The study of the thermal annealing of the Bragg gratings induced in the hydrogenated birefringent optical fiber with an elliptical stress cladding

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Abstract. In this work the comparative results on the dynamics of fiber Bragg gratings inscription in both the conventional and the subjected to hydrogenation birefringent optical fiber with elliptical stress cladding as well as in the same type of lightguide with the increased GeO\textsubscript{2} concentration are presented. Also the research on the thermal impact on the fiber Bragg gratings written in the birefringent fiber with elliptical stress cladding has been carried out. The dependences of the fiber Bragg reflectance coefficient on the time of the thermal impact, obtained by annealing of the refractive index gratings, induced in the optical fibers with increased photorefractivity, are shown.

1. Introduction
The first fiber Bragg grating (FBG) was obtained in 1978 [1]. In about 10 years FBG was inscribed through a lateral surface of optical fiber (OF) for the first time [2]. Currently the intensive implementation of fiber-optic sensors (FOS) takes place in many high-tech areas [3, 4] due to its resistance to electromagnetic disturbance, small weight, size and relatively low cost. Phase interferometric sensors (PIS) are considered to be ones of the most precise FOS [5]. Thus, acoustic monitoring systems based on the fiber optic hydrophone arrays multiplexed with FBGs, can completely replace the existing analogues based on piezoceramic elements.

During the fiber Bragg grating inscription in the conventional OF one faces the difficulties related to the low photosensitivity of the material which this fiber was made of. Several methods to increase the photorefractivity of germanium-silica fibers were proposed in literature [6]. The conventional way is to increase the GeO\textsubscript{2} concentration in core on the stage of OF preform formation. But this method has several disadvantages such as the growth of OF linear losses and additional losses occurring during the coupling of such lightguides to the conventional ones (that have the standard GeO\textsubscript{2} concentration). The method of low temperature hydrogenation is of big interest too. The hydrogenation of the fabricated OF at low temperatures and high pressure significantly raise its photorefractivity that allows to obtain Bragg grating inscription with the sufficient refractive index (RI) modulation.
The hydrogen treatment of the OF used in this work had been carried out under the following conditions: the optical fiber wound around the plastic tube with the diameter of 20 mm was placed in the gas cylinder, filled with the grade “A” hydrogen (mol. percentage of hydrogen was 99.99%) under the pressure of 10.4 MPa and was kept for 32 days at the temperature of 18 °C.

2. FBG writing scheme

The Bragg gratings studied in this work were written with KrF excimer laser Coherent COMPex Pro 102 F with the phase mask method [7]. The FBG inscription scheme is presented in the Figure 1.

![Figure 1. Phase mask method FBG inscription scheme](image)

The laser with the pulse energy of about 250 mJ generates pulses with 20 ns duration at the 248 nm wavelength. The attenuator with the built-in shutter allows to select a single pulse out of its sequences when the laser has already been derived to a stationary mode. The slot filters out the laser beam area that is not used in the inscription process. The cylindrical lense focuses the laser beam along one of the axes to achieve the energy density needed.

In the present work the birefringent fiber with elliptical stress cladding obtained with the technology [8] was used for FBG writing. The design of the birefringent fiber with the elliptical stress cladding is presented in the Figure 2.

![Figure 2. The birefringent OF with elliptical stress cladding design](image)
3. FBG writing results

It is known that hydrogen, dissolved in glass, changes its RI, which leads to some grating resonance wavelength shift. For example, in the work [9] is shown that the spectrum of the FBG, inscribed in the OF, subjected to hydrogen treatment, is shifted to longer wavelengths by about 1.2 nm. The amplitude of this wavelength shift depends on the initial hydrogen concentration and can reach a few nanometers. Also this method increases the photosensitivity of optical fibers and provides the effective FBG inscription in them.

One of the most important FBG parameters is the value of the induced RI modulation $\Delta n$. The following formula can be used to estimate the Bragg grating RI modulation amplitude (1):

$$\Delta n = \frac{\lambda_B}{\pi \cdot l} \cdot \tanh^{-1}(\sqrt{r_{\text{max}}})$$

where $\lambda_B$ – the central wavelength of the Bragg resonance; $r_{\text{max}}$ - reflectance coefficient at the central grating reflectance wavelength; $l$ - FBG length.

In Figure 3 the dynamics of the reflectance coefficient growth of the Bragg gratings induced in the birefringent fiber with elliptical stress cladding that had been subjected (ESC-4 mol.% GeO$_2$ (H$_2$)) and hadn’t been subjected (ESC-4 mol.% GeO$_2$) to hydrogenation, as well as in the fiber with increased germanium dioxide concentration (ESC-12 mol.% GeO$_2$) are shown. The laser pulse energy density on the OF was approximately about 500 mJ/cm$^2$, the exposition time was 5 minutes at the laser pulses rate of 1 GHz.

![Figure 3. The dynamics of the reflectance coefficient growth of the Bragg gratings versus time](image)

Considering the fact that the FBGs’ length $l$ in all cases is 8 mm and the central wavelength of reflection $\lambda_B$ is 1550 nm, the induced RI modulation value $\Delta n$ for OF ESC-4 mol.% GeO$_2$ is $8.6 \times 10^{-6}$, for OF ESC-12 mol.% GeO$_2$ is about $6.4 \times 10^{-5}$, and for OF ESC-4 mol.% GeO$_2$ (H$_2$) is about $1.3 \times 10^{-4}$.

The figure shows that both methods of the photorefractivity amplification are effective for the FBG inscription in the birefringent OF with elliptical stress cladding. In addition in both cases the induced RI change value is sufficiently high. Nevertheless, the method of increasing of germanium dioxide
concentration in the fiber core has some disadvantages related to the optical linear losses growth, therefore it is inferior to the hydrogen treatment method.

4. The research on the FBG thermal stability

After that the research on thermal stability of the FBGs induced in this type of birefringent OF subjected and not subjected to hydrogenation had been conducted.

To conduct this investigation the laboratory stand for FBG annealing and spectral properties controlling had been assembled. The experimental method of FBG thermal stability investigation is based on the subjection of the several similar fiber diffractive structures to certain heat treatment during which the spectral properties changes are registered.

During the FBG heating the Bragg resonance wavelength is shifting towards the area of longer wavelengths due to the thermal expansion of silica OF and thermo-optical effect. After the reaching of the annealing temperature the smooth decrease of the reflection coefficient begins [10].

![Figure 4. The dependence of the FBG normalized reflection coefficient on the time of annealing at different temperatures for OF ESC-4 mol.% GeO\textsubscript{2} (H\textsubscript{2})](image)

In the figure 4 the change of the reflection coefficient of the Bragg gratings inscribed in the fiber ESC-4 mol.% GeO\textsubscript{2} (H\textsubscript{2}) during the annealing process at different temperatures lasting for 2 hours, is presented. It is seen that that the major decrease of the reflection coefficient occurs during the first 10 minutes and after that the process stabilizes. At the end of the 2 hour annealing at the temperature of 440°C the reflection coefficient decreases by about 80%.
In Figure 5 the change of the reflection coefficient of the Bragg gratings inscribed in the fiber ESC-12 mol.% GeO$_2$ with increased germanium dioxide concentration in the core during the annealing process at different temperatures lasting for 2 hours, is presented. It is seen that the major decrease of the reflection coefficient occurs during the first 10 minutes and after that the process stabilizes. At the end of the 2 hour annealing at the temperature of 440°C the reflection coefficient decreases by about 60%.

5. Conclusion

The experiments that had been carried out demonstrate the effectiveness of the low-temperature hydrogen treatment for the increasing of photorefractivity of the birefringent optical fibers with elliptical stress cladding and also show that FBGs induced in the investigated fiber that was subjected to the hydrogen treatment have less thermal stability in comparison to the samples with increased GeO$_2$ concentration in the fiber core. But at the same time the thermal stability is sufficient for many applications, i.e. as PIS reflective elements, that are operated at the temperature range from -40°C up to +70°C.

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