ISSN 1064-2269, Journal of Communications Technology and Electronics, 2016, Vol. 61, No. 6, pp. 639–645. © Pleiades Publishing, Inc., 2016.
Original Russian Text © I.A. Zaitsev, O.V. Butov, V.V. Voloshin, I.L. Vorob'ev, M.Yu. Vyatkin, A.O. Kolosovskii, S.M. Popov, Yu.K. Chamorovskii, 2016, published in Radiotekhnika i Elektronika, 2016, Vol. 61, No. 6, pp. 602–608.

Optical Fiber with Distributed Bragg-Type Reflector

I. A. Zaitsev, O. V. Butov, V. V. Voloshin, I. L. Vorob'ev, M. Yu. Vyatkin, A. O. Kolosovskii, S. M. Popov, and Yu. K. Chamorovskii

Kotel'nikov Institute of Radio Engineering and Electronics (Fryazino Branch), Russian Academy of Sciences, pl. Vvedenskogo 1, Fryazino, Moscow oblast, 141190 Russia

e-mail: sergei@popov.eu.org

Received March 27, 2015

Abstract—Optical fiber (OF) with a relatively high level of the backward signal at a certain wavelength is developed and studied. An increase in the backward signal is reached due to the recording of multiple weak fiber Bragg gratings (FBGs) in the course of fiber pulling. A scheme that is simpler than the direct FBG recording through a phase mask is proposed and implemented. Fibers with FBG recorded with different ratios of the region with recorded gratings to the total length of OF are fabricated. An increase in the level of the backward signal relative to the level of the Rayleigh scattering by more than 30 dB is reached. Results of experimental study of the proposed OFs and examples of practical application are presented.

DOI: 10.1134/S106422691606022X

INTRODUCTION

The construction of new systems for fiber-optic monitoring of various objects necessitates the development of new types of optical fibers (OFs) for an increase in the quality of such systems. A promising approach involves the application of sensors based on fiber Bragg gratings (FBGs) [1, 2] and the development of systems for distributed (with respect to length) monitoring based on coherent methods for signal detection using the Rayleigh scattering [3, 4]. The development of such systems is impeded by a relatively low level of the desired signal: the Rayleigh scattering at a wavelength of 1550 nm is about –82 dB of the level of the propagating signal for a pulse with a duration of 1 ns. The application of FBGs for distributed monitoring [5–7] involves the application of spectral and spatial multiplexing. The corresponding problems are related to a limited number of the measured points upon spectral division of channels and difficulties of the recording of large FBG arrays over the fiber length.

Optical fibers with distributed FBGs are also interesting for the development of random type fiber lasers [8, 9].

Several methods can be used for fabrication of FBG arrays. The step-by-step recording of FBGs employs the removal of protecting coating at a fragment of fiber, recording of grating, and protection of grating using specific coating [10]. Such a method for the fabrication of the FBG arrays is technologically simple but a disadvantage is related to the fact that the removal of the OF protecting coating leads to a significant decrease in the OF mechanical strength. The method for the fabrication of the FBG array in the course of the OF pulling is free of such a disadvantage. The recording of FBG with the aid of a single UV laser pulse has been demonstrated in [11]. Such a technology makes it possible to produce FBG arrays in the course of OF pulling: a UV laser and interferometer that produces interference fringes on the OF have been used in [12] for the FBG recording. A variation in the period of the interference fringes has been reached in [13] using the tuning of the interferometer mirrors. Such an approach allows the recording of the FBG array with the resonance wavelength of the Bragg reflection that is varied over the OF length. Precise mechanical tuning of components is needed in the systems based on interferometers. In addition, relatively high time coherence of the UV laser is needed in the above systems.

We have substantially simplified the technology for FBG recording in the course of the OF pulling using a conventional method for the recording of gratings with the aid of a UV laser and a phase mask. Relatively large FBG arrays (up to 10 000 units per single OF) have been recorded in OFs. Note that the number of FBGs can be increased and the distance between gratings and the reflection spectrum depend on the parameters of pulling regime and generation of excimer laser. Note also that the proposed technology allows a variation in the resonance wavelength of FBG over the OF length due to variations in parameters of the pulling regime and OF that can be taken into account in preforms. In addition, the method makes it possible to record gratings with specific profiles of reflection spectra (e.g., chirped gratings [14]). In this work, we use the arrays of gratings that are recorded with the aid of the above procedure as sensors for systems of distributed measurements of temperature and mechanical deformations.

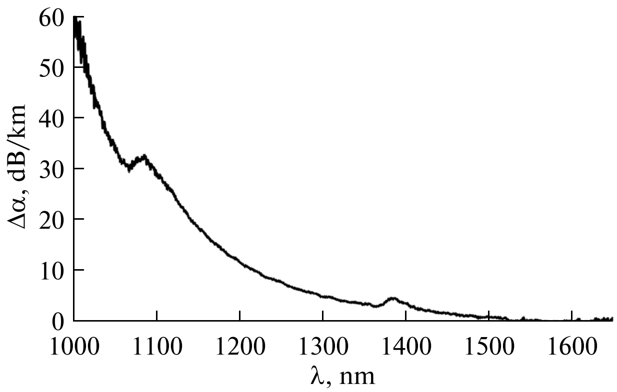

Fig. 1. Typical spectral dependence of the difference between losses in the OF sample that is irradiated using a UV laser in the course of pulling and unirradiated OF sample.

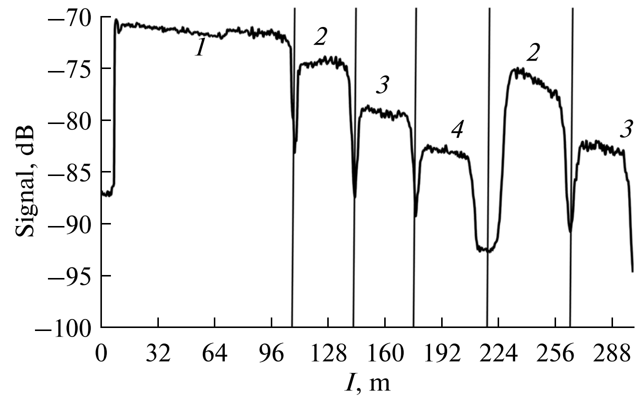

Fig. 2. Reflectogram of the OF with gratings that are recorded at UV laser pulse repetition rates of (*1*) 9, (*2*) 5, (*3*) 2, and (*4*) 1 Hz using a Luna 4600 reflectometer (OFDR) at a wavelength of λ = 1552 nm.

EXPERIMENTAL RESULTS AND DISCUSSION

FBGs are recorded at the Institute of Radio Engineering and Electronics using a setup for pulling of specific OFs. The conventional elements of the setup are supplemented with a CL-5100 excimer laser with a radiation wavelength of 248 nm that is placed in the vicinity of the pulled fiber. The laser radiation is focused by a lens system through a phase mask with a period of 1070 nm directly on the OF in front of the spinneret with protecting coating. The parameters of the pulling regime (pulling rate, temperature in the high-temperature oven, and OF tension) and laser (pulse repetition rate and mean energy of laser pulse) can be varied in the course of pulling and FBG recording. Signal decay, reflection coefficient, and widths of reflection spectra of a single FBG and FBG array are the main parameters that must be taken into account in the construction of the monitoring system based on the proposed OFs. Thus, we choose the corresponding parameters of the optical system and the regimes of FBG recording in the course of the OF pulling. In the experiments, single-mode OFs are pulled from preforms with germanium-silicate core and a numerical aperture of NA ~ 0.27.

A significant increase in the decay in the short-wavelength spectral region due to the formation of defects in the core glass can be expected upon FBG recording owing to high-power UV-laser irradiation. The experimental results prove such an expectation (Fig. 1). Note the absence of a noticeable increase in the decay in the spectral region of the recording (1550 nm). The peak related to the recorded FBGs is not observed in Fig. 1, since the resolution of the spectrum analyzer (2 nm) is significantly greater than the width of the FBG reflection spectrum and the total reflection of the recorded gratings is relatively low on the plot scale.

Figure 2 shows the distribution of the backward signal over the length of the 300-m-long OF. Note that the FBGs at different OF fragments are recorded under different regimes of the excimer laser (pulse repetition rate) and OF tension upon pulling (the last two FBG series are pulled at a higher OF tension). Six FBG arrays are recorded on the OF with relatively short intervals between the arrays. A Luna 4600 optical frequency-domain reflectometer (OFDR) is used for the measurements. Note that the FBG reflection is spectrally selective, so that the backward reflection depends on the spectrum of the signal source. The analysis of Fig. 2 shows that the maximum increase in the backward signal related to the FBG is about 17 dB relative to the level of Rayleigh scattering. The pulse repetition rates for the FBG arrays are 1, 2, 5, and 9 Hz, respectively. Thus, the on–off ratio upon the FBG recording in the arrays and the levels of the backward signal are different. Figure 2 also shows that a gradual decrease in the repetition rate of the excimer laser in the first four series leads to a proportional decrease in the measured backward signal. This result is due to the fact that a relatively large number of FBGs corresponds to the spatial resolution of the device. Hence, the desired backward signal is proportional to the spatial density of FBGs that is determined by the repetition rate of the UV-laser pulses. The first array with a length of 100 m contains about 9000 FBGs. However, even such a number of the FBGs in the array does not cause significant loss of the desired signal (Fig. 2). At a higher spatial resolution of the reflectometer, an increase in the desired signal relative to the Rayleigh scattering is 30 dB (Fig. 3). Relatively high spatial resolution of the reflectometer makes it possible to observe the structure of reflection of each grating. The nonuniformity of the reflection coefficient with respect to the length of grating is presumably due to the spatial nonuniformity of the UV-laser beam.

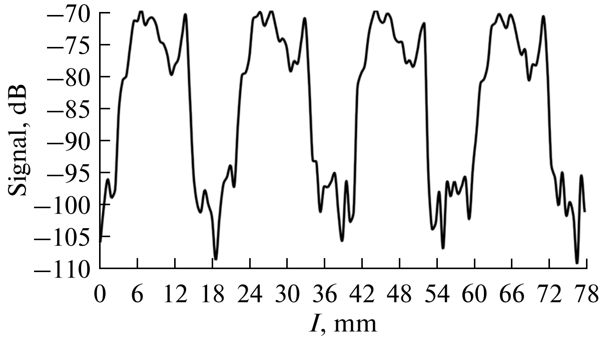

Fig. 3. Reflectogram of the OF with four gratings that are recorded at a pulse repetition rate of 5 Hz and tension of 60 g using a Luna 4600 reflectometer (OFDR) at a wavelength of λ = 1550.8 nm.

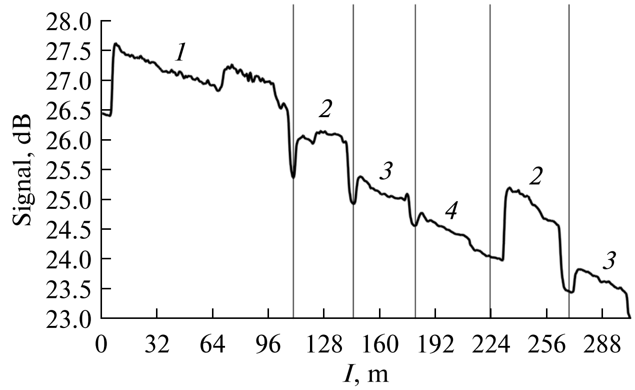

Fig. 4. Reflectogram of the OF with gratings that are recorded at UV laser pulse repetition rates of (*1*) 9, (*2*) 5, (*3*) 2, and (*4*) 1 Hz using an Anritsu MW9076 reflectometer (OTDR).

For comparison, Figure 4 presents the reflectogram that is measured on the same fragment of OF using a conventional incoherent reflectometer (Anritsu MV9076B optical time-domain reflectometer (OTDR)). The contrast of the reflectograms of OFs with FBGs that are recorded using the OFDR method is higher than the contrast of the measurements using the OTDR method (Figs. 2, 4). This result is due to the greater width of the spectrum of the OTDR source (the band at a level of 10 dB is about 1540–1556 nm). Only a part of a relatively wide spectrum of the OTDR source is reflected by the grating. A narrow-band tunable laser is employed in the OFDR measurements, and the spectral width of the laser line is less than the width of the reflection spectrum of gratings. Thus, a significantly higher contrast of reflectograms can be obtained (Figs. 2, 3). When a narrow-band source is used in OTDR (the spectral width is no greater than the bandwidth of FBG in OF), the contrast of reflectograms is also high.

Figure 5 presents a typical reflection spectrum of the FBG array in OF. It is seen that the bandwidth of the FBG arrays is about 0.2 nm at a level of 50%. Figure 6 shows the scheme for the measurement of reflection spectrum. The broadband radiation of a superluminescent diode (SLD) is delivered to the OF via a directional fiber coupler. The second end of the coupler is interfaced with the optical spectrum analyzer. The comparison of the reflection spectra (Fig. 5) measured for two ends of the OF (perpendicularly cleaved OF end with a reflectance of 3.6% and obliquely cleaved OF with a reflectance of less than −65 dB) makes it possible to estimate the integral reflectance at the resonance wavelength of the FBG array: the reflectance is −23.5 dB (about 0.45%) for the array of 600 FBGs.

An important feature of the OF with a relatively large number of reflectors is the presence of rereflections and superposition of signals from reflectors. The results of [15] show that the transmission coefficient of

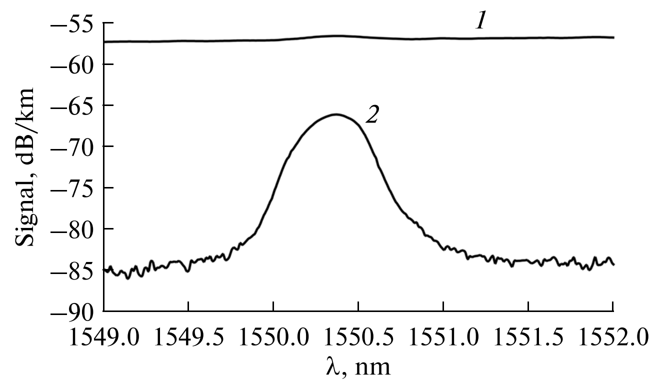

Fig. 5. Reflection spectra of the array of 600 FBGs that are measured for (*1*) perpendicularly cleaved OF end with a reflectance of 3.6% and (*2*) obliquely cleaved OF with a reflectance of less than −65 dB.

an array of N gratings each of which has transmittance t is t^N with allowance for the rereflection effects. Therefore, a reflection coefficient of −23.5 dB for the array of 600 FBGs corresponds to a reflection coefficient of −51 dB for a single grating.

We also measured the reflection spectrum for ten FBGs using OFDR (Fig. 7). The comparison of Figs. 5 and 7 shows that the reflection spectra are in good agreement within experimental accuracy. This

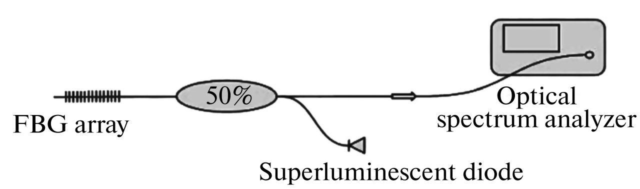

Fig. 6. Scheme for the measurement of the reflection spectrum of FBG array using a spectrum analyzer.

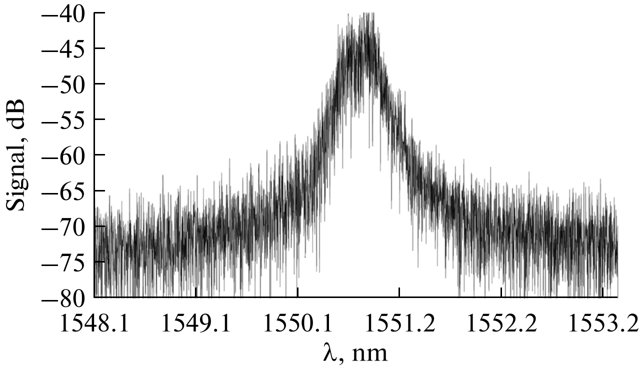

Fig. 7. Spectral dependence of the signal reflected from the OF fragment with ten FBGs (the OF is pulled at tension of 60 g).

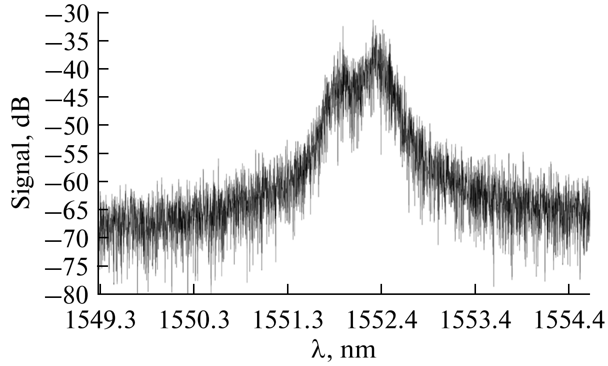

Fig. 8. Spectral dependence of the signal reflected from the OF with FBGs (the OF is pulled at tension of 30 g).

result indicates relatively high uniformity of the recorded gratings under real pulling conditions.

Figure 8 shows the reflection spectrum that is measured for ten gratings of OF produced under different pulling conditions (tension of 30 g). We observe a significant shift of the central wavelength of FBG relative to the reflection spectrum of gratings that are produced at a tension of 60 g (Fig. 7). The FBG reflection spectrum also shifts by several nanometers for OFs with different refractive indices of the fundamental mode that are pulled from preforms with different profiles of refractive index. Such a result is in agreement with the condition for the Bragg reflection

$$\lambda_B = 2(n + \Delta/2)\Lambda, \tag{1}$$

where λ_B is the working wavelength of the grating (nm), n is the effective refractive index of the fundamental mode of OF, Δ is an increase in the refractive index due to UV irradiation, and Λ is the period of grating.

OFs with FBG arrays can be used in distributed fiber-optic sensors (FOSs). The following experiments illustrate implementation of a sensor based on OF with FBG arrays.

Tensile stress is exerted on a fragment of OF with FBG array. Reflectograms that are measured with the aid of conventional OTDR as well as variations in the reflection spectrum measured with the aid of optical spectrum analyzer and superluminescent diode laser depend on the external stress (Fig. 6). The integral reflection coefficient of the FBG array for the radiation source with the known spectral dependence is given by

$$R_S = \frac{\int_{-\infty}^{+\infty} S(\lambda) R(\lambda - \lambda_B^m) dx}{\int_{-\infty}^{+\infty} S(\lambda) d\lambda}, \tag{2}$$

where $S(\lambda)$ is the power spectral density of the radiation source and $R(\lambda - \lambda_B^m)$ is the reflection spectrum of the array of gratings with resonance wavelength of Bragg reflection λ_B^m.

The FBG resonance wavelength depends on temperature and tensile stress. Figure 9 presents the reflection spectra of the FBG array measured under different tensile stresses. It is seen that the shift of the central length of the FBG array is proportional to the OF tension. Figure 10 shows the OTDR reflectograms of the FBG array under different OF tensions. The curves correspond to an OF fragment with an FBG array with a length of 13 m inside a conventional telecommunication fiber. Tensile stress ranging from 1.2 to 9.5 N is exerted on a fragment of the telecommunication fiber with a length of 1.5 m. An increase in the reflected signal at the OF fragment 10–23 m corresponds to the FBG array. The tension of the OF fragment at a distance of 13.5 m leads to the aforementioned shift of the resonance wavelength of the FBG array, which results in the observed variation in the reflected signal. Figure 11 shows that the power spectral density of the OTDR source decreases with increasing wavelength in the range of variation in the reflection spectrum of the FBG array. This result makes it possible to interpret the dip in Fig. 10 that is caused by tension of the OF with FBG.

In the next experiment, a tensile stress of 5 N is exerted on two fragments of the OF under study. The length of each fragment is 1 m, and the distance between fragments is 4 m. The backward reflection signal is detected using the OTDR (Fig. 12). The positions of dips on the reflectogram correspond to the fragments on which the tensile stress is exerted.

The results show that the OF with FBGs may serve as an array of fiber sensors. The interrogation of sensors in the experiments is implemented with the aid of the OTDR reflectometry. The wavelength dependence of the power spectral density of the OTDR source is

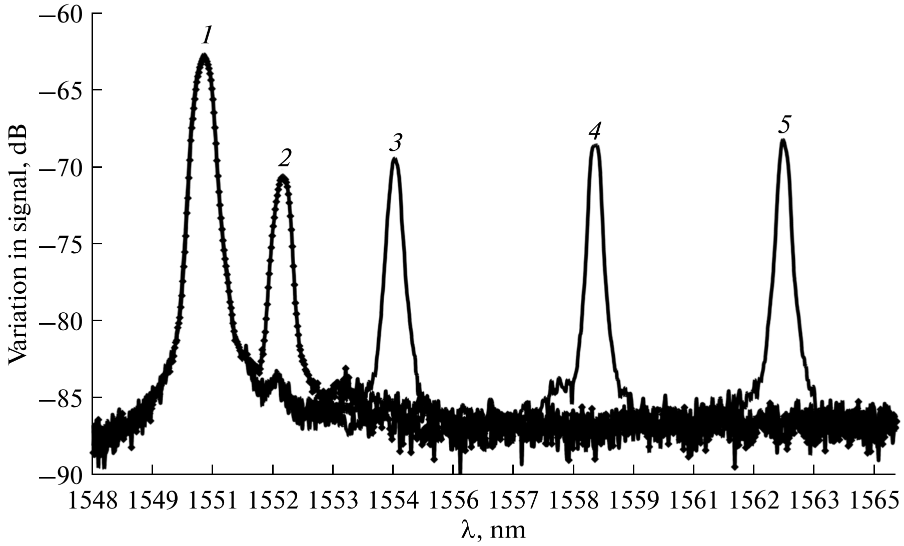

Fig. 9. Reflection spectra of the OF fragment with FBG array measured (*1*) in the absence of load and in the presence of tensile stress of (*2*) 1.25, (*3*) 3.1, (*4*) 6.42, and (*5*) 9.5 N.

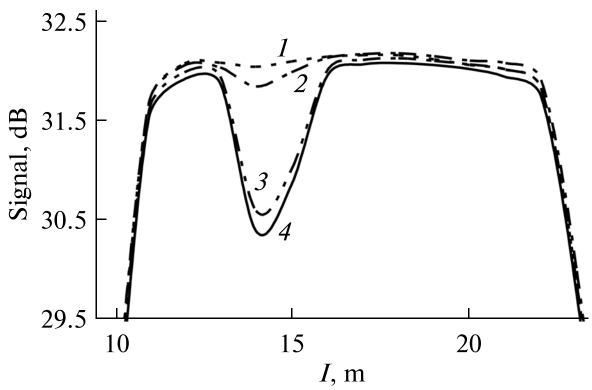

Fig. 10. Reflectograms of the OF with gratings in the presence of tensile stresses of (*1*) 1.25, (*2*) 3.1, (*3*) 6.42, and (*4*) 9.5 N exerted on control fragment (the measurements are performed using an Anritsu MW9076 reflectometer (OTDR)).

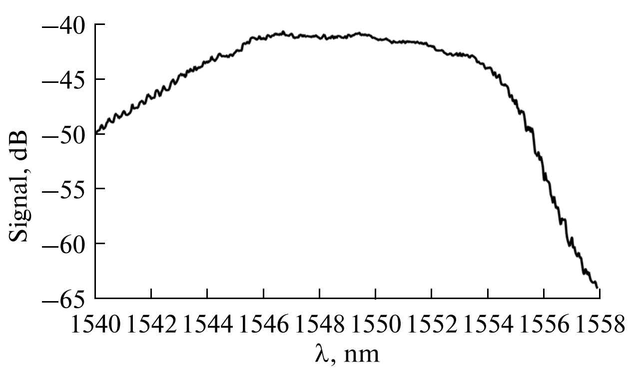

Fig. 11. Spectrum of radiation of incoherent optical reflectometer (Anritsu MW9076 reflectometer (OTDR)).

important for the application of such an approach. On the assumption of the linear dependence of the power spectral density on wavelength, the slope of the dependence determines the sensitivity of the system and the spectral width determines the measurement interval. Note the absence of specific requirements on the shape and stability of the spectrum of source in the presence of variations in external parameters (e.g., temperature) in conventional OTDRs. Therefore, radiation sources with predetermined and stabilized spectral shape must be used in OTDRs in the systems for distributed measurements of temperature and tension.

The application of OFDR makes it possible to substantially improve the spatial resolution and measurement accuracy. In the next experiment, a tensile stress of 9.5 N is exerted on the fragment of OF with FBG

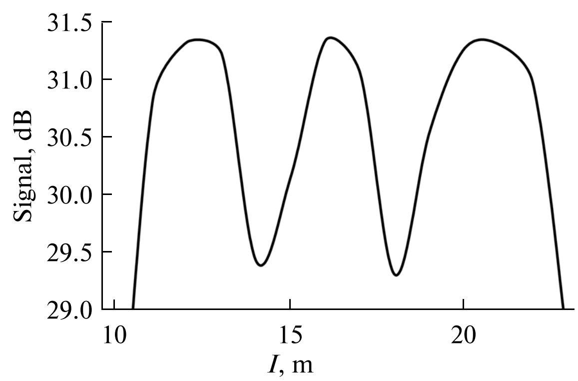

Fig. 12. Reflectogram of the OF with gratings in the presence of a load of 5 N that is applied to two fragments of the fiber (the measurements are performed using an Anritsu MW9076 reflectometer (OTDR)).

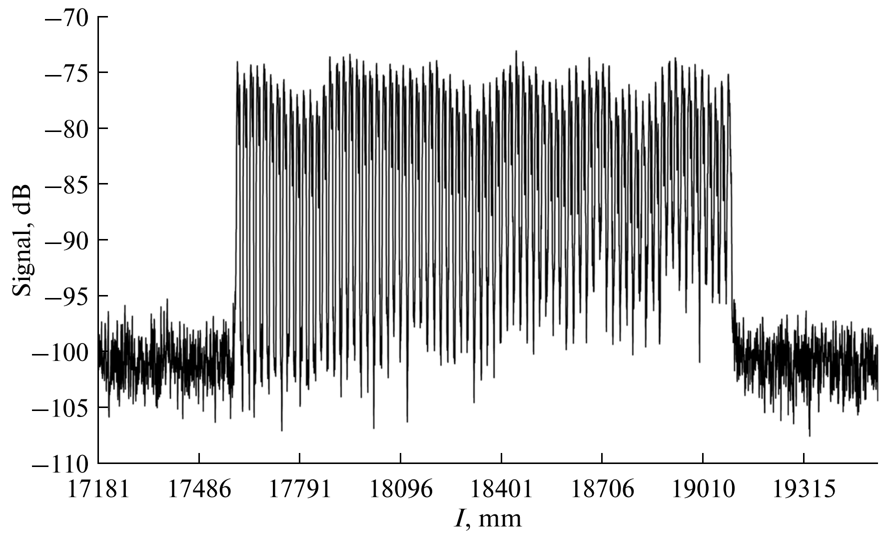

Fig. 13. Reflectogram that is measured with the aid of a Luna 4600 OFDR in the presence of a tensile stress of 9.5 N that is exerted on a fiber fragment with a length of 148.6 cm.

with a length of 1.5 m. The reflectometer allows high-accuracy measurement of the position and length of extended fragment, and the shift of the wavelength of the FBG resonant reflection can be used to determine the extension. A narrow-band tunable laser is used in OFDR. We choose the central wavelength of laser and the wavelength tuning interval in such a way that only FBGs with the shifted (due to mechanical load) reflection spectrum correspond to the scanning interval. Thus, we obtain the reflectogram of Fig. 13. Reflectogram ripple is due to a relatively high spatial resolution that makes it possible to observe single FBGs. The source of the reflectometer is tuned to a wavelength of 1563.15 nm that coincides with the resonance of the FBG under stress. The Bragg wavelength of the FBGs at the OF fragment that is free of tension is outside the scanning interval of the tunable source of OFDR. This circumstance accounts for the difference of signals from different OF fragments. Only the signal of Rayleigh scattering corresponds to the tension-free fragments.

In the measurements of the mechanical sensitivity of the OF with FBGs, the shift of the resonance wavelength of the Bragg reflection in the presence of tension is 0.013 nm/g at a wavelength of 1.55 μm.

CONCLUSIONS

We have proposed and implemented a technological procedure for FBG recording in the course of the OF pulling using phase masks that may serve as an alternative to the existing interferometric scheme.

The application of masks significantly simplifies the technological process and makes it possible to record FBGs with complicated structure of gratings (e.g., chirped FBGs). The measured increase in the backward signal in comparison with the level of the Rayleigh scattering is greater than 30 dB at a wavelength of 1550 nm. Note a substantially lower increase in the general level of radiation decay due to relatively narrow directional pattern of the reflected signal that strongly differs from almost uniform directional pattern of the Rayleigh signal. A variation in the central wavelength of FBG over the OF length can be reached using the same mask due to variations in the pulling parameters (temperature and tension) and/or variations in the OF parameters (e.g., tapering or application of the OF preforms that are inhomogeneous with respect to length). We have measured the main characteristics of the OFs with more than 9000 FBGs distributed over a 100-m-long OF fragment (the on–off ratio of the gratings is higher than 90%). The practical application of the OFs under study in modern systems for distributed monitoring of temperature and mechanical deformations is considered.

ACKNOWLEDGMENTS

This work was supported by the Russian Foundation for Basic Research (project no. 14-29-08195).

REFERENCES

1. Yun-Jiang Rao, Meas. Sci. Technol. **8**, 355 (1997).
2. S. C. Tjin, Y. Wang, X. Sun, et al., Meas. Technol. **13**, 583 (2002).

3. R. Juskaitis, A. M. Mamedov, V. T. Potapov, and S. V. Shatalin, Opt. Lett. **19**, 225 (1994).
4. S. V. Shatalin, V. N. Treschikov, and A. J. Rogers, Appl. Opt. **37**, 5600 (1998).
5. M. Froggatt and J. Moore, Appl. Opt. **37**, 1741 (1998).
6. B. A. Childers, M. E. Froggatt, S. G. Allison, et al., Proc. SPIE **4332**, 133–142 (2001).
7. J. Sancho, S. Chin, D. Barrera et. al., Opt. Express **21**, 7171 (2013).
8. S. K. Turitsyn, S. A. Babin, A. E. El-Taher, et al., Nature Photonics **4**, 231 (2010).
9. A. A. Fotiadi, Nature Photonics **4**, 204 (2010).
10. W. W. Morey, G. Meltz, and W. H. Glenn, Proc. SPIE **1169**, 98 (1990).
11. C. C. Askins, T. E. Tsai, and G. M. Williams, Opt. Lett. **17**, 833 (1992).
12. L. Dong, J.-L. Archabault, L. Reekie, et al., Electron. Lett. **29**, 1577 (1993).
13. C. G. Askins, M. A. Putnam, G. M. Williams, and E. J. Friebele, Opt. Lett. **19**, 147 (1994).
14. K. O. Hill and G. Meltz, J. Lightwave Tech. **15**, 1263 (1997).
15. Shapira O. and B. Fischer, J. Opt. Soc. Am. B **22**, 2542 (2005).

Translated by A. Chikishev