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# The optical measurement method for structural twist monitoring with using tilted Bragg grating sensor

***Abstract**. This paper presents the proposal for application of optical fiber sensor based on tilted Bragg gratings (TFBGs) for monitoring of structural twist. Article also shows the fully optical method for sensor signal demodulation using single passive fiber structure as traditional fiber Bragg grating (FBG). In such system the power of light reflected from FBG carries the information about twist between selected sections of monitored structure. This allows to avoid the expensive and vulnerable equipment for demodulation of TFBG spectral properties.*

***Streszczenie.** Niniejszy artykuł przedstawia propozycję zastosowania czujnika światłowodowego opartego o skośną siatkę Bragga (ang. TFBG) do monitorowania kąta skrętu. Przedstawiona została także metoda demodulacji sygnału optycznego z takiego czujnika za pomocą pasywnego elementu filtrującego w postaci tradycyjnej prostej siatki Bragga. W takim układzie, moc światła odbitego od siatki filtrującej niesie informację o skręcie pomiędzy wyznaczonymi segmentami badanej struktury. Zastosowanie takiej metody pozwoli na wyeliminowanie konieczności użycia wartościowego i delikatnego sprzętu specjalistycznego do określenia charakterystyk spektralnych czujnika.* ***Zastosowanie czujnika światłowodowego opartego o skośną siatkę Bragga do monitorowania kąta skrętu***

**Keywords**: optical fiber technology, tilted fiber Bragg grating, optical sensing, fiber sensors.
**Słowa kluczowe**: technologia światłowodowa, skośna siatka Bragga, sensoryka światłowodowa, czujniki światłowodowe.

## Introduction

From the beginning of their development, fiber Bragg gratings (FBGs) have been considered as excellent optical fiber sensing elements, suitable for measuring strain, temperature and force [1-3]. Advantages over the traditional electronic sensors such as low cost, immunity to electromagnetic interference and high multiplexing capability are the reason why FBG sensors recorded a rapid development in recent years. Extremely small size and lightweight makes them suitable for being embedded or attached into measured structure [4,5]. Typically in sensing applications there are traditional Bragg structures which are described as a periodic pattern of refractive index perturbations inscribed in core of single mode optical fiber. There are some possible modifications in such structures as chirp or tapering of fiber to obtain the desirable characteristics of manufactured grating [6]. Another technological modification which could be performed while inscribing process is introducing a tilting angle between fiber cross-section plane and refractive index pattern fringe in fiber core [7]. This change have a strong influence on spectral characteristics of created structure, especially in transmission spectrum. The most visible effect is appearance of series dips in the spectrum which is connected with enhancing of coupling light from the core mode to a large number of counter propagating cladding modes[8,9]. Tilted Bragg gratings (TFBGs) are most commonly used in fiber refractometry where the phenomenon of spectral dips disappearance with changes of sensor surrounding refractive index.

Monitoring of structural health is an important request in many fields of engineering. One of the key parameters which are carrying information about the state of monitored structure is its twist. During the designing of optical fiber twist sensors, the most often used approach is to measure the change in circular birefringence induced by twist of polarization maintaining fiber, such as circular birefringence in Sagnac loops [10,11]. This kind of sensors usually suffer from temperature dependence and instability. Long period fiber grarings (LPFGs) have been also presented in twist sensing but their also present a cross sensitivities between different physical parameters such as pressure, temperature, strain. The sensors which are using interferometric measurements usually require a relatively complex and complicated interrogation of output signal.

The interesting property of TFBG structures is sensitivity of their selected spectral parameters to input light polarization state. The twist sensors with TFBG transducers were proposed in many configurations. The asymmetry of internal structure of fiber makes it sensitive to polarization state of input light. The tilt angle and loss coefficient of selected cladding modes which is mostly induced by the amplitude of refractive index modulation, are the most influencing technological parameters. The rotation measurement is generally based on analysis of loss in transmission spectrum of high-ordered cladding mode while changing of input light polarization plane angle [12]. The internal structure of TFBG inscription is well definite in the volume of fiber core. The angle of illuminating light polarization plane have to be define based on the arrangement of planes of refractive index fringes of sensor. Figure 1 shows the basic parameters of TFBG structure where $\Theta_{TFBG}$ is the tilt angle between plane of refractive index perturbation and cross-section plane (xy) of fiber and $\Theta_P$ is the angle of input light polarization plane and yz plane.

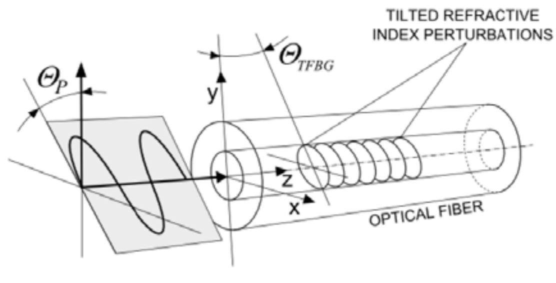


Fig.1. The scheme of TFBG internal structure and angle of input light polarization definition

In many cases of fiber sensing applications optical spectrum analyzers (OSAs) have been used for demodulation of fiber sensor output. In practical application where some environmental conditions could be unfavorable and the cost of this apparatus is too high, the other interrogation systems could be used. Generally interrogators could be divided to units with narrowband tunable source of light and units using broadband light source connected with fiber. Some of specified filtering systems are based on measurement of output signal and reference value which allows to compensate the light source power fluctuations and improve the resolution of measurement. A conventional fiber Bragg grating could be used as a filtering element in transmission or reflection configuration. This paper presents the practical application of FBG reflection filtering method for interrogation of TFBG based, polarization dependent torsion sensor. The characteristics of photonic elements are shown and described. The performance of proposed method have been demonstrated.

**Sensor fabrication and sensing principle**

The photonic structures were inscribed in photosensitive Ge-doped optical fiber with using KrF excimer laser and phase mask method. A tilt angle of 6° leads to obtain a large number of high order cladding resonances. Because of the existence of tilt angle, the core mode couples into a multitude of cladding modes where each has a different wavelength which is shown up as a series of loss peaks visible in transmission spectrum. The transmission of proposed TFBG sensor illuminated by broadband SLED source is shown in fig. 2.

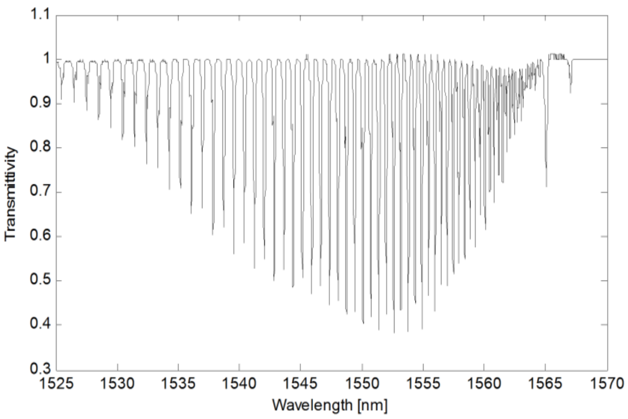


Fig.2. The transmission spectrum of 6° TFBG based twist sensor

The Bragg wavelength and the i-th order cladding mode resonance wavelengths of TFBG could be expressed as[13]:

(1) $$\lambda_B = \frac{2n_{eff}(core)\cdot\Lambda}{\cos(\theta)}$$

(2) $$\lambda^i_{clad} = \frac{(N_{eff}(core)+N^i_{eff}(clad))\cdot\Lambda}{\cos(\theta)}$$

where $N_{eff}(core)$ and $N^i_{eff}(clad)$ are the effective indices of the fiber core and cladding and $\Lambda$ is the period of refractive index perturbations in fiber core. The polarization state of input light is a very important parameter which influences on the spectral properties of TFBG sensing structures. The spectral response of selected high order cladding mode influenced by different input light polarization angles is shown in Fig. 3. The two peaks of transmission loss appear for boundary cases of polarization angle. It is connected with occurrence of even and odd resonances in cladding-guided light modes. It is shown, that changing of angle in 0 – 90° range causes the monotonic changes in amplitude of transmission power connected with selected cladding mode. That makes this method possible, to use it in measurements of physical quantities which could be transformed to rotation of polarization plane angle. The wavelength compartment marked as “window” contains one of split mode parts which could be used as a transducer of twist value transformed to change of polarization angle.

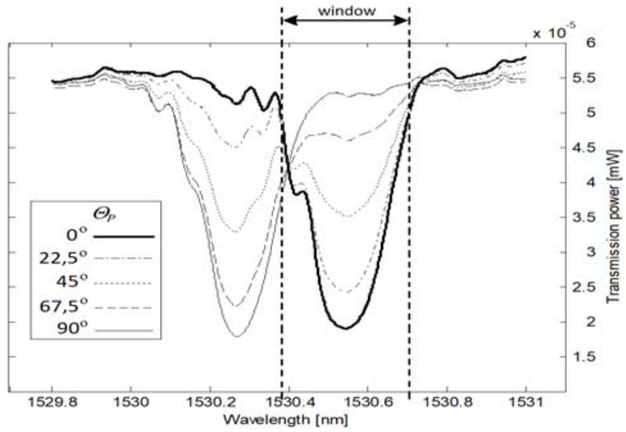


Fig. 3. The typical changes in transmission spectrum of TFBG high order cladding mode influenced by different input light polarization angles

In fact, from a practical sensing point of view the polarization dependency of such structures could be only useful when the input light polarization state could be precisely controlled. It could be obtained by e.g using of source of light with linearly polarized output and half-wave plate as an element used to control the angle of polarization plate. Another proposition is to apply the source of non-polarized light and the polarizer a plate or the fiber element to tune the state of light illuminating sensor. The polarization maintaining optical fibers are non-suitable for inscribing the Bragg gratings in its structure so they could be used only as a transmission media to maintain the specified state of guided light.

**Experimental setup and measurement results**

As it is mentioned in introduction, most commonly used apparatus for demodulation of TFBG sensors is the optical spectrum analyzer. Apart from the high cost of the device, this kind of interrogation needs an additional signal processing system for performing necessary calculations of measured spectra. The property of TFBG polarization dependency allows to apply the filtering devices as a demodulators of selected sensor parameters. The proposed measurement system for interrogation of TFBG sensor influenced by tuned input light polarization angle has been shown in fig. 4. The twist of polarization plane was introduced by electronically driven rotation table with half-wave plate mounted.

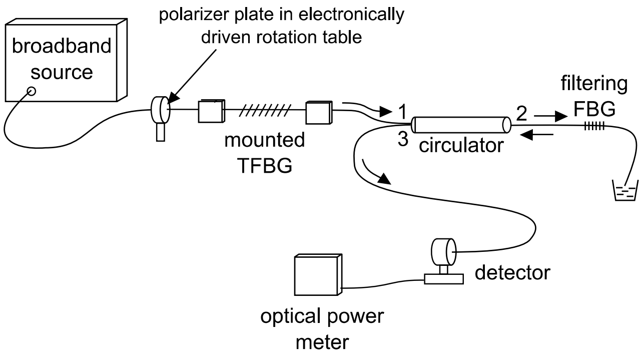


Fig.4. The scheme of proposed interrogation setup for demodulation of input light polarization plane angle

To be precise, the system which is shown in fig. 4 could be implemented for interrogation of selected cladding mode loss amplitude. The filtering FBG is matched in function of wavelength to selected high order cladding mode of TFBG sensor ($\lambda_{cl}$). Changes of input light polarization angle affect on loss coefficient of cladding modes. Transmission spectrum of TFBG illuminates the filtering device via the optical circulator. The spectral characteristics reflected from FBG changes as a function of loss of the selected cladding mode according to principle described in fig. 5. The upper plot shows the transmission spectrum of TBFG high order cladding mode and the lower graph shows the reflected spectrum of filtering Bragg grating. The characteristics are changing while the input light polarization angle is tuned for 0, 45 and 90°. The line which marks the matched wavelength shows the idea of fitting the peak wavelengths of sensing and filtering structures. The 0° input light polarization plane angle was established as parallel to yz plane of fiber scheme shown in fig. 1 (as a consequence 90° is parallel to zx plane).

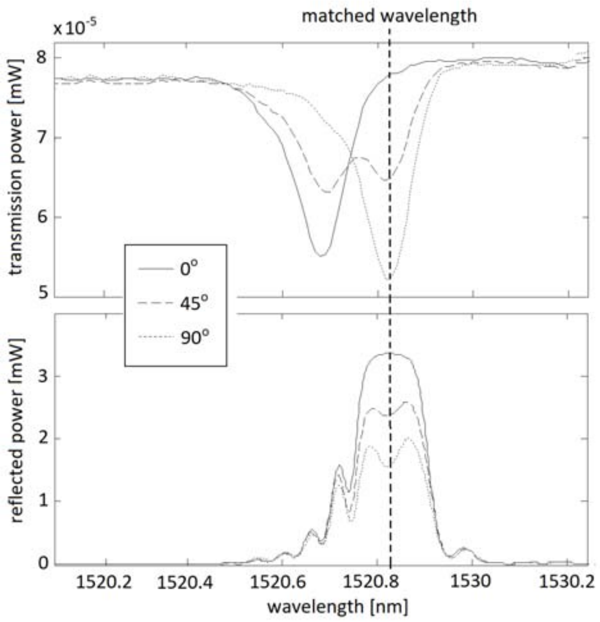


Fig.5. The illustration of measurement idea by showing transmission of cladding mode of TFBG sensor illuminated by light with 3 cases of polarization and reflection response of FBG filter

Optical power meter applied at the end of the interrogation system measures the optical power reflected from filtering FBG which is actually represented as the field under the spectral curve plotted in lower section of fig.5. It is shown that increase of selected TFBG cladding mode loss value causes decrease of peak power amplitude of filter FBG reflection. It is equivalent to decrease of power value measured with using optical power meter in proposed experimental setup. The changes of TFBG sensor transmission and the output reflection of filtering grating are shown in three characteristic input light polarization states: 0 and 90 degrees shows the boundary cases and 45 is the middle state which presents in general the changes of reflection spectrum.

Figure 6 shows the evolution of filtering FBG reflected spectrum response while changing of polarization angle of input light illuminating twist sensor in 0 – 90° range measured with 9° step in experimental setup described in fig.4. It could be seen that at the beginning and end of this range, the dynamics of response is weaker than in the middle of the measurement range. It is connected with spectral properties of TFBGs which high order cladding modes reacts with the similar way. It is also visible that changes of reflected power are substantial which promises that demodulation of input light polarization twist with proposed measurement system will be efficient.

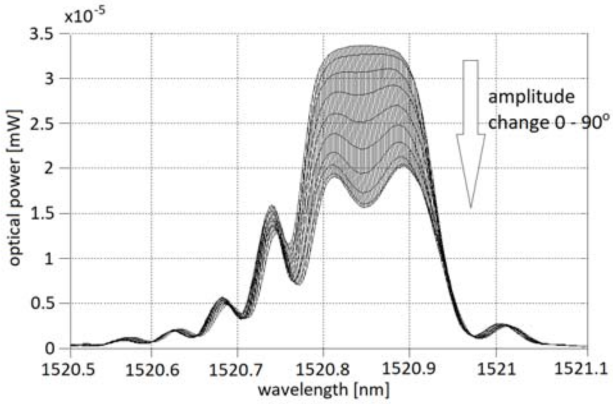


Fig.6. The changes of reflected spectrum of filtering FBG illuminated by transmission of TFBG illuminated with different polarization states of input light

The application of FBG with proper peak wavelength is crucial to obtain the interrogation method successful. The effectiveness of optical signal demodulation depends strongly on the reflectance of applied optical filter. However, the dynamics of proposed system response is highly dependent on the transmission loss of selected TFBG cladding mode. It is desirable to obtain high transmission loss for polarization state parallel to zx plane (fig.1) and minimal transmission loss for polarization parallel to yz plane. These parameters are influenced in manufacturing process by creating a periodic variations of refractive index in optical fiber core with proper amplitude. The result of higher reflective index is better dynamics and higher amplitude of output signal from whole interrogation system. In proposed solution, the filtering grating reflectance was 99% which maximizes the value of reflected optical power. The higher value of output optical signal also provides the better signal to noise ratio.

The source of input light is also the very important element of measurement system. The higher value of input optical power leads to obtain more distinct reflected signal which provides better dynamics and better signal to noise ratio. In experimental setup the SLED source with 1550 nm center wavelength. The continuous change of polarization angle was obtained with using half-wave plate mounted in precise rotator. Figure 7 shows the performance characteristic of reflected power changes in function of tunable polarization angle of input light.

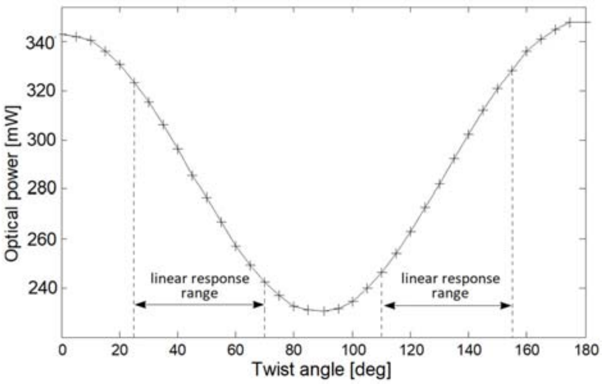


Fig.7. The characteristic of reflected power value changes while twisting of input light polarization angle which illuminates TFBG sensor

The figure 7 shows that in twist range between 25 and 65 degrees, the power response is quasi linear. Similar property of presented characteristic could be observed in 115 – 155 degrees of twist. It allows to apply this method with approximation to linear shape of processing characteristic in proper twist range. However, if the direction of twist is not known, the method requires to distinguish two independent measurement ranges.

The best fitting line obtained with using least square method is shown in fig. 8 as a dotted line. The fitting was applied in measured twist range specified based on measurement results shown in fig. 7.

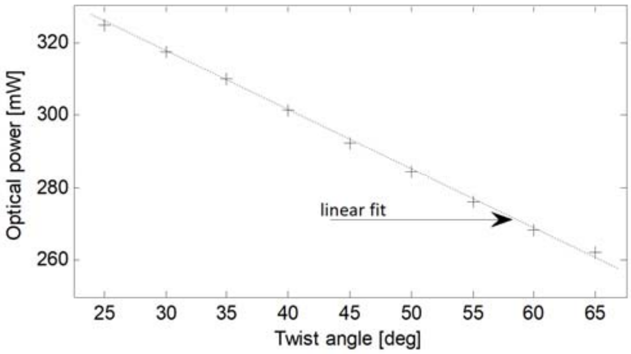


Fig.8. The results of reflected optical power value measured to different twist angles in linear range and best fitting line (dotted line)

The strong linear character of described reflected power dependence on TFBG sensor input light polarization twist is confirmed by $R^2$. In performed measurements with presented interrogation method, $R^2$ = 0,988 was calculated for 25 – 65 deg twist range. In fact, distinguished possible angle range could be transformed into 0 – 40 degrees by appropriate arrangement of optical elements which influences on polarization of light which illuminates sensor.

**Conclusions**

The possibility for using the tilted Bragg gratings for measurement of twist have been shown. The paper also shows the approach to substitute the Optical Spectrum Analyzer and complicated analysis of measured data by simple optical method based on passive elements. In proposed TFBG interrogation system, the traditional fiber Bragg grating is applied as a filter configured in reflection mode using optical circulator or fiber coupler. The peak wavelength of filter is matched with selected cladding mode of TFBG sensor which reacts on twist of input light polarization by changing of transmission loss. When transmission loss is increasing while changing of polarization angle, the optical power in matched wavelength is getting lower and therefore the power reflected from FBG filter is also decreasing. It is noteworthy that temperature sensitivities of sensing TFBG and filtering FBG are dependent on the optical fiber properties. When both sensor and filter are inscribed in the same kind of optical fiber, their spectral shift caused by temperature changes is the same. This condition makes this method temperature insensitive which increases the possible application range. Based on the polarization-dependent properties of TFBG applied as transducer, in proposed method could be distinguished two compartments of possible to measure angles: when optical power reflected from FBG filter increases with increase of rotation angle and when optical power value decreases for growth of angle. In proposed interrogation method, both of this measurement ranges are characterized by linear response of filter signal for changes of polarization angle.


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## REFERENCES


[1] Harasim D., Yussupova G., Improvement of FBG peak wavelength demodulation using digital signal processing algotithms, *Proc. SPIE 9662, Photonics Applications in Astronomy, Communications, Industry and High-Energy Physics Experiments 2015, 966212*

[2] Kahandawa G.C., Epaarachchi J., Wang H., Canning J., Lau K.T., Extraction and processing of real time strain of embedded FBG sensors using a fixed filter FBG circuit and artificial neural network, *IEEE Sensors Journal,* 8 (2008), nr 7, 1229-1235

[3] Hong C.Y., Zhang Y.F., Zhang M.X., Ming L., Leung G., Liu L.Q., Application of FBG sensors for geotechnical health monitoring, a rewiev of sensor design, implementation methods and packaging techniques, *Sensors and Actuators A: Physical,* 244 (2016), 184-197

[4] Xiangyi G., Mingshun J., Linlin G., Qinglin W., Yuxi J., Qingmei S., Lei J., Dongsheng L., Sensing characteristics of FBG sensor embedded in CFRP laminate, *Measurement,* 98 (2017), 199-204

[5] Harasim D., Kashaganova G., Kussambayeva N., Accuracy improvement of fiber bragg grating peak wavelength demodulation using wavelet transform and various center wavelength detection algorithms, *Przegląd Elektrotechniczny,* 92 (2016), nr 6, 86-89

[6] Kisala P., Generation of a zone chirp in uniform Bragg grating as a way of obtaining double functionality of a sensor, *Metrology and Measurement Systems,* 19 (2012), nr 4, 727-738

[7] Albert J., Shao L.Y., Caucheteur C., Tilted fiber Bragg grating sensors, *Laser & Photonics Reviews,* 7 (2012), nr. 1, 83-108

[8] Harasim D., The influence of fibre bending on polarization-dependent twist sensor based on tilted Bragg grating, *Metrology and Measurement Systems,* 24 (2017), nr 3, 577-584

[9] Kisała P., Harasim D., Mroczka J., Temperature-insensitive simultaneous rotation and displacement (bending) sensor based on tilted fiber Bragg grating, *Optics Express,* 24 (2016), nr 26, 29922-29929

[10] Zu P., Chan C.C., Jin Y.X., Gong T.X., Zhang Y.F., Chen L.H., Dong X.Y., A temperature insensitive twist sensor by using low-birefringence photonic-crystal-fiber-based Sagnac interferometer, *IEEE Photonics Technology Letters,* 23 (2011), 920-922

[11] [Silva R. M., Ferreira M., S., Frazao, O., Temperature independent torsion sensor using a high-birefringent Sagnac loop interferometer, *Optics Communications,* 285 (2012), 1167-1170

[13] Chen X., Zhou K. M., Zhang L., Bennion I., In-fiber twist sensor based on a fiber Bragg grating with 81 tilted structure, *IEEE Photonics Technology Letters.,* 18 (2006), 2596-2598.

[14] 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 (2014), nr 5, 491-494