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EXPERIMENTAL DETERMINATION OF THE CHARACTERISTICS OF A TRANSMISSION SPECTRUM OF TILTED FIBER BRAGG GRATINGS

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Abstract

In this article, we study tilted fiber Bragg gratings (TFBGs) with tilt angles of 6° and 8°, their transmission spectra, and spectral parameters that have a linear dependence on the refractive index of the environment. It is shown that there can be several such characteristics, such as the minimum, width and energy of the spectrum. The linear dependence of the spectrum width on the refractive index does not depend on the tilt angle. The linear dependence of the spectrum minimum is only observed for a tilt angle of 8°. The results of this work can be used to create a sensor system based on an optical fiber.

Keywords: optical fiber, phase mask method, tilted fiber Bragg grating.

1. Introduction

Fiber Bragg gratings elements are used in many applications like lasers [1], sensors [2], and telecommunication systems [3]. The *tilted fiber Bragg grating* (TFBG) is a new kind of fiber-optic transducer. It has the ability to record a change in the state of the environment through its spectral response. This feature is very desirable in optical sensors. Since the response to an external quantity change between the cladding modes and the core modes with different effective refractive indices is different, a compact sensor can be created on the basis of TFBG to measure the effect of several physical quantities at once.

To date, several types of sensors are available which use TFBG: a concentration sensor for monitoring anions [4]; a refractive index sensor based on measuring the transmission power of an inclined Bragg fiber array [5]; a sensor for simultaneously measuring the level of the liquid and the refractive index of the environment [6]; mechanical and biochemical sensors [7]; sensors in which the values of the refractive index are measured by the correlation of the concentration of dopants inside the fiber core [8]; the refractive index sensor obtained by combining the FBG etching method and wet chemical silica [9]; the method for measuring twisting based on the influence of changes in the input light polarization state on the tilted Bragg grating. In the proposed sensor with the interrogation method, changes in the amplitudes of high-order cladding modes are measured by wavelength-matched fiber Bragg grating filters working in reflection mode. According to Cięszczyk *et al.* [10], the method for the analysis of *tilted fiber Bragg grating* (TFBG) transmission spectra is given. The processing method is based on the transmission spectrum contour length, which is calculated in the wavelength range in which the cladding modes appear [11].

Each of the sensors mentioned above has its advantages. However, with the increased use of fiber-optic TBGF sensors to determine the refractive index, other measurement methods need to be improved and proposed. In our work, using a similar measurement method, we proposed a new method for calculating indirectly measured quantities on the basis of TFBG spectra.

The difference between our study and similar ones is that we used two types of TFBG, conducted an experiment for 24 values of the refractive index, constructed the dependencies of the refractive index on the spectrum width also its minimum.

2. Description of the experiment

In the experiment, we use the phase mask technique and Excimer Laser (Coherent Inc.) to inscribe *tilted fiber Bragg gratings* (TFBGs) with tilt angles of 6° and 8° (Fig. 1). All structures were produced with the same laser settings, operating at a 100 Hz repetition rate. For the TFBG inscribtion SMF-28 fiber with a core field diameter of 10.4 μm (@ 1550 nm), core diameter 8.2 μm, cladding diameter 125 μm and coating diameter 242 μm was used. According to our previous works these values of grating angles allow to achieve appropriate number of minima in the optical spectrum [12]. The ultra-violet light was applied to a photosensitive single-mode optical fiber using the phase mask method. Here, the structure length and TFBG period are 10 mm and 540 nm, respectively.

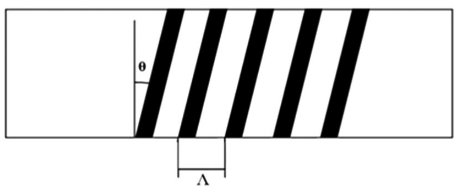

Fig. 1. Inscribed *tilted fiber Bragg grating* (TFBG) structure with the basic parameters marked.

The refractive index of the environment was set using a water solution of cane sugar. For this purpose, 24 variants of the solution with different sugar concentrations were used. As a result, the refractive index of the solution had 24 different values ranging from 1.3344 to 1.3706 at a constant ambient temperature. The values of the refractive index of the environment are given in Table 1.

The light from the laser diode was incident on the TFBG which was immersed in an aqueous solution of cane sugar. The transmission spectra of TFBG were measured using an optical spectrum analyzer. A generalized scheme of the experimental setup is shown in Fig. 2.

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Table 1. Cane sugar solution refractive index [13].

% concentration of sugar in solution	Refractive index	% concentration of sugar in solution	Refractive index
0	1.3330	13	1.3526
1	1.3344	14	1.3541
2	1.3359	15	1.3557
3	1.3374	16	1.3573
4	1.3388	17	1.3590
5	1.3403	18	1.3606
6	1.3418	19	1.3622
7	1.3433	20	1.3639
8	1.3448	21	1.3655
9	1.3464	22	1.3672
10	1.3479	23	1.3689
11	1.3494	24	1.3706
12	1.3510		

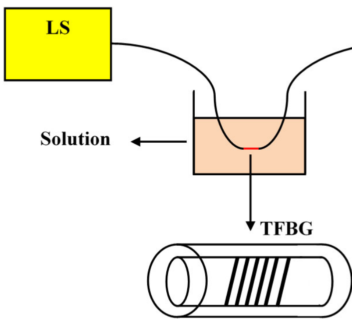

Fig. 2. The scheme of the experimental setup. LS – light source; OSA – optical spectrum analyzer; TFBG-tilted fiber Bragg grating.

Figure 3 shows a real view of the experimental setup, where the TFBG spectrum is indicated on the spectrum analyzer.

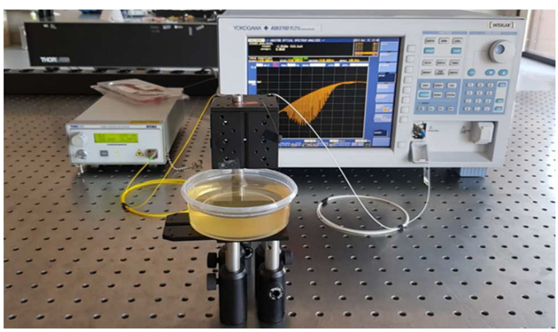

Fig. 3. The scheme of the experimental setup.

Figure 4 shows some examples of the TFBG transmission spectrum with a tilt angle of (a) 6° and (b) 8°, obtained using our experimental setup.

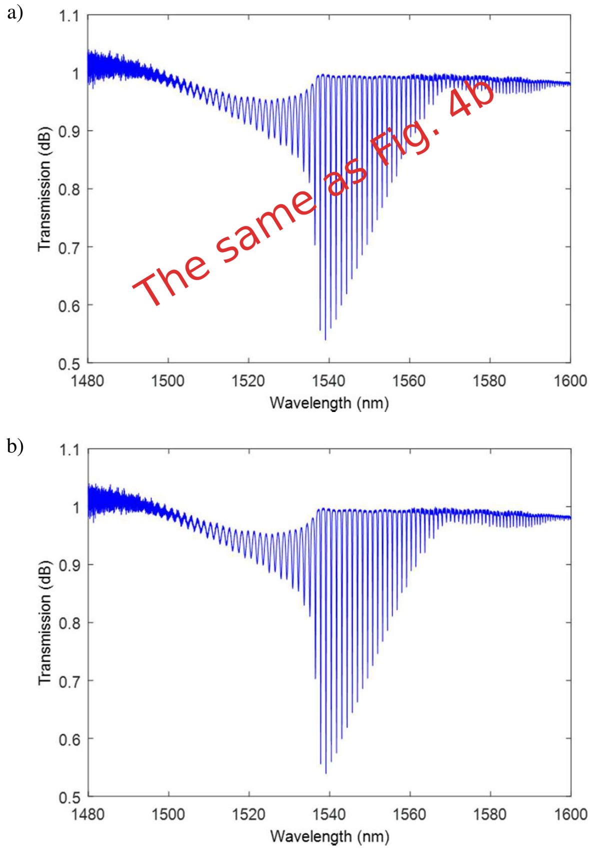

Fig. 4. TFBG transmittance spectra with a tilt angle equal (a) 6° and (b) 8°.

The essential objective of the experimental study is to determine the dependence of the transmission spectrum characteristics of TFBG on the refractive indices of the environment. Various characteristics can be considered for this purpose. For instance, in [5], the processing of experimental data considers the dependence of the transmission spectrum power on the refractive index. However, in their work, in some cases, the dependence of the power of the transmission spectrum on the refractive index of the environment has a nonlinear, cubic form. For the technical implementation of the sensor, a linear relationship is preferred. In the study for linear relationships between the refractive index of the environment and the characteristics of the transmission spectrum, we investigated other characteristics. In our work, we considered other dependencies: 1) the dependence of the width and 2) the minimum of the transmission spectrum on the refractive index of the solution.

To determine the width of the spectrum, a certain threshold value was introduced. Since the transmission spectrum changes monotonically, its width can be determined using two points. The first of these points is located on the descending part of the spectrum as an intersection point between the threshold line and the spectrum graph. Accordingly, the second point is in the ascending part of the spectrum, it is also determined by the intersection of the line and

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the threshold and the spectrum graph. The distance between these points on the abscissa is the width of the spectrum. Fig. 5 shows an example of how the spectrum width and its minimum are determined according to the above algorithm.

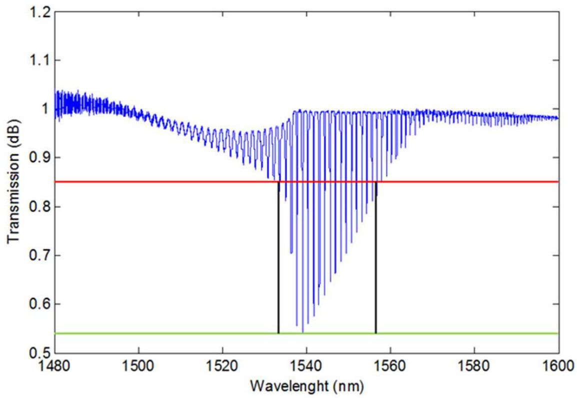

Fig. 5. An example of determining the width of the spectrum and its minimum.

In Fig. 5, the red line indicates the threshold value, which, in this case, is equal to 0.85. The green line shows the position of the minimum of the spectrum and it is equal to the lowest value of the spectrum. Vertical black lines indicate the width of the spectrum. It should be noted that the threshold value of 0.85 is the best fit to the experimental data. It is possible that other thresholds are required for other grating tilt angles. In this regard, we believe that in order to clarify this issue, it is necessary to conduct a series of experimental measurements at other grating tilt angles and at various ambient temperatures. The selection of the best threshold is done by the search method. To do this, we went through various threshold values and made an estimate of the error according to formula (3). Thus, the best value of the threshold value corresponds to the minimum value of the error.

In our work, we investigated whether a linear dependence of the transmission spectrum characteristics on the refractive indices existed. For this purpose, the experimental data were processed using Matlab. The results of the experimental data processing are shown in Figs. 6 to 8.

As we see from Fig. 6, the minimum of the TFBG spectrum for 8 degrees tends to grow monotonically depending on the refractive index of the environment. But for the grating tilt angle equal 6 degrees, this dependence is not unambiguous, while it generally tends to fall. This point requires additional investigation for other grating tilt angles.

In Figs. 6 and 7, the blue crosses correspond to the experimental results and the red line corresponds to the approximating curve. At the Fig. 6, we can see that the dependence of the minimum of the transmission spectrum on the refractive index for the case of a tilt angle of 6° is not linear, while for a tilt angle of 8°, it is linear. Since the dependence of the minimum of the spectrum on the refractive index is not always linear, this dependence is not unambiguous and, accordingly, in our opinion, has no practical application.

From Fig. 7, we can see that the dependence of the width of the spectrum ($\triangle\ \omega$) on the refractive index (n) in both cases is linear. According to the experimental data for the tilt angle of 6°, this dependence is defined as follows:

$$\Delta\omega = 496.53 - 338.98n \qquad (1)$$

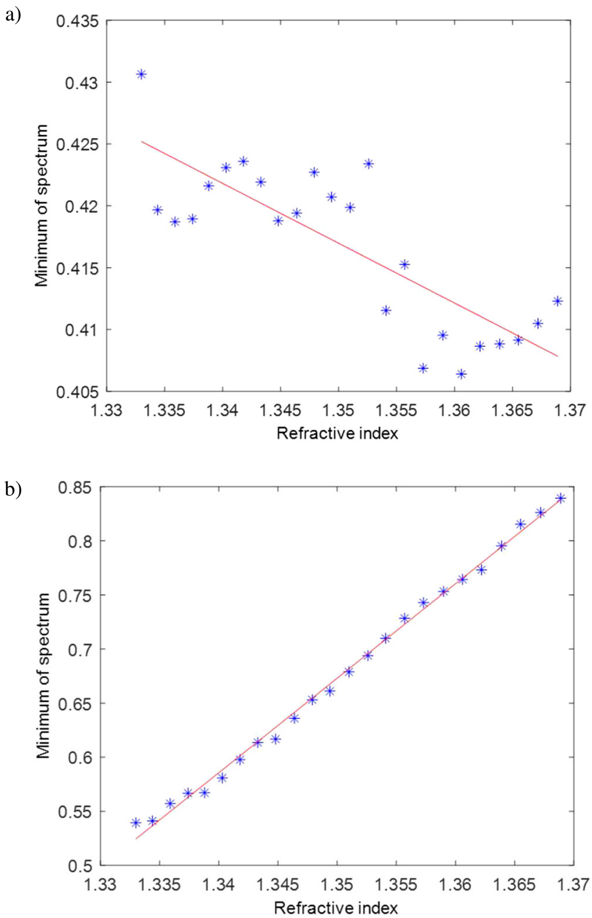

Fig. 6. The dependence of the minimum value of the spectrum on the refractive index: for (a) TFBG 6° and (b) TFBG 8°.

and for the tilt angle of 8°, the dependence of the width of the spectrum on the refractive index is defined as follows:

$$\Delta\omega = 894.9 - 653.93n. \tag{2}$$

To quantify the degree of linearity of the dependence of the width of the spectrum on the refractive index, the errors of the coefficients of the first-order approximation polynomial are calculated. If the first-order approximation polynomial is represented in the form $y = a + bx$, where a is numerical coefficient, then for k quantity measurement the mean square error (S_b) of determining the coefficient b is found by the formula:

$$S_b = \sqrt{\frac{\sum\limits_{i=1}^{k}(y_i - bx_i - a)^2}{(k-2)\sum\limits_{i=1}^{k}(x_i - \overline{x})^2}}. \tag{3}$$

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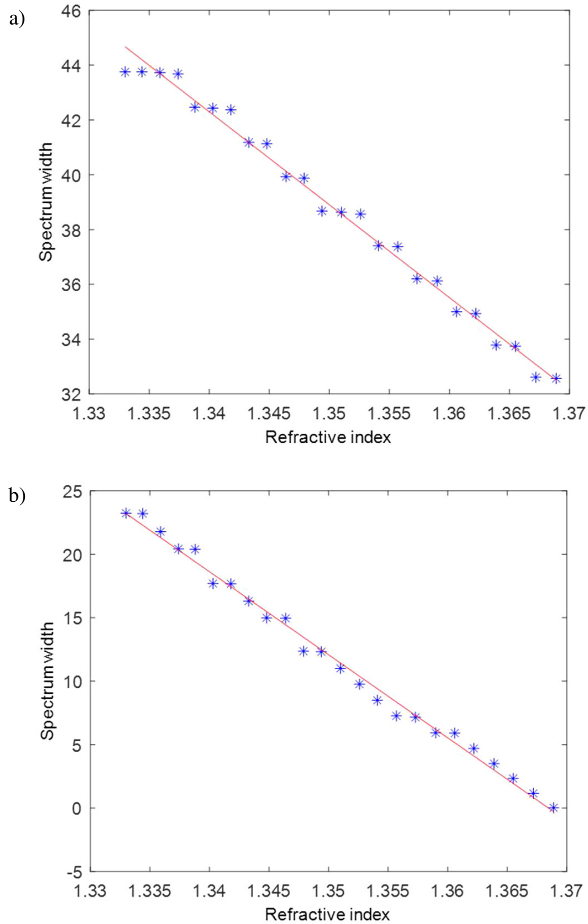

Fig. 7. The dependence of the width of the spectrum on the refractive index: for (a) TFBG 6° and (b) TFBG 8°.

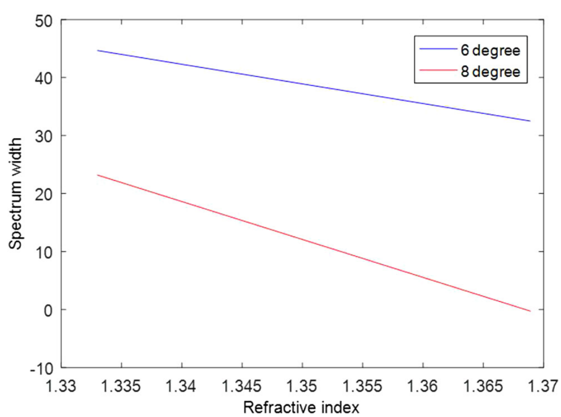

Fig. 8. The dependence of the width of the transmission spectrum on the refractive index for TFBG 6° and TFBG 8°.

The absolute error is calculated using the formula: $\Delta b = S_b \cdot t_\alpha$, where t_α is the Student's coefficient. Thus, the relative errors (ξ_b) associated with determining the coefficient b take the following values: $\xi_b = 4.6\%$ for a tilt angle 6° and $\xi_b = 3.7\%$ for a tilt angle 8°.

The relative errors associated with calculating the coefficient b are rather small, for both tilt angles. Therefore, it can be argued that the dependence of the width of the transmission spectrum on the refractive index is effectively described by a linear dependence.

Nevertheless, it should be noted that the dependence of the minimum of the spectrum on the refractive index of the medium for the case of a tilt angle of 8° is the most linear among all the cases considered in this paper. For this dependence, the error in determining the coefficient b turned was equal to 2.7%. This is the smallest value among all calculated errors.

3. Conclusions

The dependencies of the width of the transmission spectrum on the refractive index for both TFBG variants (tilt angles of 6° and 8°) show a linear relationship. Accordingly, the width of the transmission spectrum can be used as an indicator of changes in the refractive index.

However, the other characteristic (the minimum of the transmission spectrum) is effectively described by a linear dependence on the refractive index only for a tilt angle of 8°. The change in the form of the dependence of the minimum of the spectrum on the refractive index depending on the angle of inclination requires additional study.

Since the dependence of the minimum spectrum on the refractive index of the environment was most linear for a tilt angle of 8°, this characteristic is of great interest in the context of practical applications. However, a strong divergence from linearity for a tilt angle of 6° requires additional research to determine the applicability of this characteristic. For this purpose, it is also necessary to repeat the same measurements for other TFBG tilt angles.

Creating a refractometer based on TFBG makes it possible to use it in harsh environmental conditions, in which it is necessary to use sensors that are immune to electromagnetic interference, in an environment that requires resistance to chemical compounds and an explosion hazard.

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