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ROTATION AND TWIST MEASUREMENT USING TILTED FIBRE BRAGG GRATINGS

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Abstract

The paper presents a method of measuring the angle of rotation and twist using a *tilted fibre Bragg grating* (TFBG) periodic structure with a tilt angle of 6°, written into a single-mode optical fibre. It has been shown that the rotation of the sensor by 180° causes a change in the transmission coefficient from 0.5 to 0.84 at a wavelength of 1541.2 nm. As a result of measurements it was determined that the highest sensitivity can be obtained for angles from 30° to 70° in relation to the basic orientation. The change in the transmission spectrum occurs for cladding modes that change their intensity with the change in the polarization of light propagating through the grating. The same structure can also be used to measure the twist angle. The possibility of obtaining a TFBG twist by 200° over a length of 10 mm has been proved. This makes it possible to monitor both the angle of rotation and the twist of an optical fibre with the fabricated TFBG.

Keywords: photonic sensors, fibre Bragg gratings, twist measurements, rotation measurements.

1. Introduction

Rotation and twist measurements are important when monitoring various engineering structures and constructions [1]. Fibre-optic methods for measuring these quantities have several important advantages, such as resistance to the impact of environmental conditions, relatively easy placing sensors on measured structures and the ability to perform simultaneous measurements in many places. There are many optical methods of rotation and twist measurement [2]. Among the sensors that use fibre optics there can be mentioned: Sagnac loop and micro-fibre coupler [3], Sagnac interferometer and PM-elliptical core fibres [4], single-mode fibre coupler [5], *long period fibre grating* (LPFG) [6], *fibre Bragg gratings* (FBG) [7] and *polarization maintaining fibre Bragg gratings* (PM-FBG) [8]. Recently, *tilted fibre Bragg gratings* (TFBG) [9–11] have been very popular in applications to measurement of rotation and other quantities. These gratings use the property of the polarization effect of the introduced light – understood as the *state of polarization* (SOP) – on the cladding mode spectrum. This is due to the fact that the TFBG structure brakes the cylindrical symmetry of optical fibre [12]. TFBG grating have all the advantages of classic FBG technologies such as ease of manufacture and small size. An additional advantage of the tilted FBG is the large number of cladding modes visible in a relatively narrow spectral

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range. TFBG structures can also be easily interrogated using the classic FBG [13] or low-cost power-detecting laser interrogation methods [14].

The spectrum of cladding modes of the TFBG grating changes under the influence of many quantities. These quantities can be: refractive index [15], bending [16], liquid level [17–19], temperature and strain [20]. The state of polarization can have a negative effect on the measurement of these quantities if it is uncontrolled or it can be used to increase the sensitivity of measurements of some quantities [21–23]. For measurements of such quantities as refractive index or liquid level, the polarization sensitivity may have a negative effect. Hence the need to maintain the state of polarization and its control [24]. TFBG can also be coated with additional layers of materials, which induces *surface plasmon resonance* (SPR). This effect additionally modifies the spectrum of these structures, enabling to achieve slightly different properties of the sensor [25]. Unfortunately, such gratings may additionally require immersion in a liquid, which considerably complicates possible practical applications [25].

In the TFBG grating, the division of the cladding modes into two separate spectral peaks for two polarizations results in obtaining asymmetrical LP1m modes. Mode splitting is the effect of the tilting plane on changes in the refractive index in the core of optical fibre. Polarized light introduced to the optical fibre depending on its orientation in relation to the tilt plane (parallel or perpendicular) causes changes in amplitudes of split modes in the form of a so-called dual-peak transmission. This property can be used to measure rotation, twist and bending. The two resulting orthogonal states of polarization are defined as P and S, of which the P-polarized state is parallel to the tilt plane and the S-polarized state is perpendicular to the tilt plane [26, 27]. The difference between the resonance wavelengths S and P is greater for the higher order modes. At the same time, the difference is greater for grating with a larger tilt angle [28]. Increasing the distance between neighbouring symmetric LP0m and asymmetric LP1m modes is possible by reducing the diameter of the optical fibre core on which the TFBG structure is written [29]. Multimode fibre tilted Bragg gratings have larger core diameters, which results in completely different spectral changes due to changes in polarization [30]. A thorough analysis of the polarization properties of the cladding modes is presented in [31].

This paper presents the properties of TFBG grating for measuring rotation and twist. For both quantities, the same mechanism of changing amplitudes of split asymmetric modes is used. With the exception, however, that for rotation measurements the change in the modes' amplitudes is the same over the entire length of the grating. For the twist measurement, this change depends on the location along the length of the grating. It has been shown that it is possible to monitor the rotation of the structure and its twisting even in a range of 200° along its length. Spectral characteristics and processing characteristics were compared for two cases: rotation and twist in two directions from the initial state.

2. Theoretical analysis of modes' coupling in optical waveguides with TFBG using coupled mode theory

In TFBG, energy is coupled between many modes along the entire length of its structure. The energy of light propagating by the core mode is coupled to many cladding modes. If the modulation of the refractive index is written at an angle to the z axis of the fibre, then in addition to the coupling of the core mode propagating in the positive direction, the core mode propagating in the negative direction is enhanced by power couplings to the cladding modes. These power couplings of the input signal to individual cladding modes occur for different wavelengths. This is manifested by losses for specific wavelengths in the transmission spectrum of

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such a structure (Figs. 1 and 3). The Bragg wavelength is expressed by the following equation [26]:

$$\lambda_B = \frac{2N_{eff}^{co}}{\cos\theta}\Lambda, \tag{1}$$

where N_{eff}^{co} is the effective refractive index for the core; Λ is the structure period; θ is the TFBG tilt angle (Fig. 2). In addition to the Bragg's main resonance, there are also a number of peaks resulted from coupling to cladding modes. These minima appear for the wavelengths described by the general equation of the form:

$$\lambda_k^{cl} = \frac{N_{eff}^{co} + N_{eff_k}^{cl}}{\cos\theta}\Lambda, \tag{2}$$

where $N_{eff_i}^{cl}$ means the effective index of the cladding.

The system of conjugated differential equations describing light propagation in the TFBG structure is shown by (3) and (4) [27]:

$$\frac{\partial A^{co}(z)}{\partial z} = \sum_{k=1}^{N}\left[i\left(C_k/2\beta^{co}\right)e^{-i\delta_k z}A_k^{cl}(z)\right], \tag{3}$$

$$\frac{\partial A_k^{cl}(z)}{\partial z} = -i\left(C_k/2\beta_k^{cl}\right)e^{+i\delta_k z}A^{co}(z), \tag{4}$$

where z is the axis along which the TFBG is written; A^{co} is the amplitude of the core mode; $A_k^{cl}(z)$ is the amplitude of the k-th cladding mode; C_k is the coupling constant of the core mode to the k-th cladding mode; N means the number of conjugate modes; β^{co} and β_k^{cl} denote the propagation constants of the core mode and the k-th cladding mode, whereas δ_k is called the detuning parameter. Since values C_k, β_k^{cl} and δ_k are functions of a wavelength λ, (3) and (4) should be solved for specific wavelengths. The calculated TFBG spectrum for a 6-degree θ angle grid is shown in Fig. 1.

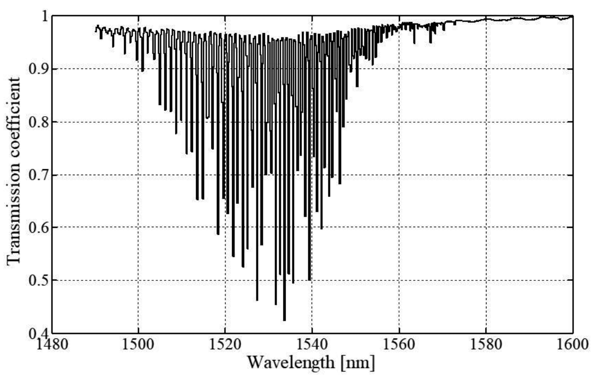

Fig. 1. The theoretical spectrum of a 6-degree TFBG.

As can be seen, the spectrum is characterised by a series of minima from cladding modes, which in this case occupy a total band of around 80 nm. The next part of the paper presents the results of rotation and twist measurements using a TFBG produced in the laboratory.

3. Idea of measuring rotation and twist using single fibre with TFBG structure

This paper presents the use of a single optical fibre with a written tilted periodic structure for measuring the optical fibre rotation angle and twist. The second section of the work demonstrates the possibility of propagating many cladding modes in such a structure. In order to perform and analyse the measurements of rotation and twist, a periodic structure has been created in which the plane of refractive index modulation is recorded at a certain angle θ in relation to the normal to the optical fibre axis, indicated in Fig. 2 as z.

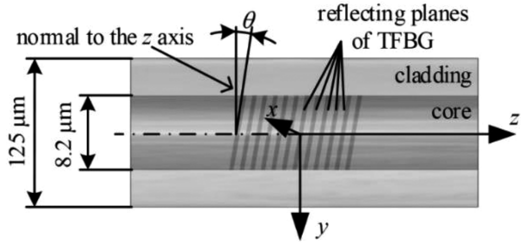

Fig. 2. Determination of characteristic parameters, axes and dimensions of the created periodic structure with inclined reflecting planes in the fibre core.

The structure was constructed by an excimer laser using the phase mask method, providing light propagation in such a way that the grating planes were placed at an angle $\theta = 6°$ in relation to the normal axis of the fibre. A single-mode optical fibre SMF-28 had been previously subjected to a photosensitization process in a hydrogen atmosphere of 190 bar pressure and temperature of 20°C for a period of 10 days. The grating after saving had a total length of 10 mm. The structure thus produced was then subjected to spectral testing. Fig. 3 shows the transmission spectrum of the created structure. As can be seen, it has a series of resonances for wavelengths shorter than the Bragg wavelength.

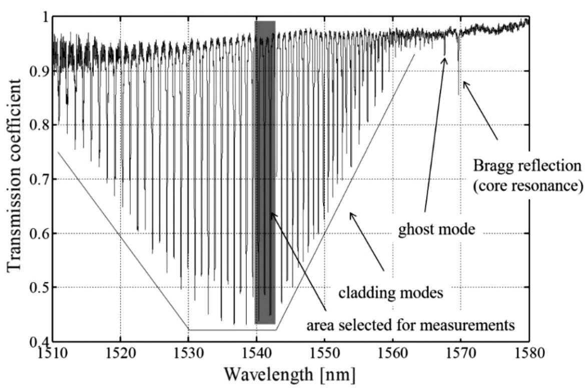

Fig. 3. The transmission spectrum of the created tilted structure. The main core resonance and a number of resonances for cladding modes have been marked. The grey rectangle indicates the wavelength range selected for analysis.

We know that an optical fibre with TFBG reacts to changes in the polarization angle of light introduced to such a fibre [26, 2]. In this work, differences in the spectral responses of such a system to changes in the angle of rotation and twist have been demonstrated. Turning and rotation are understood as changes in the parameter values of position and geometry of the fibre optic with the TFBG structure stored inside this fibre. The idea of setting and measuring the rotation and twist of such a system is shown in Fig. 4.

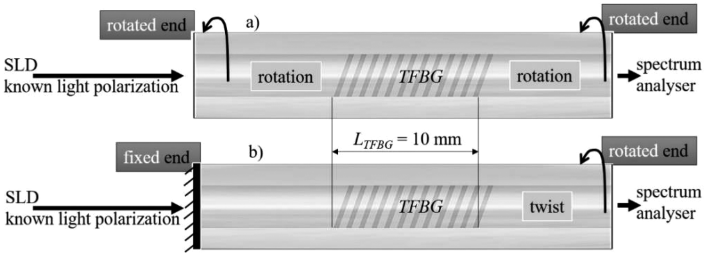

Fig. 4. A method of setting and measuring rotation (a); twist (b): an optical fibre in which the TFBG structure has been recorded.

According to Fig. 4, during the measurements the optical fibre was subjected to both rotation (case a) and twist (case b). In the case of rotation, both ends of the fibre with the saved TFBG element were rotated by the same angle, which caused the whole fibre to rotate. The length of the TFBG element was $L_{TFBG} = 10$ mm, while the fibre length from rotated ends to TFBG was 15 mm. In the case of fibre optic twist (case b), the 10 mm TFBG element was placed directly at the fixed end. The TFBG distance from the rotated end was 30 mm. An SMF-28 fibre with a core mode field diameter of 10.4 μm (@ 1550 nm), core diameter 8.2 μm, clad diameter 125 μm and coating diameter 242 μm was used. A length of SMF-28 was 1 m. In both cases light with known linear polarization was introduced into the fibre. An SLD light source with a maximum power of 2.5 mW, central wavelength 1550 nm and optical bandwidth 90 nm was used. The measurement was carried out for a 200 mA source current and at temperature of 20°C. The polarization of light was determined/controlled by using additional optical elements.

In the first case (Fig. 4a) both ends of the fibre were rotated using a high-precision bare fibre rotor Thorlabs HFR007 by the same angle with an accuracy of two degrees. The rotation of the fibre caused changes in the energy distribution between the individual cladding modes in the TFBG structure. Changes in this distribution were observed using a Yokogawa AQ6370D optical spectrum analyser. The analyser had a monochromator slot (spectral resolution) set to 0.02 nm. The optical spectrum was measured in a range from 1490 to 1600 nm with a sampling resolution 0.004 nm.

In the second case (Fig. 4b) the measurements looked similar except that only one end of the optical fibre was rotated, which resulted in twisting of the optical fibre.

4. Spectral characteristics of rotated and twisted TFBG structure

This section presents the results of spectral measurements of fabricated structures subjected to rotation and twist in accordance with the procedure outlined in the previous section. The idea of the measurement system is presented in Fig. 5. The light from the super-luminescent diode was directed through the lens (OB1) to the polarizer (P) and the half-wave plate ($\lambda/2$). Then, through the lens (OB2), the light was directed to the single-mode optical fibre with TFBG inscribed in the core. The coupling of light between fibres and lenses was carried out using Thorlabs manipulators

(x, y, z). To pass all the incident light by controlling only the state of its polarization, the half-wave plate ($\lambda/2$) was used. Both points (reference points 1 and 2) were used to cause and control the rotation and twist of the fibre with the TFBG sensor. The signal was measured after passing through the entire system using the *Optical Spectrum Analyser* (OSA).

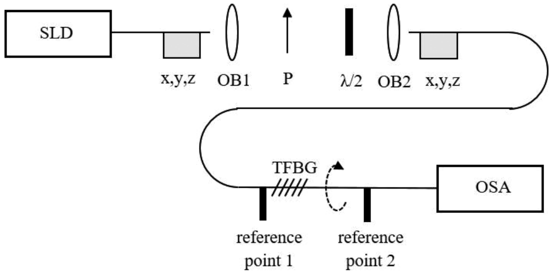

Fig. 5. The idea of the measurement system.

In all measurements, the TFBG grating with an angle of $\theta = 6°$ was used, the measurements were carried out at a stabilized ambient temperature of 20°C and at a constant temperature and SLD current of 200.8 mA. For the sake of clarity, the remainder of the section is divided into two parts, one concerning the results of rotation measurements, the other concerning the twist.

4.1. Rotation

Figure 6 shows the results of spectral fibre measurements with TFBG rotated from 0 to 90 degrees. The direction of rotation was in line with the mark in the drawing and in the study is referred to as a so-called positive rotation (+).

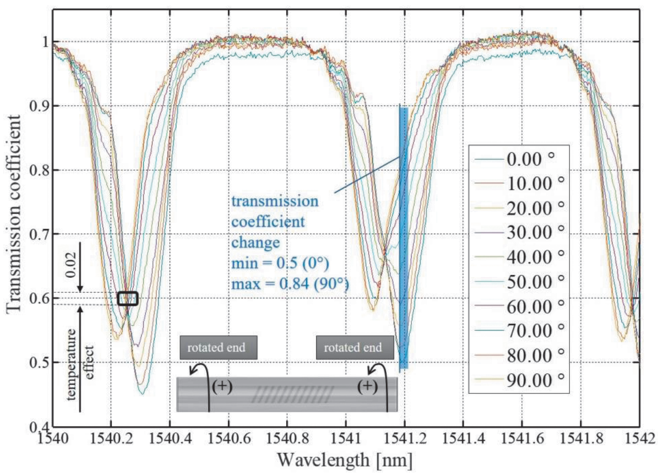

Fig. 6. The transmission characteristic of the produced TFBG structure for different rotation (+) angles.

As can be seen, rotation of the fibre optic with TFBG changes the degree of stimulation of S and P modes propagating in the structure. This is due to the change in the power coupling ratio between individual modes. This effect can be used to determine the angle of rotation, *e.g.* by measuring power values for a given wavelength. For this purpose, a wavelength of 1541.2 nm was chosen in the study, for which there is a significant change in power due to the rotation of the fibre. This wavelength can be used for indirect measurements of the angle of rotation. According to Fig. 6, for the initial position, the transmission coefficient value is 0.5, the structure's rotation by 90° causes an increase in the transmission coefficient value for the selected wavelength to 0.84.

The obtained spectral characteristics have an area in which the power value does not change (or changes slightly) due to rotation. This area is marked with a black rectangle. Individual modes exchange energy, but the power value for wavelengths of *e.g.* 1540.25 nm and 1541.13 nm (Fig. 6) undergoes a very small change. Any change in the power values for these wavelengths is due to a change in temperature. If the temperature changed during the measurement, then the entire spectrum would be shifted, which would result in a change in power for these specific wavelengths. In this study the phenomenon is called the temperature effect and it will be the subject of research described in subsequent studies.

Analysing Fig. 7, it can be seen that the rotation of the fibre in the negative direction (−) in a range from 0° to 90° results in an analogous effect in relation to the rotation in the positive direction (+). The maximum value of the transmission coefficient of the structure reached 0.84, which occurs at an angle of rotation equal to 90°. For an angle equal to 0°, the value of the transmission coefficient for the selected wavelength (1541.2 nm) was 0.5. The nature of changes is identical, both rotations (−) and (+) cause analogous changes in the spectral characteristics of the structure. By measuring the optical power value for the selected wavelength – in our case it is 1541.2 nm – we can determine the angle of rotation of the optical fibre with the TFBG structure recorded in it.

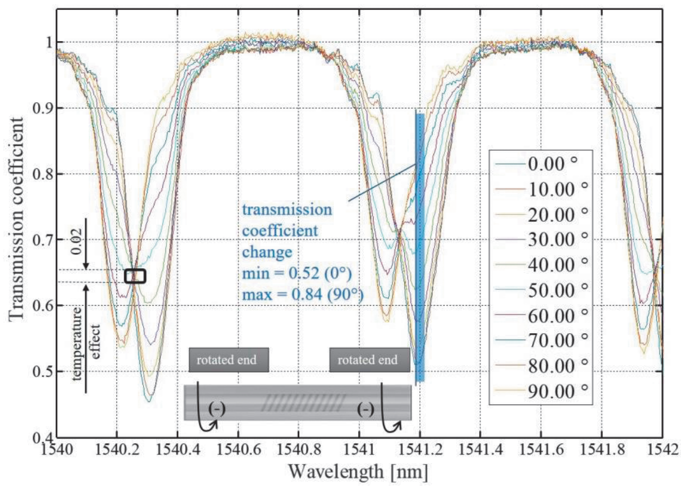

Fig. 7. The transmission characteristic of the produced TFBG structure for different rotation (−) angles.

4.2. Twist

In this section we present the results of spectral measurements of the produced TFBG structure subjected to twisting in accordance with Fig. 4b. The spectra were examined when twisting the structure towards (−) and (+). The twist angle given is an angle by which the TFBG structure has been twisted along its length. The measurements were also made at the initial excitation of different structure modes, both corresponding to the S and P polarity [26, 27].

Figure 8 shows the transmission spectra for four cases. First, the right TFBG mode was activated by appropriately setting the polarization of the input light, and the entire structure was subjected to a positive (+) twist (Fig. 8a). The right TFBG mode was then stimulated and the negative (−) structure was induced at the same time (Fig. 8b). In the subsequent experiments, the left TFBG mode was stimulated and the structure was simultaneously twisted in the positive (+) direction (Fig. 8c). Finally, the left TFBG mode was stimulated and at the same time a positive (−) structure was generated (Fig. 8d). As in the case of rotation – the wavelength for which the transmission coefficient value was determined was also selected in this part of measurements. Due to the positions of peaks coming from cladding modes in the case of rotation, the wavelength for which the transmission coefficient value was determined was 1541.4 nm (Fig. 8 – the area marked with a vertical grey line).

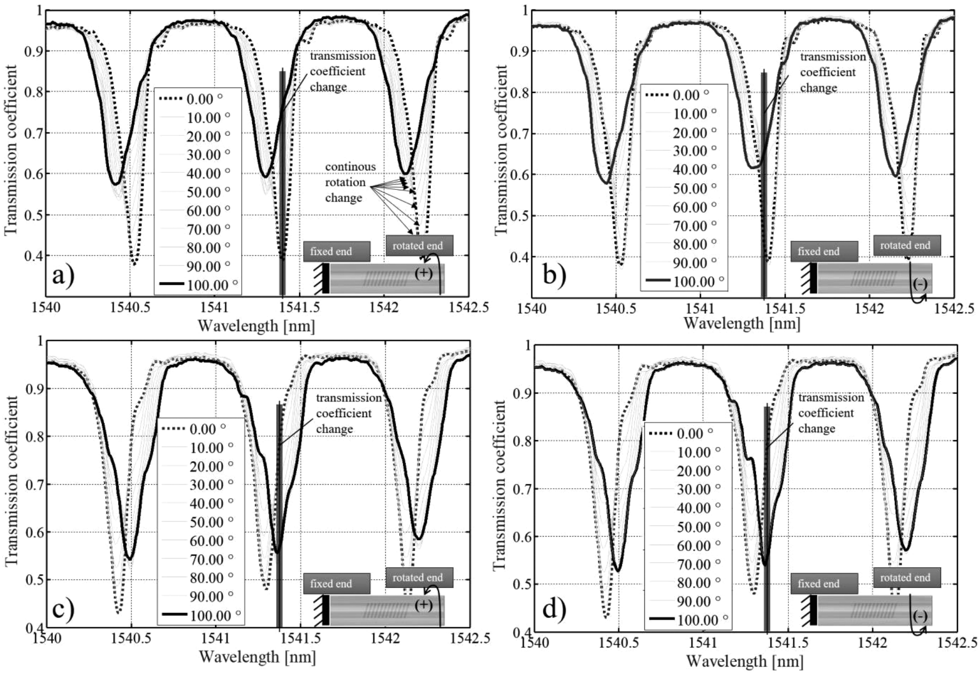

Fig. 8. The transmission characteristics of the produced TFBG structure for different twist angles: twist (+) right polarization mode stimulated (a); twist (−) right polarization mode stimulated (b); twist (+) left polarization mode stimulated (c); twist (−) left polarization mode stimulated (d).

As can be seen, twisting of the TFBG structure also causes an energy exchange between the left and right modes. This can be seen in the form of changing the intensity of resonances of individual modes. Decreasing the amplitude of the left mode increases the amplitude of the right mode and vice versa. The measure of the twist can therefore be both the shift of the minimum of the selected mode, as well as, for example, the value of the transmission coefficient for the selected wavelength as assumed in this work. In addition, it is characteristic that the *Full Width at Half Maximum* (FWHM) of all minima from cladding modes also changes. The FWHM change can also be a measure of the structure's twist. Analysing the characteristics of 8a–8b, it can be seen that FWHM increases up to two times, *i.e.* from 0.1 nm to 0.2 nm.

5. Processing characteristics of proposed rotation and twist sensor

In this section we present selected processing characteristics of the produced periodic structure described in the previous sections. Fig. 9 shows the results of measurements of the transmission coefficient of the structure for the selected wavelength (1541.2 nm). On one graph, the measurement results for the (+) and (−) turnover are summarized. As can be seen, the transmission coefficient reaches its minimum value for the non-rotated structure (a rotation angle equal to 0). Rotation to the right is marked in bold.

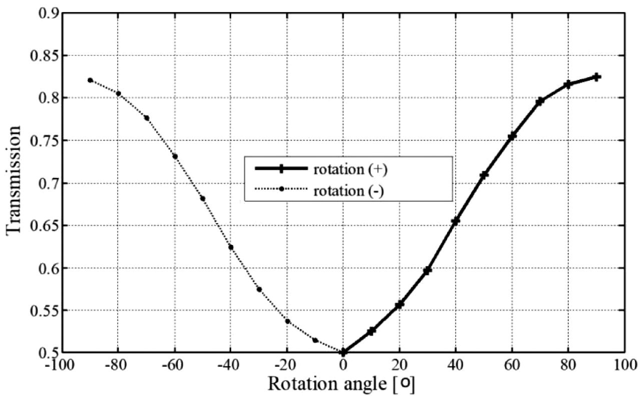

Fig. 9. The processing characteristics of the produced TFBG structure for different rotation angles: the solid line represents rotation in the positive direction (+), the dotted line represents rotation in the negative (−) direction.

As can be seen, rotation of the sensor causes an increase of TFBG transmission. The highest sensitivity was obtained in the central part of the processing characteristics, for angles from 30° to 70°. The nature of changes in the transmission coefficient is the same for the (+) and (−) rotations, as shown by the symmetry of the characteristic (Fig. 9). For comparison, analogous curves were plotted in the case of sensor twisting, as shown in Fig. 10. Rotation to the right is indicated by the bold lines.

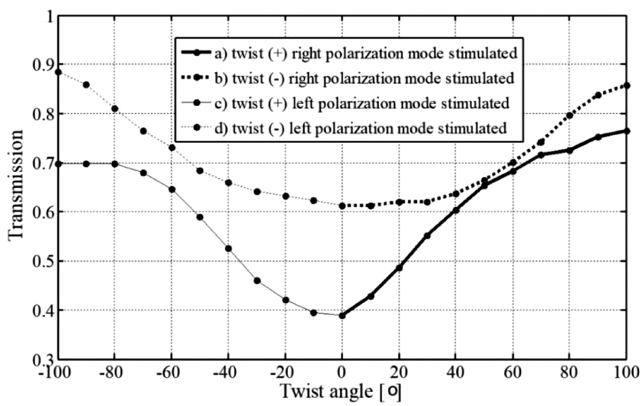

Fig. 10. The processing characteristics of the produced TFBG structure for different twist angles: the solid line represents twist in the positive direction (+), the dotted lines represent twist in the negative (−) direction.

It can be seen that twisting of the TFBG structure affects the value of the transmission coefficient for a selected wavelength. Twisting of the sensor causes – as in the case of rotation – a change in the transmission coefficient value. In Fig. 10 the bold line shows the results when the right polarization mode is activated. The thin lines show the situation when the left polarization mode is activated. In addition, the dashed lines mean twist ($-$), while the continuous lines – twist ($+$). The twist's limiting values were from $+100$ to -100 degrees. The symmetry of the twisted structure shows that a monotonic increase in the transmission coefficient should occur in an angle range from $+90$ to -90 degrees. A wider range of angle changes obtained during the measurements probably results from the apodisation profile of the created structure. As can be seen, the characteristics do not maintain as much symmetry as in the case of rotation (Fig. 9). This is due to the fact that the right part of graph (angles from 0 to 100°) was determined for the wavelength corresponding to the stimulation of another (in this case right) polarization mode than in the case of the left part of graph (angles from 0 to -100°). The structure reacts to twisting in a range from $+100^\circ$ to -100° by changing the transmission coefficient value for a selected wavelength.

6. Conclusions

In this paper we show the possibility of measuring the degree of both rotation and twist of an optical fibre with the TFBG structure recorded therein with a tilt angle of 6°. It has been shown that rotation of the sensor by 180° causes a change in the transmission coefficient value from 0.5 to 0.84 at a wavelength of 1541.2 nm. It has been proved that the highest sensitivity can be obtained in the central part of the processing characteristics, for angles from 30° to 70°. It has been demonstrated that the same structure can also be used to measure the twist angle. TFBG reacts to twisting by 200° along a length of 10 mm (from -100° to $+100^\circ$) by changing the transmission coefficient value in a range from 0.39 to 0.89 at a wavelength of 1541.4 nm. This makes it possible to monitor both angle of rotation and twist of an optical fibre with the inscribed TFBG.

References

[1] Li, F., Du, Y., Sun, X., Zhao, W. (2018). Sensing performance assessment of twisted CFRP with embeddedfiber Bragg grating sensors subjected to monotonic and fatigue loading. *Sensor Actuat. A-Phys.*, 271, 153–161.

[2] Budinski, V., Donlagic, D. (2017). Fiber-Optic Sensors for Measurements of Torsion, Twist and Rotation: A Review. *Sensors*, 17(3), 443.

[3] Chen, Y., Semenova, Y., Farrell, G., Xu, F., Lu, Y.Q. (2015). A compact sagnac loop based on a microfiber coupler for twist sensing. *IEEE Photonic Tech. L.*, 27(24), 2579–2582.

[4] Song, B., Zhang, H., Miao, Y., Lin, W., Wu, J., Liu, H., Yan, D., Liu, B. (2015). Highly sensitive twist sensor employing Sagnac interferometer based on PM-elliptical core fibers. *Opt. Express*, 23(12), 15372–15379.

[5] Li, H., Wang, Z., Liu, Y., Liang, H. (2017). FFT Algorithm-Assisted Polarimetric Twist Sensor. *IEEE Photonic Tech. L.*, 29, 2083–2086.

[6] Gao, R., Jiang, Y., Jiang, L. (2014). Multi-phase-shifted helical long period fiber grating based temperature-insensitive optical twist sensor. *Opt. Express*, 22(13), 15697–15709.

[7] Liu, Q., *et al*. (2018). Discriminating Twisting Direction by Polarization maintaining Fiber Bragg Grating. *IEEE Photonic Tech. L.*, 30(7), 654–657.

[8] Yiping, W., Wang, M., Huang, X. (2013). In fiber Bragg grating twist sensor based on analysis of polarization dependent loss. *Opt. Express*, 21(10), 11913–11920.

[9] Dong, X., Zhang, H., Liu, B., Miao, Y. (2011). Tilted fiber Bragg gratings: principle and sensing applications. *Photonic Sensors*, 1(1), 6–30.

[10] Albert, J., Shao, L.Y., Caucheteur, C. (2013). Tilted fiber Bragg grating sensors. *Laser Photonics Rev.*, 7(1), 83–108.

[11] Guo, T., Liu, F., Guan, B.O., Albert, J. (2016). Tilted fiber grating mechanical and biochemical sensors. *Opt. Laser Technol.*, 78, 19–33.

[12] Caucheteu, C., Guo, T., Albert, J. (2017). Polarization-assisted fiber Bragg grating sensors: Tutorial and review. *J. Lightwave Technol.*, 35(16), 3311–3322.

[13] Cięszczyk, S., Harasim, D., Kisała, P. (2018). Novel twist measurement method based on TFBG and fully optical ratiometric interrogation. *Sensor Actuat. A-Phys.*, 272, 18–22.

[14] Yan, Z., Mou, C., Zhou, K., Chen, X., Zhang, L. (2011). UV-inscription, polarization-dependant loss characteristics and applications of 45° tilted fiber gratings. *J. Lightwave Technol.*, 29(18), 2715–2724.

[15] Cięszczyk, S., Harasim, D., Kisała, P. (2017). A novel simple TFBG spectrum demodulation method for RI quantification. *IEEE Photonic Tech. L.*, 29(24), 2264–2267.

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

[17] Jiang, Q., Hu, D., Yang, M. (2011). Simultaneous measurement of liquid level and surrounding refractive index using tilted fiber Bragg grating. *Sensor Actuat. A-Phys.*, 170(1–2), 62–65.

[18] Mou, C., Zhou, K., Yan, Z., Fu, H., Zhang, L. (2013). Liquid level sensor based on an excessively tilted fibre grating. *Opt. Commun.*, 305, 271–275.

[19] Osuch, T., Jurek, T., Markowski, K., Jedrzejewski, K. (2016). Simultaneous measurement of liquid level and temperature using tilted fiber Bragg grating. *IEEE Sens. J.*, 16(5), 1205–1209.

[20] Miao, Y., Liu, B., Zhao, Q. (2008). Simultaneous measurement of strain and temperature using single tilted fibre Bragg grating. *Electron. Lett.*, 44(21), 1242–1243.

[21] Bialiayeu, A., Ianoul, A., Albert, J. (2015). Polarization-resolved sensing with tilted fiber Bragg gratings: theory and limits of detection. *J. Opt.*, 17(8), 085601.

[22] Caucheteur, C., Shevchenko, Y., Shao, L.Y., Wuilpart, M., Albert, J. (2011). High resolution interrogation of tilted fiber grating SPR sensors from polarization properties measurement. *Opt. Express*, 19(2), 1656–1664.

[23] Caucheteur, C., Voisin, V., Mégret, P. (2013). Light Polarization-Assisted Sensing with Tilted Fiber Bragg Gratings. *Open Optic. J.*, 7(1).

[24] Yan, Z., Mou, C., Sun, Z., Zhou, K., Wang, H., Wang, Y., Zhang, L. (2015). Hybrid tilted fiber grating based refractive index and liquid level sensing system. *Opt. Commun.*, 351, 144–148.

[25] Shen, C., Zhou, W., Albert, J. (2014). Polarization-resolved evanescent wave scattering from gold-coated tilted fiber gratings. *Opt. Express*, 22(5), 5277–5282.

[26] Lu, Y., Shen, Ch., Chen, D., Chu, J., Wang, Q., Dong, X. (2014). Highly sensitive twist sensor based on tilted fiber Bragg grating of, polarization-dependent properties. *Opt. Fiber Technol.*, 20(5), 491–494.

[27] Lu, Y.C., Geng, R., Wang, C., Zhang, F., Liu, C., Ning, T., Jian, S. (2010). Polarization effects in tilted fiber Bragg grating refractometers. *J. Lightwave Technol.*, 28(11), 1677–1684.

[28] Lu, Y.C., Huang, W.P., Jian, S.S. (2010). Full vector complex coupled mode theory for tilted fiber gratings. *Opt. Express*, 18(2), 713–726.

[29] Shao, L.Y., Xiong, L., Chen, C., Laronche, A., Albert, J. (2010). Directional bend sensor based on re-grown tilted fiber Bragg grating. *J. Lightwave Technol.*, 28(18), 2681–2687.

[30] Guo, T., Liu, F., Guan, B.O., Albert, J. (2014). Polarimetric multi-mode tilted fiber grating sensors. *Opt. Express*, 22(6), 7330–7336.

[31] Alam, M.Z., Albert, J. (2013). Selective excitation of radially and azimuthally polarized optical fiber cladding modes. *J. Lightwave Technol.*, 31(19), 3167–3175.