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Optical fibres and fibre tapers with an array of Bragg gratings

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Abstract. **The properties of optical fibres with an array of fibre Bragg gratings written directly during the fibre drawing are considered. Such optical fibres offer new possibilities for producing new types of active and passive fibre elements due to the enhanced back-reflected signal of the so-called artificial Rayleigh scattering, and are of interest for modelling physical phenomena associated with the statistics of reflecting centres in optical fibres, such as, e.g., localisation of photons. We studied fibres with an array of Bragg gratings written in photosensitive fibres, ordinary single-mode optical fibre of the SMF-28 type and in fibre with a core doped with erbium ions. To control the spectrum width of the reflected signal, we used chirped phase masks, as well as writing arrays of gratings in tapered optical fibres.**

Keywords: *tapered optical fibres, active optical fibres, arrays of fibre Bragg gratings, optical sensors, fibre lasers.*

1. Introduction

Optical fibres (OFs) are widely used as passive and active elements for transmission lines, sensor systems, and fibre lasers. Of particular interest are sensor systems based on the principle of coherent reflectometry [1, 2]. In such systems, sensitivity and dynamic range are limited by the value of the feedback signal determined by Rayleigh scattering. In this case, the making of distributed sensor systems requires promising OFs with a returned signal significantly exceeding the Rayleigh backscattering signal [3, 4]. Usually, fibre Bragg gratings (FBGs) are used to increase it. Their writing, as a rule, is carried out step by step, and consists of such stages as removing the coating, writing the grating, restoring the coating and moving to the next section of the OF followed by the repetition of the whole procedure [5, 6]. This writing method leads to a significant increase in the feedback signal, but at the same time to a decrease in the mechanical strength of the FBG array. This significantly reduces the application area of such FBG arrays. In addition, the number of FBGs in such an array is limited. There is also a method for femtosecond writing of FBG arrays [7], the advantage of which is the possibility of writing through an OF coating (both polymer and polyamide). The disadvantages of this method include some deterioration in the strength of the OF with FBGs when writing an array, as well as a limited number of FBGs in the array, as in the previous method.

There is an alternative solution, namely, writing the FBG array directly in the process of OF drawing [8–12]. The formation of an FBG array in such an OF is implemented by exposure to UV laser radiation through a phase mask. The number of FBGs per 100 meters of such OF can reach 10 000, and the length of samples can reach 1 km. The increase in the return signal compared to the Rayleigh scattering signal is approximately 50 dB at λ = 1550 nm. A typical reflection spectrum width of an FBG array is 0.3 nm [11]. Previously, OF with an aluminum coating, capable of operating at temperatures up to 500 °C, was demonstrated [12]. An FBG array was also written in a multi-core OF during the drawing process [11], which is necessary for spatial bending sensors [13, 14].

Optical fibres with an FBG array are usually used at ambient temperatures, which can vary widely (from –60 °C to 125 °C). This can lead to a shift up to 2 nm in the wavelength of the maximum reflection coefficient of the FBG array. For this reason, expanding the reflection spectrum of the FBG array is an urgent task, which is also necessary for the possibility of working with optical sources of coherent reflectometers emitting at different wavelengths in the C-band. The simplest solution to this problem is to use chirped phase masks for writing FBG arrays.

An option of fabricating an extended chirped reflector can be to record an array of FBGs in a tapered waveguide. It is known, that the wavelength corresponding to the maximum of the FBG reflection coefficient is $\lambda = n_{\mathrm{eff}}\Lambda_{\mathrm{pm}}$ [15], where Λ_{pm} is the phase mask period, n_{eff} is the effective refractive index. Changing the diameter of the OF leads to a change in the effective refractive index and, in turn, the wavelength of the maximum reflection coefficient of the FBG written in such an OF. In this case, the length of the tapered section is determined by the length of the drawn OF, that is, it can reach several kilometres, and the coefficient of the OF tapering can reach 18 [16]. Thus, the writing of FBG arrays in a tapered OF should lead to an extension of the spectrum of reflection of the array from different sections of the tapered waveguide. In addition, the ability of such a tapered fibre to reflect the signal in different regions of the optical fibre can be used to

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create optical processors for processing complex signals (for multiplexing and demultiplexing) [17].

A separate, extremely interesting field of application of such arrays is the development of resonators for the so-called random lasers [18–21]. In such lasers, the amplification of radiation is achieved due to Raman scattering or SBS, and Rayleigh scattering provides the feedback. However, due to the low level of the return signal of a standard single-mode SMF-28 telecommunication OF, the typical cavity length of such a laser can be as large as 25 km [22]. An increased level of the return signal of the FBG array allows reducing the cavity length to 100 m [18, 19]. In this case, single-frequency lasing with the radiation spectral width smaller than 10 kHz at $\lambda = 1550$ nm can be observed [19]. In addition, it is known that in the OF with FBGs, a photon localisation effect was observed [23, 24], which is interesting because it allows implementing strong and broadband reflection distributed along the length of the laser cavity. For this reason, the use of FBG arrays written in active OF is extremely promising for producing narrow-band laser sources.

In this work, we consider the manufacturing technology and the possibility of using OF with a large array of FBGs written directly during the drawing of the OF for a number of practical applications. Thus, for coherent reflectometry systems the increased return signal obtained in such OFs allows increasing the sensitivity and dynamic range. The manufactured active OF doped with Er^{3+} ions with an FBG array was used for a cavity of a random laser operating in a single-frequency continuous-wave regime. The possibility of expanding the reflected signal spectrum by using chirped phase masks and (or) the OF taping during it drawing is demonstrated.

2. Materials and methods

During the experiments, the setup schematically shown in Fig. 1 was used to write FBG arrays. A writing system for Bragg gratings is installed on the tower for drawing fibres (in the part preceding the polymer coating area). The radiation source at a wavelength of 248 nm is a standard Optosystems CL-5100 excimer UV laser. The pulse energy density is 400 mJ cm^{-2} with a pulse duration of 10 ns. Both ordinary (Λ = 1070 nm) and chirped phase masks manufactured by Ibsen Photonics with a base length of ~10 mm were used. Typical drawing speed was ~10 m min^{-1}. In our experiments, we used both photosensitive silicate preforms (with a core doped with $B_2O_3 + GeO_2$), and ordinary single-mode germanosilicate preforms (for drawing the SMF-28 OF), and even active fibre preforms. The concentration of GeO_2 and B_2O_3 in photosensitive preforms was 20 mol.% and 1.5 mol.%, respectively. The difference between the refractive indices of the core and the cladding is ~0.025, the cut-off wavelength is 1350 nm, and the diameter of the OF core is 6 μm. The waveguide parameters of single-mode low-doped germanosilicate preforms correspond to the G.652 specification.

To write FBG arrays in the active OF, a fibre with the core doped with erbium ions was used. The absorption coefficient at a wavelength of 976 nm was 12 dB. The difference between the refractive indices of the core and the cladding was 0.0045, and the cut-off wavelength was 1.06 μm.

The parameters of the obtained optical fibre with an FBG array were measured using both the frequency reflectometry (OFDR) method [25] with the Luna 4400 instrument and the spectral method using the Yokogawa AQ6370D optical spectrum analyser. The radiation source for spectral tests was a superluminescent diode with a fibre output or a halogen lamp.

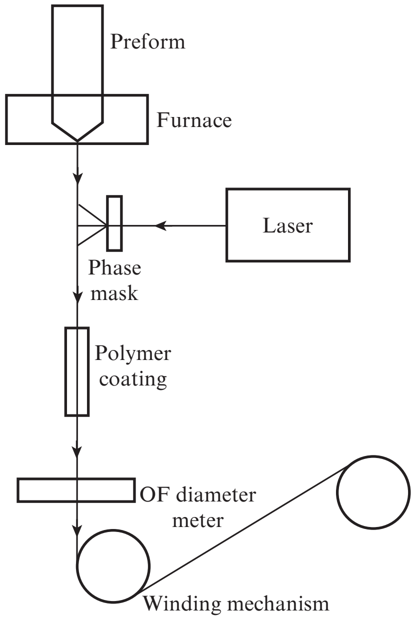

Figure 1. Schematic of the setup for writing FBG arrays.

3. Experimental results and discussion

The use of FBG arrays in coherent reflectometry systems requires good compatibility with existing measurement lines. In particular, welding two OFs (with and without an FBG array) must introduce minimal optical losses. For this reason, one of the main tasks was the drawing of a single-mode fibre with an FBG array from a preform for a standard single-mode fibre of SMF-28 type. The frequency reflectogram of a single-mode sample of SMF-28 type with an FBG array written during the drawing of the sample is shown in Fig. 2. The writing contrast (the excess of the return signal level over the level of the Rayleigh scattering signal) in such an optical waveguide array reaches 30 dB at a wavelength of 1546.3 nm. Such a fibre can be easily integrated into existing coherent reflectometry measuring systems [26], and the increased scat-

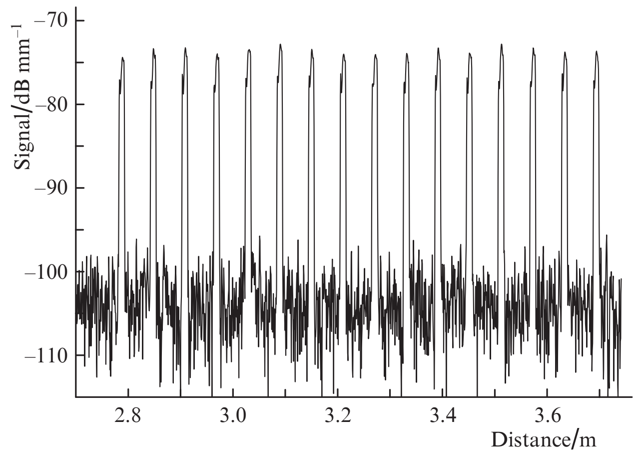

Figure 2. Frequency reflectogram of the SMF-28 OF with an FBG array written during its drawing with a step of 6 cm.

tering signal from the array of gratings provides high spatial resolution and fast operation of the measurement system by minimising the signal accumulation time. The width of the reflection peak in such an OF is ~0.3 nm.

However, as noted above, for the system to operate in a wide temperature range, it is necessary to expand the reflection peak at least to 2 nm. For this purpose, an FBG array was written using a chirped phase mask with a chirp of 3 nm cm^{-1}. Figure 3 shows the frequency reflectograms of samples with filling of 100% and 50%. Some nonuniformity of the reflection coefficient of the gratings in the FBG array is explained by the inhomogeneity of the radiation beam from the excimer laser, as well as some instability of its output power.

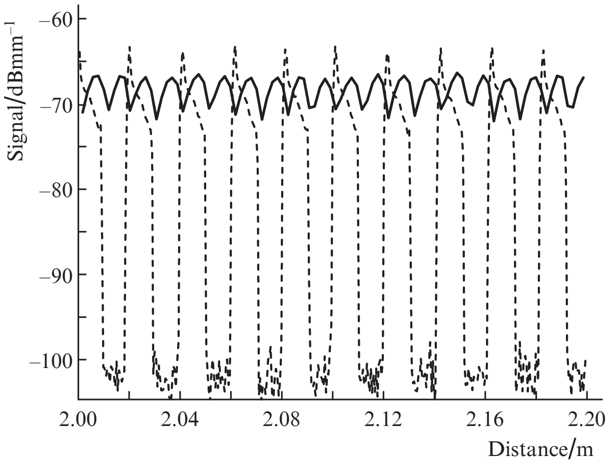

Figure 3. Frequency reflectogram of FBG arrays with fillings of (solid curve) 100% and (dashed curve) 50%.

Since the use of a chirped phase mask in comparison with a phase mask with a constant period leads, ceteris paribus, to a decrease in the reflection coefficient of the array by about 10 times, a special photosensitive preform with an increased germanium content in the core, additionally doped with boron oxide, was used to record the FBG arrays. This even allowed increasing the overall reflection coefficient by about an order of magnitude, despite the use of a chirped mask. The reflection spectrum of a single grating is shown in Fig. 4. Its width reaches 4 nm, which allows using the grating when the temperature changes in the range up to 350 °C (taking into account the OF temperature coefficient 0.011 nm $°C^{-1}$), in particular, for creating special monitoring systems operating in a wide temperature range (security systems, oil industry, technological monitoring, etc.).

The excess of the magnitude of the return signal over the magnitude of the Rayleigh scattering signal reaches 10^5, which is not always necessary. Thus, e.g., when designing extended monitoring systems, it is necessary to ensure scanning of the entire length of the sensor section of the fibre, which can be difficult with a large reflection coefficient of the FBG array. For this reason, it becomes necessary to control the integral reflection coefficient. One of the ways of such control is to change the writing density from 100% (complete filling of the entire surface of the OF with the array) to 50%, 20%, 1% or less. Such a change in the writing density leads to a proportional decrease in the reflection coefficient of the FBG array, which makes it possible to control this parameter

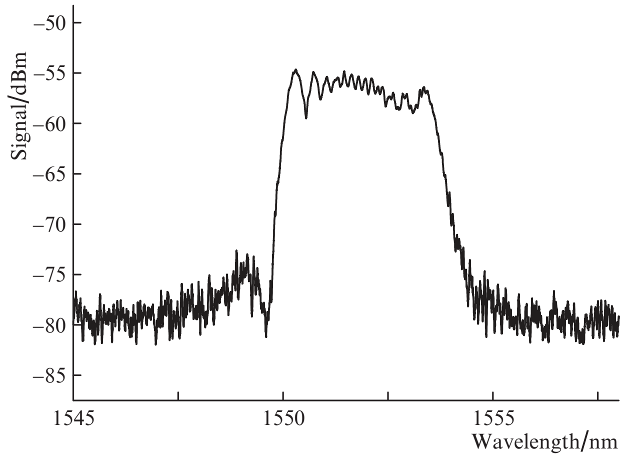

Figure 4. Reflection spectrum of a single FBG in the array.

over a wide range. In this case, there is no need to change the configuration of the writing module for Bragg gratings, the photosensitivity of the preform, etc.

Recall that the contrast of the writing of the gratings during the drawing of a fibre waveguide can reach 30 dB or more. As noted above, the presence of FBG leads to the localisation of photons [23, 24]. For this reason, it is of interest to use FBG arrays (written in OFs doped with ions of rare-earth materials, in particular Er^{3+}) as a random laser cavity. We wrote FBG arrays in the process of drawing in the OF doped with Er^{3+} ions. The cavity of a random laser is formed based on reflecting centres, the unphased Bragg gratings. Due to the large number of gratings in the resonator, a high uniformity of distribution of the reflecting centres in it is ensured, and an increased reflection coefficient allows the formation of positive feedback in the random laser in a relatively short portion of the active fibre. Figure 5 shows the frequency reflectogram of an FBG array measured at a wavelength of 1547.6 nm. A 5 m long FBG array written in an Er^{3+} doped OF was used as a cavity for the random laser. The laser was pumped by a Gooch and Housego laser diode at a wavelength of 976 nm (line width less than 1 MHz). Continuous-wave narrow-band lasing was obtained (Fig. 6). The threshold power of the laser pump radiation was ~100 mW.

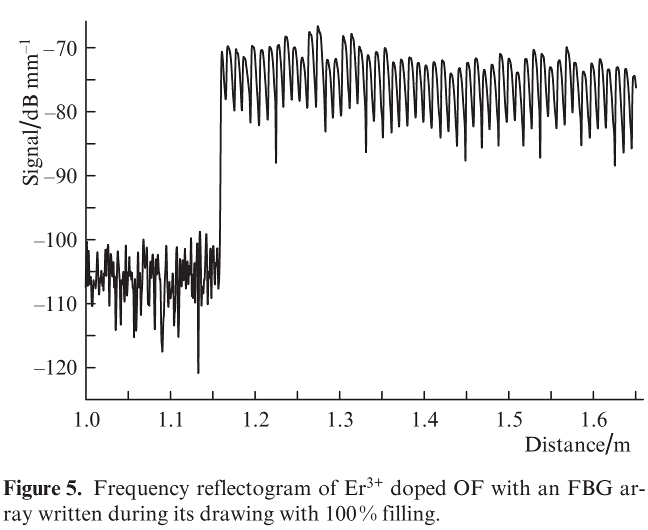

Figure 5. Frequency reflectogram of Er^{3+} doped OF with an FBG array written during its drawing with 100% filling.

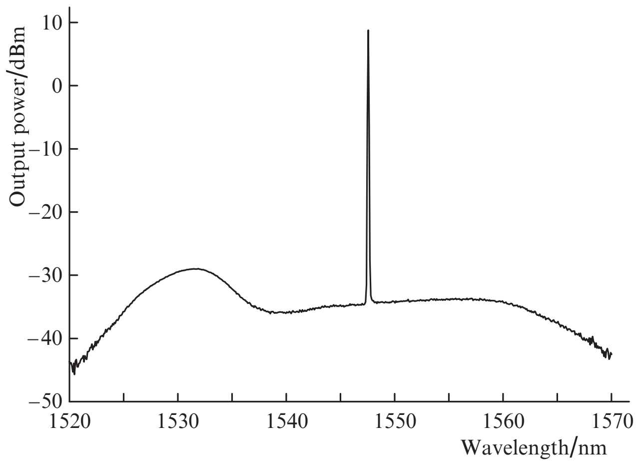

Figure 6. Output spectrum of a random OF laser with an FBG array for the pump radiation power of 350 mW at λ = 976 nm.

As noted above, one of the options for expanding the reflection spectrum of an FBG array is to record FBG arrays in a tapered OF. Samples of tapered fibres were manufactured by controlling the drawing speed, which leads to a smooth change in the diameter of the OF and, in turn, to a change in the effective refractive index of the OF. Two samples of tapered OFs with an FBG array were drawn from the photosensitive preform. In this case, the OF diameter varied from 80 to 125 μm (sample No. 1) and from 125 to 230 μm (sample No. 2). Figure 7 shows the profiles of the change in the diameter and wavelength of the maximum reflection coefficient of the array of FBG samples with a change in the OF length. One can see a complete correlation between the fibre diameter and the Bragg reflection wavelength, the change of which in both samples reached 4 nm. The reflection coefficient of tapered OFs with an FBG array when measured by the spectral method at particular wavelengths was 5% – 6% [20, 21, 27].

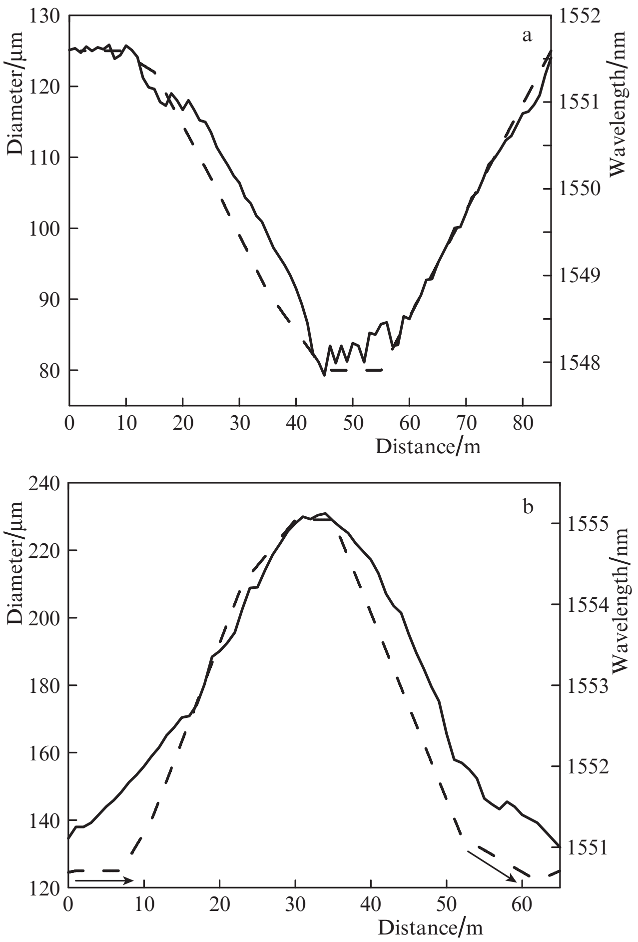

Figure 7. Change in the diameter of the OF along the tapered sample Nos (a) 1 and (b) 2 (dashed curves). The solid curve corresponds to the change in the wavelength of the maximum reflection coefficient of the FBG array.

4. Conclusions

Samples of OF with a return signal increased as a result of reflection of radiation from written FBG arrays were manufactured. In particular, a single-mode optical waveguide with an FBG array with a return signal exceeding the Rayleigh scattering signal by up to 30 dB at a wavelength of 1546.3 nm was obtained, which is necessary for coherent reflectometry systems. The use of a chirped phase mask makes it possible to increase the width of the reflection spectrum to 4 nm, which is important for practical use under the conditions of temperature changes and OF mechanical tension. Owing to the writing of FBG arrays in OFs 5 m long doped with Er^{3+} ions, continuous-wave narrow-band laser oscillation at a wavelength of 1547.6 nm with a threshold pump radiation power of ~100 mW at a wavelength of 976 nm was obtained. The writing of FBG arrays during the drawing procedure in a tapered waveguide allowed shifting the reflection spectrum along the axis of the waveguide in the range up to 4 nm.

The developed type of optical waveguide with an FBG array can be used as cavities for fibre lasers and amplifiers, in sensor systems with high spatial resolution and sensitivity, as well as in optical processors.

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