http://doi.org/10.35784/iapgos.2882 *received: 22.02.2022 | revised: 11.03.2022 | accepted: 28.03.2022 | available online: 31.03.2022*

TILTED FIBER BRAGG GRATING SENSORS FOR REFRACTIVE INDEX MEASUREMENTS OF LIQUID SOLUTIONS

Damian Harasim
Lublin University of Technology, Faculty of Electrical Engineering and Computer Science, Department of Electronics and Information Technology, Lublin, Poland

Abstract. *This publication presents the basic assumptions about the light guiding mechanisms in tilted fiber Bragg gratings, transmission spectra of the fiber with such structures and their sensor properties related to the occurrence of the so-called cladding modes. The light in the form of modes coupled to the optical fiber cladding causes their spectral properties to depend on the difference in the refractive index of the surrounding medium and the fiber cladding. With the introduction of a small inclination angle of the diffraction fringes forming the Bragg grating, the cladding modes show sensitivity to changes in the refractive index of the environment of aqueous solutions, which makes the spectrum of their applications broad. This publication presents changes in the spectra of selected modes measured for solutions with a specific refractive index, shift sensitivity, and changes in the mode transmission coefficient and processing characteristics at a selected concentration range of solutions. Experimental results show that high order cladding modes respond both by shifting the central wavelength as well as by changing the transmission minimum. In selected ranges, these parameters show a linear characteristic as a function of changes in the concentration of the cane sugar aqueous solution. In the case of TFBG with a tilt angle of 8°, the sensitivity of wavelength changes is 0.012 nm/RIU for solutions with concentrations ranging from 0% to 10% by weight.*

Keywords: fiber Bragg gratings, tilted fiber Bragg gratings, refractive index measurement, surrounding refractive index

ŚWIATŁOWODOWE SKOŚNE SIATKI BRAGGA JAKO CZUJNIKI W POMIARACH WSPÓŁCZYNNIKA ZAŁAMANIA CIECZY

Streszczenie. *Niniejsza publikacja prezentuje podstawowe założenia dotyczące mechanizmów prowadzenia światła w światłowodowych skośnych siatkach Bragga (ang. tilted fiber Bragg grating), widma transmisyjne światłowodu z wytworzonymi takimi strukturami oraz ich właściwości czujnikowe związane z występowaniem tzw. modów płaszczowych. Prowadzenie światła w postaci modów sprzęganych do płaszcza światłowodu sprawia, że ich właściwości spektralne zależne są od różnicy współczynników załamania ośrodka otaczającego oraz płaszcza włókna. Przy wprowadzeniu niewielkiego kąta pochylenia prążków dyfrakcyjnych tworzących siatkę Bragga, mody płaszczowe wykazują wrażliwość na zmiany współczynnika załamania otoczenia roztworów wodnych, przez co spektrum ich zastosowań jest szerokie. W niniejszej publikacji przedstawiono zmiany widm wybranych modów mierzonych dla roztworów o określonym współczynniku załamania, czułości przesunięcia oraz zmiany współczynnika transmisji modu oraz charakterystyki przetwarzania przy wybranym zakresie stężenia roztworów. Wyniki eksperymentalne wskazują, że mody płaszczowe wysokich rzędów reagują zarówno przesunięciem centralnej długości fali jak również zmianą minimum transmisji. Parametry te w wybranych zakresach wykazują charakterystykę liniową w funkcji zmian stężenia roztworu wodnego cukru trzcinowego. W przypadku TFBG o kącie pochylenia 8°, czułość zmian długości fali wynosi 0,012 nm/RIU dla roztworów o stężeniach od 0% do 10% stężenia wagowego.*

Słowa kluczowe: światłowodowe siatki Bragga, skośne siatki Bragga, pomiar współczynnika załamania, współczynnik załamania ośrodka

Introduction

Optical fiber technology was developed as an efficient way for transmission of large amount of data. On the other hand, optical fiber properties have become an object of interest for applications as physical quantities sensors [1, 4, 8]. Development of a novel areas in industry and a challenges of maintaining the quality of existing structures creates a new approaches for sensing applications. According to the advantages such as extremely small size, electromagnetic interference immunity and capability for the possibility of embedding them inside the measured structure, Fiber Bragg Gratings (FBGs) has emerged as a promising transducers for sensing applications [12–14]. In case of sensor systems based on FBGs important advantages are also the independence of measurement accuracy from fluctuations in the light source and the ability to build more complex measurement systems by placing many sensors on a single fiber optic fiber. The basic idea of this structures is to create a periodic zones of increased refractive index in single mode fiber core. This kind of structures found their application in temperature, strain etc. measurements. Consecutive fringes of grating perturbations cause a the ability to reflect light radiation of a strictly defined wavelength λ_B, while being transparent to light of other wavelengths. Bragg wavelength is defined by:

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

where n_{eff} is the effective refractive index of a fiber core and Λ is a grating period. By basing the measurement on determining the relative shift of the central wavelength, fluctuations in the optical power of the light source do not affect its accuracy. There are many methods of determining the Bragg wavelength, also allowing for its determination on the basis of spectra containing strong noise [9]. Linear conversion of the measured quantity to the shift of the characteristic wavelength called the central Bragg wavelength makes them natural converters of physical quantities.

Two basic technical parameters which determines optical properties of manufactured structures are apodization and chirp. An important parameter determining the usefulness of a given periodic structure is minimizing the side lobes. Apodization is one way to achieve this effect by changing the modulation depth of the refractive index changes in the fiber core along its axis. The multitude of special applications of fiber-optic periodic structures exact the implementation of apodization functions into the techniques of their production. The profile of apodization is commonly given by the power distribution of inscribing laser beam. Usually the profile is defined as Gaussian function [6]:

$$f(x) = a \cdot \exp\left(-\left(\frac{x-b}{c}\right)^2\right) \qquad (2)$$

The conventional gratings are created with a constant distance between following zones with internal refractive index perturbations. Another possibility for adjusting a spectral properties for particular application is creating a chirp by differentiation of distances between consecutive refractive index perturbations [3]. Most commonly used is linear chirp which allows to extend the width of reflected light spectrum by creating grating which operates as a series of short structures with increasing Bragg wavelength.

Another group of periodic structures are Tilted Fiber Bragg Gratings (TFBGs) which are manufactured by creating a tilt angle Θ_{TFBG} between refractive index fringes and fiber cross-section plane [7, 11]. Figure 1 shows schematically internal structure of tilted increased refractive index zones pattern and a coupling of backward propagating core mode and cladding modes guided by outer optical fiber layer.

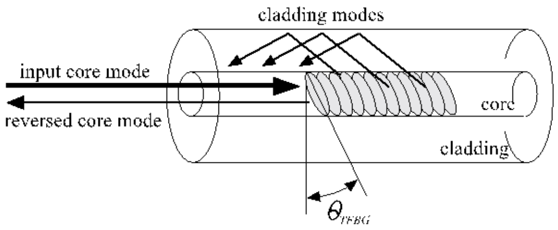

Fig. 1. Scheme of internal structure of TFBG grating and coupling mechanism of core-cladding resonances

1. Principles of TFBG operation and RI sensing

Fiber modification presented in Introduction cause a coupling of backward propagating modes in cladding of fiber. Occurrence of cladding modes reveals as series of dips in transmission spectrum in wavelengths shorter than Bragg wavelength. The resonant wavelengths of the cladding modes, corresponding to the backwards-propagating coupling between the core mode and the cladding modes, are given by:

$$\lambda_{clad\_i} = \left(n_{eff\_clad} + n_{eff}\right)\frac{\Lambda}{\cos(\Theta_{TFBG})} \tag{3}$$

where n_{eff} is the effective refractive index of a core, n_{eff_clad} is the effective refractive index of the i-th cladding mode, $i = 1\ldots m$ where m is the total number of cladding modes. Figure 2 shows schematically transmission spectra of a) conventional FBG and b) 2° tilt TFBG. Temperature sensitivity of this kind of structures equals about 10 pm/°C and is similar to traditional FBGs sensitivity. Measurement of bending and surrounding refractive index (SRI) requires more advanced method of transmission spectra analysis.

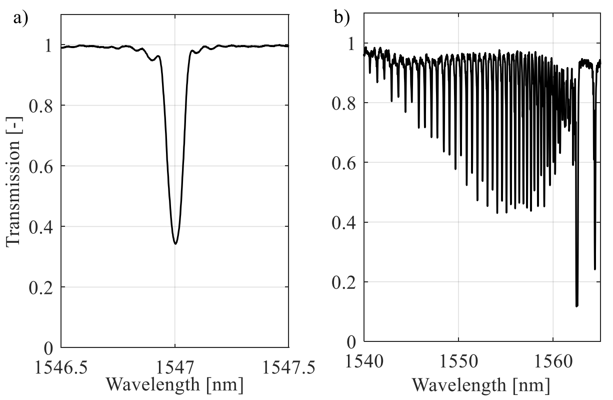

Fig. 2. Transmission spectra of: a) conventional FBG with Gaussian apodization, b) TBFG with 2° tilt angle and the same apodization profile

The propagation of light in the close proximity of the outer border of the optical fiber makes the spectral parameters of the minima observed in transmission dependent on the refractive index of the medium outside the optical fiber. Tilt angle has strong influence on grating possibilities and conditions the optical properties of the spectrum and ddetermines which modes will be visible in spectrum and their intensity. Transmission spectra of 2°, 4° and 6° tilt structures are presented on figure 3. Tilting of refractive index pattern and cross-section plane of fiber cause a widening of wavelength range of cladding-coupled modes. The dips with wavelengths closest to the Bragg resonance are called low-order modes and are guided in close proximity to fiber core. The cladding modes with shortest wavelengths are high-order modes. It is visible that increasing of non-parallelism between High order modes are stronger coupled when tilt angle is greater and are guided closer to the external surface of the optical fiber. This makes them sensitive to changes in the refractive index of the medium surrounding the optical fiber with TFBG written in the core [2, 10]. Together with increasing of surrounding refractive index value, particular cladding modes disappears – the coupling is weakening.

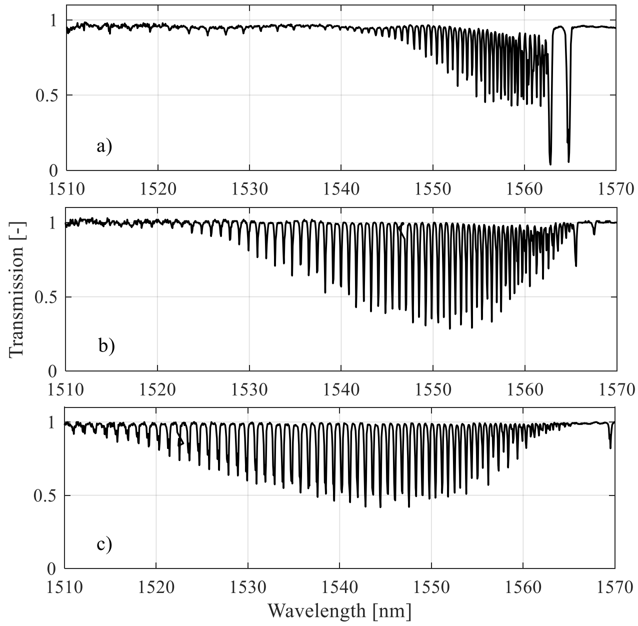

Fig. 3. Transmission spectra presented for three TFBG structures with a): 2° tilt, b) 4° tilt and c) 6° tilt

Spectrum is getting smoother, amplitude of dips related with individual modes is reduced, and then the peaks disappears. Increasing SRI reach the value of effective refractive index of specified cladding mode which results with extraction of this mode outside fiber structure. At further decreasing wavelengths there comes a point which the grating couples light to modes that are no longer guided by the cladding. These modes have resonance positions that do not shift in wavelength in response to SRI changes, but only in amplitude. Therefore, cut-off cladding mode could be use as indicator of surrounding refractive index changes. In most applications, refractive index of examined medium has value close to a water which is 1.3333.

2. TFBG transmission spectra under various refractive index of surrounding medium

The possible application with expected range of possible refractive index is determines the tilt angle of manufactured TFBG transducer. Solutions with RI close to the refractive index of fiber cladding requires week tilted structures which leads to coupling of small amount of low order modes. When examined solution has lower value of forseen RI, the tilt angle have to be greater to ensure coupling of higher order modes guided for shorter wavelengths. For the purposes of this article 10 solutions of glucose in water were prepared. Table 1 presents a refractive indexes of water solutions with 0% to 10% glucose concentrations.

Table 1. Refractive index of proposed glucose solutions with different concentrations

No	Concentration	RI
1	0%	1.3333
2	1%	1.3344
3	2%	1..3359
4	3%	1.3374
5	4%	1.3388
6	5%	1.3403
7	6%	1.3418
8	7%	1.3433
9	8%	1.3448
10	9%	1.3463
11	10%	1.3478

According to refractive indexes of prepared solutions, the chosen tilt angle of internal TFBG structure was 8°. The grating was inscribed on Ge-doped single mode photosensitive fiber by using excimer UV laser and phase mask technique. Transmission spectra were measured by using Optical Spectrum Analyzer (OSA). TFBG was illuminated by broadband light source which allows to observe a slight changes of fiber transducer optical properties. Figure 4. presents a scheme of equipped system for measuring transmission characteristics of 8° TFBG immersed in water solutions with differ refractive indexes according to table 1.

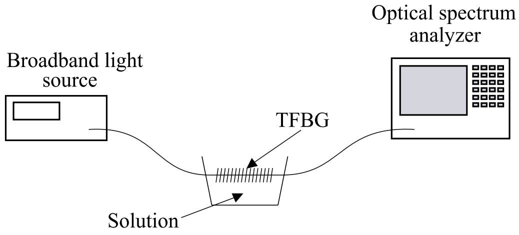

Fig. 4. Scheme of measurement system for characterization transmission spectra of TFBG immersed in solutions with different RI

Changes in transmission spectrum could be divided into two types: global and local. Global changes are related with the variations of shape of spectrum measured in wide range of wavelengths containing number of cladding modes. Analysis of many modes could give an improvement of accuracy or extension of possible refractive index range. However it is related with a need for measurement of spectrum which requires a specialized equipment – Optical Spectrum Analyzer (OSA). Methods which are based on analysis of selected cladding mode are so-called local methods. Surveys about the properties of cladding modes should be conducted with using OSA to obtain a detailed sensitivities of selected resonance. Properties and sensitivities of one selected cladding mode designated with OSA could be also used with measurement systems build by optical filters. In this kind of systems, expensive laboratory equipment could be replaced by passive optical filters (usually conventional FBGs) and photodiode with electrical voltage converter. On figure 5 are presented transmission spectra of four cladding modes in two ranges of wavelengths: a) 1536–1541 nm and b) 1546–1551 nm. As it could be seen, changes of surrounding medium refractive index induces different changes in spectral parameters of following cladding modes. Inset a presents modes with longer wavelengths which are presenting strong sensitivity of transmission coefficient to SRI. Cladding resonances presented on inset b) of Fig. 5. stands out with stability of optical power amplitude and shift of center wavelengths.

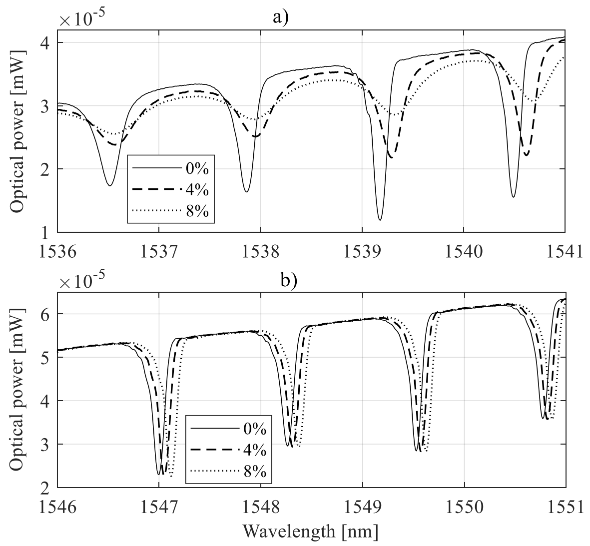

Fig. 5. Transmission spectra of 8° angle TFBG measured for grating immersed in 0%, 4% and 8% sugar solutions presented for two ranges of cladding modes: a) 1536–1541 nm and b) 1546–1551 nm

Figure 6. presents a detailed view of selected cladding modes of TFBG with 8° internal angle, which have greatest sensitivity of spectral parameters related to changes in sugar concentration (from 0 to 10%) in water solution. Figure 6 presents higher order mode which shows changes of transmission coefficient.

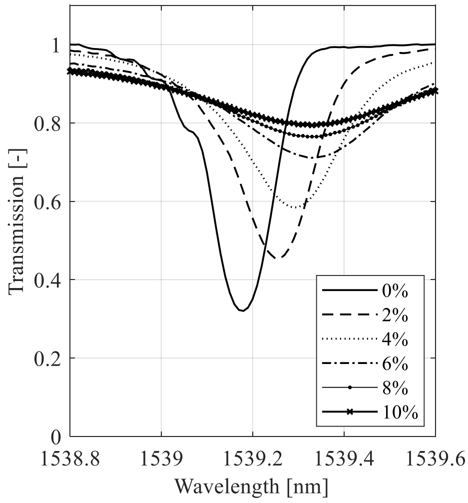

Fig. 6. Transmission spectra of selected cladding mode, when TFBG immersed in solutions with different refractive index

Transmission spectra presented on figure 6. were used to determinate a characteristic of shorter wavelength mode transmission to changes of cane sugar concentration in water solution, which is presented in figure 7.

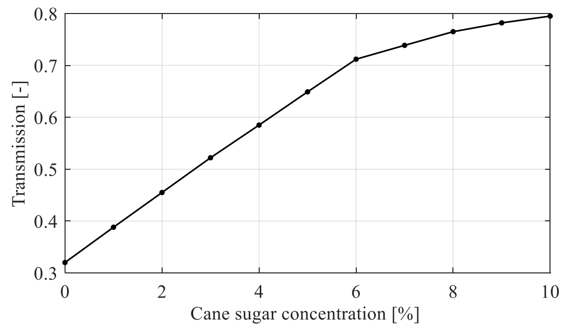

Fig. 7. Scheme of measurement system for characterization transmission spectra of TFBG immersed in solutions with different RI

As it is visible, changes of refractive index of surrounding medium have a quasi-linear influence on transmission. In 0–6% range, sensitivity is greater, and when the refractive index of surrounding medium is getting close to the effective index of selected cladding mode, transmission is changing weaker. It have to be noted, that the angle of internal tilt should be adjusted to assumed possible values of SRI according to different sensitivities of following resonances.

3. Surrounding refractive index measurements with designed system

As it was mentioned before, analysis of selected cladding mode spectral parameters allows to create measurement system which are not using optical spectrum analyzer. Results presented in this chapter are related with measurement setup which is using FBG as passive optical filer for determination of common part of selected cladding mode and filter spectrum. Configuration with optical bandpass filter most often requires use of optical circulator. High selectivity of signals between channels, provides ability for measurements of signal reflected from FBG filter. Central wavelength of filtering grating have to be adjusted to wavelength of TFBG cladding mode. Changes of transmission coefficient affects the shape of reflected light spectrum which is also detectable a change of the intensity. For measurement of spectral characteristics it is necessary to provide broadband source of input light. In presented measurements was used SLED Thorlabs S5FC1550P-A2 source. Figure 8. presents reflection spectrum of FBG filter measured for sensor head immersed in water solutions with different concentrations of cane sugar.

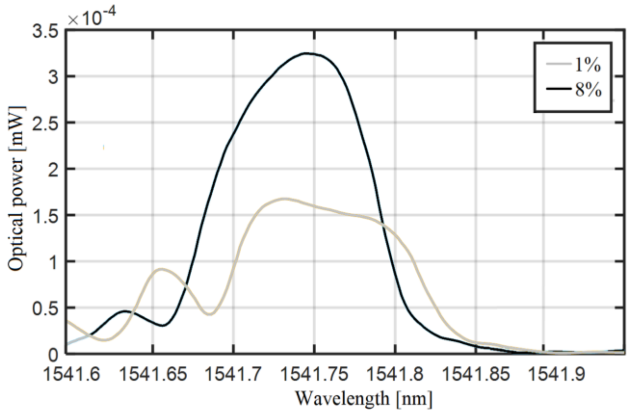

Fig. 8. Spectra of light reflected by FBG filter with TFBG sensor immersed in water solutions with different values of cane sugar concentrations

Analysis of spectra presented in figure 8 shows, that the area under a spectrum is getting bigger while a concentration of sugar is greater. This is related with changing of transmission of cladding mode of TFBG which has wavelength matched to filtering FBG. When sugar concentration is higher, transmission of cladding resonance sensitive to SRI is bigger so more of the light reflected from filter is transferred to analyzer. This property makes the measurement setup able, to use photodetector instead of OSA. When the area under the spectrum is greater, it means that the integral value will be greater could be detected as a intensity of radiation. Optical spectrum analyzer was replaced by Thorlabs- PDA30B-EC detector, which gives output signal as a value of direct voltage. Figure 9 presents a value of output voltage which was measured, for TFBG immersed in water solutions with increasing concentration of sugar.

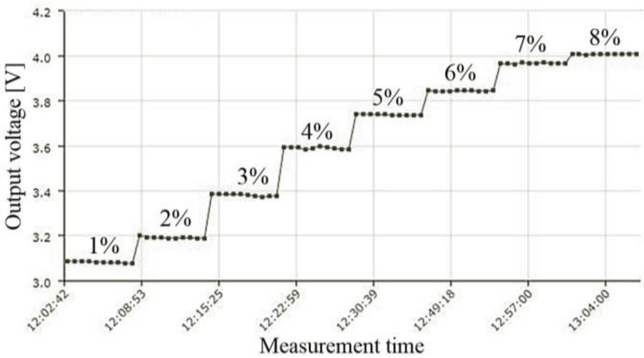

Fig. 9. Output voltage of measurement setup measured for different refractive index of surrounding medium

For each concentration, value of voltage was measured ten times at intervals of 10 seconds. It is visible, that voltage has constant value when SRI is not changing. Transformation of spectral changes into voltage value, makes results much easier to process than in case of spectral characteristics. It has to be noted that measurement results will be different with application of different optical components.

4. Conclusions

This paper presents an approach for using a TFBGs as a transducers of refractive index of medium surrounding optical fiber. Introducing a tilt angle between planes of grating fringes and fiber cross-section provides strong coupling of resonances guided by cladding. According to this property, spectral characteristics of cladding modes are related to refractive index of surrounding medium. Creating of measurement setup with FBG works as a reflective filter, allows to measure SRI in range related with few-percentage changes of cane sugar concentration in water solution. Application of photodetector for light intensity measurement allows to get output signal in form of votage, which is easy to process for example in microprocessor drivers. Exemplary results presented in this paper obtained for usage of TFBG with 8° tilt of internal structure, shows that changes of slight changes of concentration could be measured.

This work was supported by Project RPLU.01.02.00-06-0020/16

References

[1] Bakaic M., Hanna M., Hnatovsky C., Grobnic D., Mihailov S., Zeisler S., Hoehr C.: Fiber-Optic Bragg Gratings for Temperature and Pressure Measurements in Isotope Production Targets for Nuclear Medicine. Applied Sciences 10, 2020, 4610 [http://doi.org/10.3390/app10134610].

[2] Caucheteur C., Mégret P.: Demodulation technique for weakly tilted fiber Bragg grating refractometer. IEEE Photonics Technology Letters 17(12), 2005, 2703–2705 [http://doi.org/10.1109/LPT.2005.859411].

[3] Chettouh S., El-Akrmi A., Triki H., Hamaizi Y.: Spectral properties of nonlinearly chirped fiber Bragg gratings for optical communications. Optik 147, 2017, 163–169 [http://doi.org/10.1016/j.ijleo.2017.08.08].

[4] Erdogan T.: Fiber grating spectra. Journal of Lightwave Technology 15, 1997, 1277–1294 [http://doi.org/10.1109/50.618322].

[5] Fazzi L., Groves R. M.: Demodulation of a tilted fibre Bragg grating transmission signal using α-shape modified Delaunay triangulation. Measurement 166, 2020, 108197 [http://doi.org/10.1016/j.measurement.2020.108197].

[6] Gong J. M., Chan C. C., Jin W., MacAlpine J. M. K., Zhang M., Liao Y. B.: Enchancement of wavelength detection accuracy in fiber Bragg grating sensors by using spectrum correlation technique. Optics Communications 212, 2002, 29–33 [http://doi.org/10.1109/OFS.2002.1000525].

[7] Guo T., Liu F., Guan B., Albert J.: Tilted fiber grating mechanical and biochemical sensors. Optics & Laser Technology 78B, 2016, 19–33 [http://doi.org/10.1016/j.optlastec.2015.10.007].

[8] Guo T., Tam H. Y., Albert J.: Chirped and tilted fiber Bragg grating edge filter for in-fiber sensor interrogation. Optical Society of America Science and Innovations 2011 [http://doi.org/10.1364/CLEO_SI.2011.CThL3].

[9] Harasim D., Yussupova G.: mprovement of FBG peak wavelength demodulation using digital signal processing algorithms. Proc. SPIE 966212, 2015, 270–276 [http://doi.org/10.1117/12.2205547].

[10] Liu F., Guo T., Liu J., Zhu X., Liu Y., Guan B., Albert J.: High-sensitive and temperature-self-calibrated tilted fiber grating biological sensing probe. Chinese Sciences Bulletin 58, 2013, 2607–2611 [http://doi.org/10.1007/s11434-013-5724-3].

[11] Lu Y., Shen C., Chen D., Chu J., Wang Q., Dong X.: Highly sensitive twist sensor based on tilted fiber Bragg grating of polarization-dependent properties. Optical Fiber Technology 20(5), 2014, 491–494 [http://doi.org/10.1016/j.yofte.2014.05.011].

[12] Mohammed N. A., Ali T. A., Aly M. H.: Evaluation and performance enhancement for accurate FBG temperature sensor measurement with different apodization profiles in single and quasi-distributed DWDM systems. Optics and Lasers in Engineering 55, 2014, 22–34 [http://doi.org/10.1016/j.optlaseng.2013.10.013].

[13] Ren L., Jia Z., Li H., Song G.: Design and experimental study on FBG hoop-strain sensor in pipeline monitoring. Optical Fiber Technology 20, 2014, 15–23 [http://doi.org/10.1016/j.yofte.2013.11.004].

[14] Wydra M., Kisała P., Harasim D., Kacejko P.: Overhead Transmission Line Sag Estimation Using a Simple Optomechanical System with Chirped Fiber Bragg Gratings. Part 1: Preliminary Measurements. Sensors 18(1), 2018, 309 [http://doi.org/ 10.3390/s18010309].

M.Sc. Eng. Damian Harasim
e-mail: d.harasim@pollub.pl

Damian Harasim has received the MSc degree in mechatronics from Lublin University of Technology, Poland in 2014. He is currently working toward the Ph.D. degree in Automation, Electronics and Electrical Engineering at Faculty of Electrical Engineering and Computer Science in Lublin, Poland. From 2015 he is employed as assistant in Department of Electronics and Information Technology at Lublin Univ. of Technology. His current research interest lie in fabrication and characterization of optical sensing systems, especially based on unconventional Bragg structures.

http://orcid.org/0000-0002-9859-5879