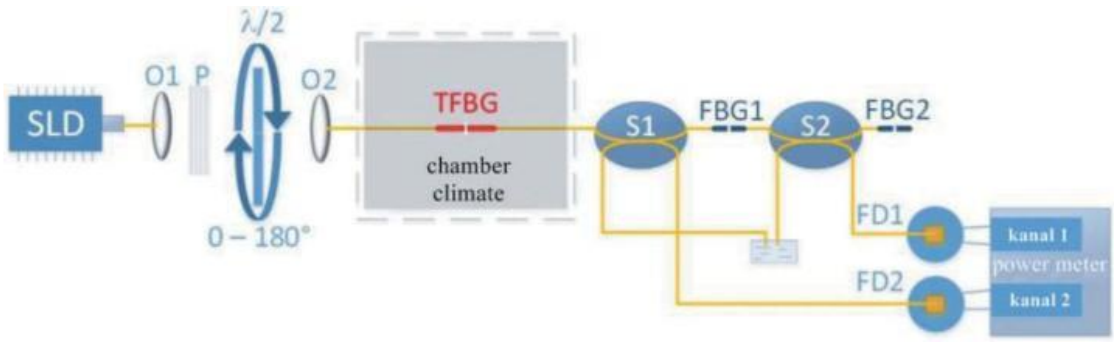


Figure 8. Interrogator of signals from polarization sensors, based on TFBG structures [12]

The method's important advantage is that all used in it elements are passive. Therefore, it possesses all merits, common to fiber-optic sensors. Flow graph, demonstrating the method's idea is given on Figure 8. An important practical aspect of the system thereof is insensitivity to light source capacity fluctuations. Moreover, TFBG transformer, FBG 1 and FBG 2 optical filters temperature insensitivity, stored at one optical fiber, single mode, is similar and constitutes approximately10 pm / ° C. It means, that in case all optical elements are under one and the same external temperature, their characteristics spectral shift will be similar, which supposes the possibility of conducting measuring the rotational angle of falling polarization plane, insensitive to temperature changes.

Extrinsic Fabry-Perot external interferometric sensors (EFPI)

For EFPI sensors an optical fiber is an input or output duct; light from the source goes through optic fiber to sensitive part, and afterwards to demodulation system. Standard EFPI sensor consists of input/output fibers and reflecting fibers, as well, of the tube with hollow core to create air chamber, namely, Fabry-Perot chamber. To connect two components there is used an adhesive. As it is shown on Fig. 9, Fabry-Perot chamber is made up between input single mode fiber and reflecting single mode or multimode fiber, and two fibers are aligned inside the tube with hollow core. At both chamber's ends there are reflections on non-coating fibers edges.

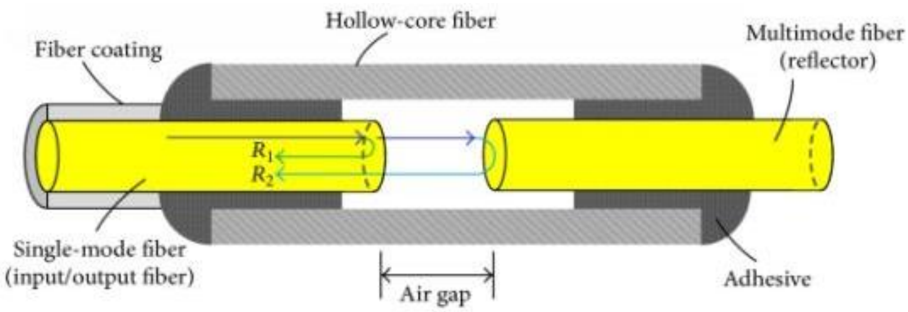


Figure 9. Measuring principle of EFPI sensor [13]

R_1 is reference reflection, which depends on applied perturbation, such as deformation and temperature. R_2 – is sensitive reflection and depends on L hollow length. Upon occurring interference, R_1 will be generated with sinusoidal output signal R_2. As the resonator length can be modulated with applied disturbance, EFPI sensor might be used for measuring the applied disturbance in compliance with an output signal. Deformation measurement can be expressed as

$$\varepsilon = \frac{\Delta l(air\ gap)}{L} \quad (3)$$

where L – is variation in the hollow.

There has been developed fiber-optic extrinsic fiber-optic interferometric transducer of Fabry – Perot (TR-EFPI) total reflection with signals digital processing algorithm to measure deformation of structures, such as buildings, bridges, aircrafts, etc. Some demodulation devices have been used to measure magnitudes and directions of deformation from conventional fiber-optic EFPI sensors, using narrow band light sources, as a signal has merely sinusoidal wave picture, connected with directed deformation change. In the research herein, the sensor for measuring the deformation magnitude and direction consists of EFPI total reflected sensor probe and simple signal digital processing algorithm for wave number, computation without any demodulation devices. The probe thereof is made of a single-mode fiber and a fiber with silica glass mirror coating, capillary tube. An output signal of that TR-EFPI optic-fiber sensor was simply processed to define the strain magnitude and direction. Tensile test on aluminum support beams sample has been carried out at universal testing machine. As a result of that experiment it can be seen, that TR-EFPI sensor's optic-fiber deformation is well compliant with electric strain sensor value.

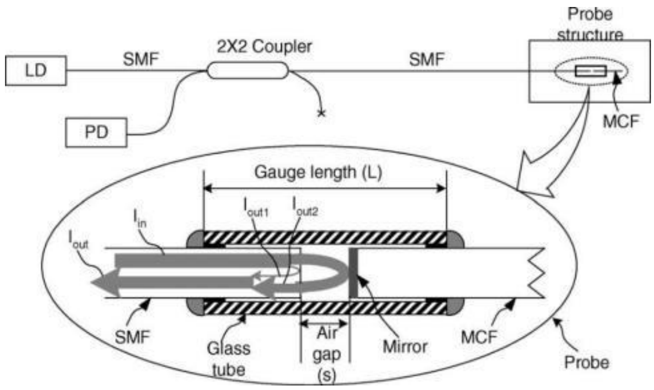


Figure 10. Principle diagram of TR-EFPI fiber-optic sensor [14]

TR-EFPI fiber-optic sensor has been constructed as it is shown in Fig. 10. Light from diode laser goes into single mode fiber (SMF) and achieves the probe through 2 × 2 optic-fiber connector. The probe consists of three parts: single-mode fiber, directing the input light to the sensor, mirror coating fiber (MCF), reflecting light and glass capillary tube, forming air gap between SMF and MCF. 97% of input light, arriving at the probe through single mode fiber passes through an air gap and, as well, 3% of input light is reflected at single fiber edge. Passing light, which is 97% of incoming light, shall scatter along an air gap, out coming from a single mode fiber and fiber mirror surface with mirror coating.

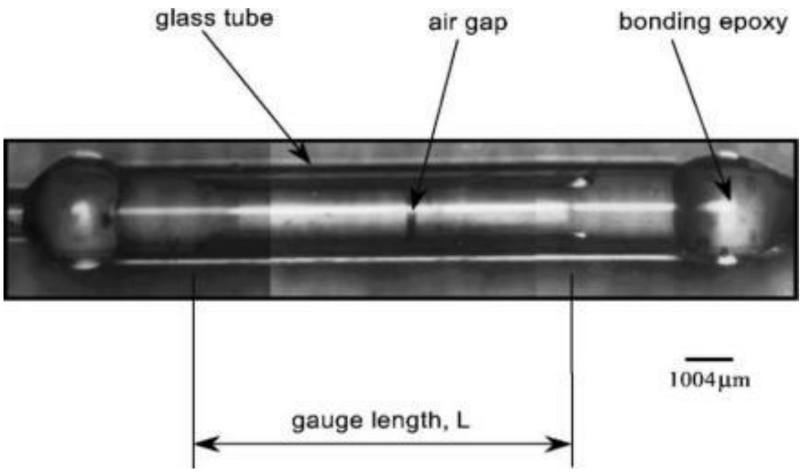


Figure 11. Manufactured probe of TR-EFPI optic-fiber sensor [14]

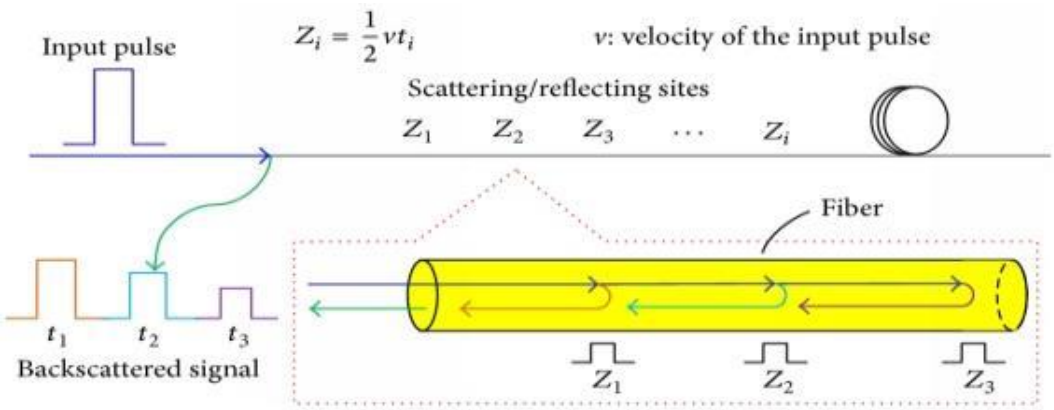


Figure 12. Measuring principle of OTDR sensor [15]

Innovations in methodologies and sensors

Sensors updating methodology. There is offered the model for describing the dependence of deformation moving about between FBG sensor fiber core and material. There has been developed a new simulated annealing algorithm for modulating the deformation profile along distributed FBG strain transducer. To investigate strain transfer from the basic structure to sensitive fiber there has been offered the model, including sharp mitigation of surrounding components behavior. On FBG basis there has been offered soft-grade recognition algorithm, based on genetic algorithm, supporting vector regression to achieve sensor network reliability [16]. To determine deformations distribution along Bragg grating there has been presented the transducer's spectral data inversion genetic algorithm [17].

Mar et al. [18] presented the fast interrogation method of dynamic and/or static strain-gage transducer, using reflection spectrum from two superimposed FBG. By means of FBG multiplexed sensors there has been developed impact shock localization algorithm in real time for various composite structures, using, stimulated with impact obtained acoustic signals [19]. Feng and others [20] in the article offered the method of static wavelet transform for processing the signals of distributed deformation data from fiber-optic sensors, based on BOTDR.

Described method of minimizing the influence of polarization changes consists in fabricating the new TFBG structure, which will be insensitive to the light polarization change. Solution in that case is in creating the structure, which, apart from infraction index modulation tilt will be twisted along its length for definite angle ϕ, as it is shown in the Figure 13.

Figure 13 shows the method of specifying the angle of structure $\boldsymbol{\phi}$ twisting. The same structure is also characterized with angle θ, defining refraction index modulation tilt in respect to surface normal to the fiber, on which is written TFBG.

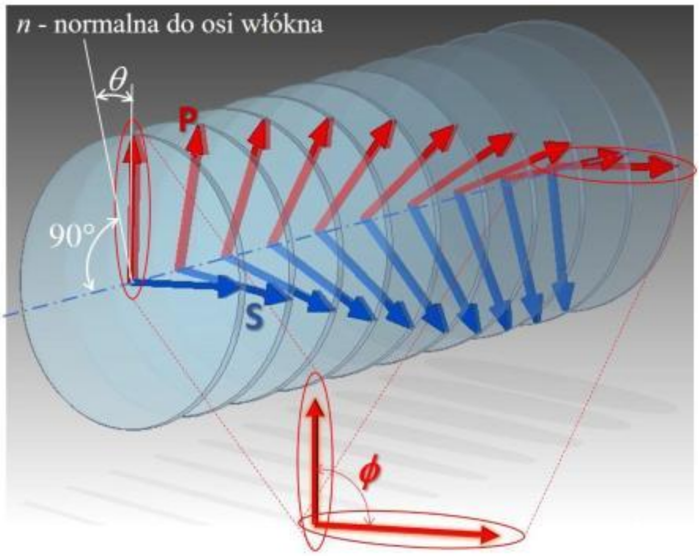


Figure 13. Twisting the TFBG structure to the angle

ϕ. Red arrows denote polarization type P, blue arrows correspond to polarization type S [21].

In order to demonstrate the structure twisting effect on the dependence of its transmission spectrum from inlet light polarization, at the first stage there has been carried out testing, in which TFBG is twisted under known angle $\boldsymbol{\phi}$. For testing there has been fabricated the TFBG structure with tilted angle $\theta = 5°$. Transmission characteristics of total structure without induced twisting have been shown in the Figure 14. Spectrum evolution due to changes of polarization for untwisted structure (ϕ=0°) is shown in the Figure 15.

Three spectral characteristics have been measured for three different values of the inlet light polarization angle in compliance with P-type polarization, polarization is turned for 45 °, which conforms to polarization S | P-type, and polarization turned for на 90 °, which corresponds to S-type polarization.

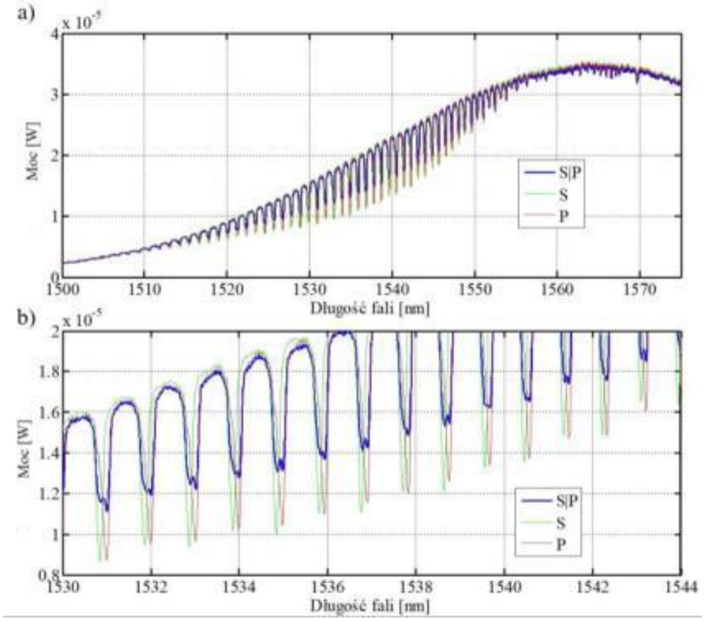


Figure 14. Outcomes of TFBG spectral measurements θ=5°, ϕ=0° has been twisted for three inlet light polarization states of inlet type for waves length: a – 1500-1575 nm, б – 1530-1544 nm [21]

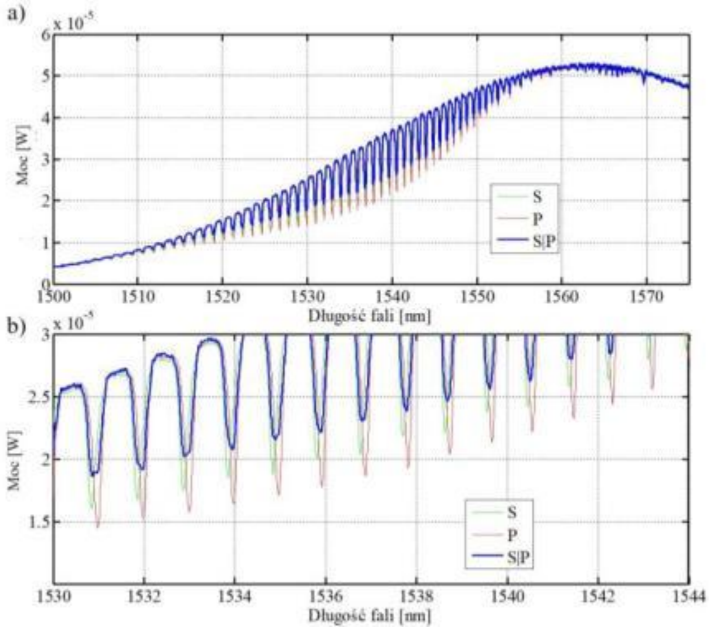


Figure 15. Outcomes of TFBG spectral measurements θ=5°, twisted under angle ϕ=45° for three inlet light polarization states for waves lengths: a – 1500-1575 nm, б – 1530-1544 nm [21]

Measurements outcomes, presented in Figures 15-16, prove, that it is possible to control sensitivity to the inlet light polarization angle changes, choosing the twisted angle of the whole TFBG structure. Amplitude change of the peak, obtained from cladding modes, so much the less, than bigger the twisting angle ϕ of TFBG structure.

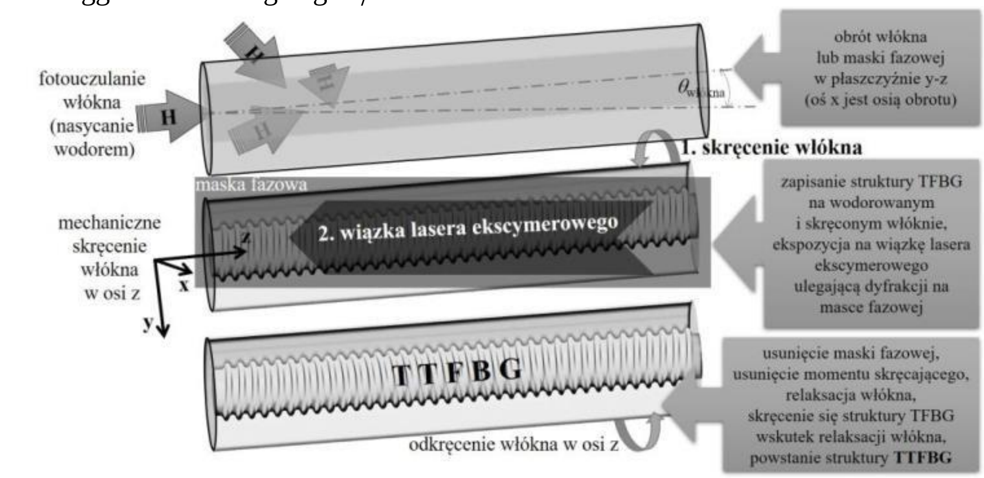


Figure 16. Diagram, showing technique of fabricating CTFBG structures [21]

With that aim there has been developed the technique of structures fabricating, which will be already twisted under definite angle. Figure 16 shows how to construct such structures. Afterwards, the technique thereof was used for fabricating of real TFBG structures, which, apart from being twisting, were marked with CTFBG symbol.

Standard single-mode fibers, the CTFBG structures will be written on, have doping level with germanium dioxide GeO_2 3%, which is enough for reaching the refraction index change only for 10^{-5}. To raise the level of refraction index change in the core it is necessary to raise doping level for several times, which is technologically complicated. All structures, having been described in this research, have been obtained by means of photosensitizing of optical fibers in hydrogen atmosphere.

Conclusions. The article herein is a concise survey of researches and workings in health monitoring of building and engineering structures, using technologies of fiber-optic probing. Based on all-round review of theories, methods, technologies and applications, grounded on optic fibers, there made following final observations: (a) thanks to own unique advantages fiber-optic sensors are widely used in healthy monitoring of civil and engineering structures, such as bridges, buildings, tunnels, pipelines, railway infrastructure and technical structures; (b) technology of optic fiber probing is able to measure deformation, temperature, acceleration, misalignment/displacement, cracks and corrosion; (c) protective measures usage upon sensors installation; as well there has been developed economically effective optic fiber demodulation devices, which are advisable in further researches.

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