Inscription and visualization of tilted fiber Bragg gratings

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Abstract. In this work the inscription and investigation of tilted fiber Bragg gratings induced in a single-mode isotropic optical fiber with increased photorefractivity are demonstrated. Using the Talbot interferometer and the KrF excimer laser system, tilted fiber Bragg gratings with different angles were fabricated, the spectra of the formed diffraction structures were analyzed, and their photographic images were taken with a confocal laser scanning fluorescence microscope in transmitted light. The calculated dependence of the tilt angle of tilted fiber Bragg gratings fabricated in the Talbot interferometer on the angle between the interference fringes created in the interferometer and the cross section of the optical fiber is experimentally verified.

1. Introduction
Tilted fiber Bragg gratings (TFBGs) are a special kind of fiber-optic gratings. They have a periodic modulation of the refractive index along the fiber axis, but they differ from the standard fiber Bragg gratings (FBG) by having a certain angle between the grating planes and the fiber cross-section, which causes a more complex mode coupling of radiation propagating along the optical fiber (OF). In addition to the coupling of the core modes propagating in opposite directions, the core modes propagating in the forward direction and the cladding modes propagating in the forward and reverse directions interact. Such structures are characterized by an all-fiber design, small size, protection from electromagnetic fields, durability, stability, low insertion loss and flexible spectral transmission characteristics [1-4].

TFBGs find their practical application in the creation of optical sensors for measuring physical parameters such as temperature, deformation, vibration, refractive index of the external environment, and also they can be used in telecommunications as part of an optical erbium-doped fiber amplifier, an optical add-drop multiplexer, optical fiber polarizer [5-7].

For optimization the fabrication of TFBGs in the domestic optical fiber, it is required to know exactly the dependence of the tilt angle of the grating fabricated in the Talbot interferometer on the angle between the interference fringes produced in the interferometer and the cross section of the optical fiber. To achieve this goal, the following tasks were solved: fabrication of TFBGs with different angles, visualization of TFBG samples on an optical microscope, and analyzing photographic images; a comparison of the experimental data and the calculated dependence of the tilt angle of TFBG on the angle between the interference fringes and the cross section of the optical fiber.
2. **Tilted fiber Bragg gratings inscription scheme**

   For this work, an interferometric fabrication method was used, which is described in [8]. This method makes it possible to change the period of the interference pattern over a wide range, which allows fabrication of TFBG with different periods, using only one phase mask for the amplitude separation of the laser beam. The functional scheme of the Talbot interferometer, optimized for TFBG inscription, is shown in Figure 1.

![Figure 1. Functional scheme of Talbot interferometer](image)

The laboratory setup was modified by installing the rotary holder of OF. By varying the angle of rotation of the OF \( \theta_{\text{ext}} \) (the external tilt angle) relative to the interference fringes, it is possible to obtain TFBG with different angles.

3. **Experimental results of tilted fiber Bragg gratings inscription**

   For experiments a single-mode isotropic OF with increased photorefractivity (quartz cladding diameter is 125 \( \mu \)m) was used. The photorefractivity of the optical fiber was enhanced by increasing the concentration of germanium dioxide to 12 mol.\% at the stage of the preform formation, and then by hydrogen treatment. The conditions for the hydrogen loading of OF are the same as in [9].

   After removing the protective acrylate coating, the optical fiber is installed in the fiber holder. For establishing the position of the OF, in which its axis would be perpendicular to the lines of the interference fringes, it is necessary to fabricate the gratings by rotating the OF with a rather small step (in the present work this step was 0.2\(^\circ\)), while monitoring in the reflection spectrum the change of the position of the peak corresponding to the Bragg wavelength. When \( \lambda_{\text{Bragg}} \) reaches its minimum value, this position of the OF is taken as 0\(^\circ\).

   To fabricate a single TFBG, the OF was irradiated for 1 minute at a frequency of 10 Hz, while the energy density on the surface of the fiber was 220 mJ/cm\(^2\). In order to track not only the change in the peak corresponding to the Bragg wavelength but also the set of peaks corresponding to the coupling of the core mode and the cladding modes, the transmission spectrum was recorded using the scheme shown in Fig. 2. The spectrum was observed on the Yokogawa AQ6370C optical spectrum analyzer with a range measurements of 600-1700 nm and a resolution of 20 pm.

![Figure 2. Scheme for registration of the transmission spectrum of the grating](image)
In the work TFBG samples with various external angles $\theta_{ext}$ were inscribed. With increasing of $\theta_{ext}$, the value of the Bragg wavelength $\lambda_{Bragg}$ also increases, but the diffraction efficiency of the Bragg resonance of the grating decreases, as shown in the graphics presented in Fig. 3. These dependences are obtained for the isotropic optical fiber without hydrogen treatment. The dependence shown in Fig. 3(a) can be used to inscribe FBG by the phase mask method, the main disadvantage of which is the fixed value of the period of the interference pattern formed behind the phase mask. Thus, by introducing a tilt angle $\theta_{ext}$, it is possible to adjust the wavelength of the Bragg resonance of the induced grating. Taking into account the fact that the larger the angle, the smaller the coupling of the core modes propagating in the forward and backward directions (Fig. 3 (b)), such adjustment can be effective only in the region of small angles.

Figure 3. Dependence of Bragg wavelength $\lambda_{Bragg}$ (a) and reflection coefficient $R$ (b) of TFBG on external tilt angle $\theta_{ext}$

Figure 4 shows the transmission and reflection spectra of TFBG with an external tilt angle of 4º, the Bragg wavelength in this case is $\lambda_{Bragg} = 1562.74$ nm. TFBG is induced in an hydrogen-loaded isotropic optical fiber.

Figure 4. Transmission and reflection spectrum of TFBG with 4º external tilt angle
4. **Visualization of tilted fiber Bragg gratings**

Using the Zeiss LSM 710 confocal laser scanning fluorescence microscope in transmitted light, when a radiation source with a wavelength of 405 nm (diode laser) was used, experiments were performed on visualization of TFBG. Figure 5 presents photographic images of TFBGs with external tilt angles of 4°, 10° and 20°. TFBG is induced in a hydrogen-loaded isotropic optical fiber. By rotation of the OF relative to its axis the position in which the TFBG strokes were perpendicular to the OF axis was attained, and then OF with the grating was rotated by the rotary holder by 90°, which corresponded to the maximum tilt angle of the TFBG. It can be seen from Fig. 5 that the internal tilt angle of the grating $\theta_{int}$ differs from the external $\theta_{ext}$ (the angle between the interference fringes and the cross section of the optical fiber) because of the appearance of a prismatic effect when the radiation passes through the OF because of its cylindrical shape. The measured values of internal tilt angles $\theta_{int}$ of the gratings were 5.4°, 12.86° and 26.57° corresponding to external tilt angles $\theta_{ext}$ of 4°, 10° and 20°.

![Photographic image of TFBGs with external tilt angles](image)

**Figure 5.** Photographic image of TFBGs with external tilt angles (a) 4°, (b) 10° and (c) 20°

The experimental values obtained are close to the theoretical values calculated from the formula (1) [6], as evidenced by the data presented in Figure 6:

$$\theta_{int} = \frac{\pi}{2} - \tan^{-1} \frac{1}{n \tan \theta_{ext}},$$

where $n$ – refractive index of the OF cladding.
Conclusion
TFBG is a universal device for selectively exciting of certain cladding modes, whereby it is possible to record a change in the state of the environment by monitoring the spectral response of the grating, which can be realized in optical sensors. Since the response to the external change in cladding modes with different effective refractive indices and core mode is different, a compact sensor can be created on the basis of TFBG to measure the impact of several physical quantities at once. Also, such structures provide the flexibility to adjust the wavelength of the Bragg resonance when the TFBGs are fabricated by the phase mask method.

In this work the Talbot interferometer was upgraded to fabricate TFBGs. TFBGs with different external tilt angles were fabricated, and also photographic images of TFBGs with external angles of inclination of 4°, 10° and 20° were obtained and analyzed. On the basis of the obtained data, the calculated dependence of the internal angle of TFBG on the external angle between the interference fringes and the cross section of the OF is experimentally verified.

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