Phase-shifted fiber Bragg gratings fabrication method

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In this paper, we showed a technique for the formation of phase-shifted fiber Bragg gratings. The analysis of the efficiency of the obtained structures was carried out with the help of an optical spectrum analyzer with the subsequent calculation of the full width at half maximum of a bandpass in reflection spectrum. Fiber Bragg gratings inscription was performed on the Talbot interferometer, the KrF excimer laser system was used as a UV radiation source, and a phase shift was introduced by the electrical discharge of an arc fusion splicer. The experimental dependence between the length of the obtained structure and the full width at half maximum of a bandpass in reflection spectrum of a phase-shifted grating was presented, the value of the last parameter varies in the range from 24 pm to 96 pm.

1. Introduction
The formation of Bragg gratings representing the modulation of the refractive index along the direction of wave propagation in the optical fiber core was first described in a 1978 [1]. Later, in 1989 [2], an interferometric inscription of the refractive index gratings through a side surface into a germanium-silicate optical fiber (with an increased value of photorefractivity) by exposure to UV radiation was presented. This publication [2] initiated the propagation of fiber Bragg gratings (FBGs), which make it possible to obtain spectral characteristics depending on the tasks assigned. Currently, fiber Bragg gratings are used in fiber lasers, in fiber optic communication systems, in sensors of various physical quantities (for example, pressure, temperature, mechanical stresses, etc.).

With the development of fiber optics, Bragg grating production technologies were also improved, and special structures were developed that made it possible to obtain spectral characteristics different from the standard refractive index gratings. Some of these structures are fiber Bragg gratings with a phase shift, the study of which was first described in 1994 [3, 4]. The distinctive feature of such gratings is the presence of a narrow transmission region in the reflection spectrum, which full width at half maximum could be on the order of a few tens, sometimes units of picometers. This type of refractive index gratings is used in the manufacture of spectral filters [5-7], lasers with distributed feedback [8], sensors of various physical quantities with increased resolution (in comparison with standard FBGs) [9, 10].

Many approaches have been proposed to the formation of Bragg gratings with a phase shift. One of the simplest techniques for the formation of such structures is the use of phase masks with a pre-formed phase shift [3]. The disadvantage of this method is the absence of the possibility of changing the grating period, as well as in a high cost of such masks manufacturing. Different techniques of phase-shifted FBGs formation are presented: with overlapping of one grating period by a region with an increased refractive index [11]; with the introduction of an air gap between the two
ends of the fibers on which the FBG is formed [12]; with ultraviolet post-processing of a narrow region in the center of the FBG formed [4]. In general, the disadvantages of the proposed techniques are associated with the use of high-precision optical and/or mechanical devices and, correspondingly, their high cost, as well as with a relatively complex adjustment of the specific position of the fibers.

The technique using an arc fusion splicer for introducing a phase shift was described in [12] and was used as a prototype. But, unlike our method, in work [12] the electric arc was effected in the center of a single FBG. Thus, firstly, there were increased requirements for an accurate determination of the center of the Bragg grating, and secondly, the diffraction efficiency of such a structure decreased after the influence of the electric arc in comparison with the originally induced standard FBG.

In this paper, we propose a technique for the formation of phase-shifted FBGs, which are inscribed on a Talbot interferometer, while a phase shift is introduced by means of the electrical discharge of an arc fusion splicer between two formed gratings. The advantages of this method consist in the possibility of adjusting the parameters (period and wavelength) of the induced Bragg grating, the absence of high-precision devices at the stage of phase shift formation and high diffraction efficiency of the formed structures.

2. Experimental setup

In this work the KrF excimer laser system MOPA CL-7550 (Optosystems Ltd, Russia) was used as a radiation source. The advantage of using such Master Oscillator–Power Amplifier laser system is a high degree of spatial (> 5 mm) and temporal (> 10 mm) coherence, which reduces the requirements for the alignment of the interferometer, and also allows obtaining an interference pattern of high contrast on the surface of the optical fiber. The radiation wavelength of the laser system is 248 nm.

![Figure 1. FBG inscription scheme by means of a Talbot interferometer and a phase shift introducing stage by means of an electrical discharge between electrodes](image)

The FBG inscription was performed on the Talbot interferometer [13], which functional scheme is shown in Fig. 1(a). The laser beam passing through the lens is focused on the phase mask, which is
used for amplitude separation of the beam. To block the zero order of diffraction, an opaque screen is installed in the scheme. +1 and -1 diffraction orders, reflected from the dielectric mirrors mounted on rotary stages, interfere with each other and as a result of the interference a fiber Bragg grating is formed in the core of the optical fiber. The rotary stages on which the mirrors are fixed allow one to change the angle of incidence of the rays onto the optical fiber $\theta$, thereby adjusting the grating period (and hence the wavelength of the Bragg resonance) by changing the angle $\varphi$ of the mirrors by equation (1):

$$\Lambda = \frac{\lambda_{\text{laser}}}{2\sin(\alpha - 2\varphi)}$$

(1)

where $\Lambda$ is the grating period, $\alpha$ is the 1st order diffraction angle, $\varphi$ is the angle of rotation of the mirrors, $\lambda_{\text{laser}}$ is the radiation wavelength of the excimer laser system.

After inscription of the first FBG, the fiber is shifted along its axis to a certain distance and the second FBG is induced (Fig. 1(b)); the formation of both Bragg gratings takes place under identical conditions while preserving the main parameters, so the period and length of the successively inscribed gratings, as well as the value of the refractive index modulation and the Bragg resonance wavelength, are the same. Then, a $\pi$-shift is induced between two FBGs, leading to destructive interference and the appearance of a narrow bandpass in a reflection spectrum of the diffraction structure.

Figure 1(c) shows a schematic representation of the phase shift formation stage. The phase difference is induced using the electrical discharge of an arc fusion splicer: the influence of the electric arc produced between the electrodes slightly changes the geometry of the fiber. The result of the described manipulations is being monitored in real time on the optical spectrum analyzer, and the number of effects of the electric arc can be different until the most appropriate spectrum is achieved. The exposure time of the electrical discharge of an arc fusion splicer was 0.3 seconds, the current value was 8 mA.

In our experiments the gratings were spaced from each other by a distance equal to 1 mm ($a$ in Fig. 1(c)). The distance control was carried out with the help of a linear micrometric stage, the error of which determines the case when the inscription of the second grating allows to induce the $\pi$-phase-shift, and there is no need for further exposure to the electric arc, but such a random hit has a small probability of occurrence.

3. Experimental results

To analyze the effectiveness of the developed technique, it is necessary to consider the spectral characteristics of obtained phase-shifted FBGs. The reflection spectra were recorded according to the scheme shown in Figure 2 by means of the Yokogawa AQ6370C optical spectrum analyzer.

![Figure 2. Principal scheme for monitoring the phase-shifted FBG reflection spectrum](image)

Optical radiation from a broadband source is coupled through the Y-coupler to an optical fiber into which a $\pi$-shifted Bragg grating is inscribed. Reaching the FBG, part of the radiation is reflected and goes to the optical spectrum analyzer through the Y-coupler. The optical isolator transmits light
from the radiation source to the induced FBG, but prevents its passage backwards in order to prevent the influence of back reflections on the spectrum of the radiation source.

According to this scheme, the reflection spectra shown in Figure 3 were obtained. As was pointed out earlier, the parameters of two gratings consecutively inscribed in an optical fiber and spaced apart by a distance of 1 mm are the same, hence, the reflection spectra of these gratings coincide. In Figure 3, the green dashed line represents the reflection spectrum of one of the two FBGs, and the blue solid line represents the phase-shifted FBG reflection spectrum.

For FBG inscription the optical fiber was irradiated for 1 minute at a frequency of 10 Hz, while the energy density on the surface of the fiber was 130 mJ/cm².

![Figure 3](image)

**Figure 3.** Reflection spectrum of a phase-shifted fiber Bragg grating: the green dashed line - the reflection spectrum of one of the two FBGs, the blue solid line - the phase-shifted FBG reflection spectrum

The shift of the Bragg wavelength for the phase-shifted FBG relative to the standard FBG, that could be seen on Figure 3, is explained by the fact that the inscription of Bragg gratings is carried out in a fiber under small tension. After inscription of the grating, the optical fiber is removed from the fiber holders and placed in the arc fusion splicer in order to induce a phase shift by means of an electrical discharge.

In Figure 3, the variable δ is the value of the full width at half maximum of a bandpass in reflection spectrum. This parameter makes it possible to compare Bragg gratings with π-shifts among themselves. When analyzing gratings of different lengths, it is noted that as the grating length increases, the full width at half maximum of a bandpass in reflection spectrum decreases. This is due to the fact that the number of spaced interfering waves increases with the length of the grating. In turn, lateral values of the reflection band make less impact and, being out of phase with each other, attenuate, leading to a decrease in the full width at half maximum of the reflection spectrum, hence the width of a bandpass in reflection spectrum also decreases. Figure 4 shows the experimental dependence of the full width at half maximum of a bandpass in reflection spectrum on the length of the induced FBG with a π-shift.
Figure 4. The blue open points - the experimental values of the full width at half maximum of a bandpass in reflection spectrum for the different grating lengths, the blue solid line - first degree spline, which was built for these experimental values

The $\pi$-shifted FBG length in mm is calculated as the total value of the two lengths of Bragg gratings without taking into account the distance to which they are spaced ($a$). The minimum value of the full width at half maximum of a bandpass in reflection spectrum was achieved with a grating length of 20 mm (two FBG of 10 mm) and equaled 24 pm.

4. Conclusion
In this paper we present an inscription of fiber Bragg gratings on the Talbot interferometer and the subsequent introduction of a phase shift by means of the electrical discharge of an arc fusion splicer between two FBGs. This method of forming such structures makes it possible to exclude the use of high-precision and expensive devices at the stage of phase-shift formation. In comparison with the method presented in [12] taken as a prototype, in the method described by us, the electrical discharge of an arc fusion splicer is produced not in the center of the generated FBG, but between two inscribed FBGs, which avoids mashing the diffraction structure induced in the optical fiber. This circumstance has a positive effect on the quality of the obtained FBG with a phase shift. The main value for comparing the gratings was the full width at half maximum of a bandpass in reflection spectrum - this parameter depends mainly on the length of the grating. As a result of the experiments, this value varies in the range from 24 to 96 pm, which allows us to conclude that it is possible to obtain a narrowband passing radiation according to the procedure described in this paper.

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