Line-by-line fiber Bragg grating fabrication by femtosecond laser radiation

A S Chernikov, K S Khorkov, D A Kochuev, R V Chkalov, V G Prokoshev and N N Davydov
Vladimir State University, 87 Gorky str., Vladimir 600000, Russia
E-mail: an4ny.che@gmail.com

Abstract
We report on the fabrication of second order and fourth order fiber Bragg gratings (FBGs) in standard single mode telecom fiber through the polymer coating made line-by-line technique using femtosecond laser radiation. Measurement of spectral characteristics were performed in the reflection mode of the input signal of tunable laser.

1. Introduction
Fiber Bragg gratings (FBGs) and long-period gratings (LPGs) are one of the most popular optical components have found wide application as sensing elements in sensor devices, as spectral filters in fibre lasers [1, 2], etc.

The interference lithography technique using a UV laser to create a periodic pattern within the core of a fiber is most prevailing way to fabricate FBGs. However, over the past decade much attention has been paid to femtosecond recording technology of FBGs. The technology is to modification the core material and, as a result, a local change of the refractive index by femtosecond laser radiation (pulse duration - $10^{-15}$ s). For such durations the change in material properties due to the processes of multiphoton absorption of laser radiation has nonlinear nature and makes it possible writing FBG in non-sensitive materials. Femtosecond laser technology using to write FBGs in optical fibers without the requirement of material photosensitivity and fabricate optical structures has high thermal stability. The main advantages of the femtosecond writing method is the ability to flexibly change the characteristics of the Bragg grating: the period length and respectively the spectral characteristics [3, 4]. When using infrared radiation, recording of FBGs can be made through the polymer coating of the fiber, and this in turn solves one of the drawbacks of the FBGs inscribed by UV laser radiation.

Femtosecond laser direct inscription technology can be divided into point-by-point technique and line-by-line technique. FBG inscribed using point-by-point technique is a set of separate points, in this case the period of the inscribed grating is given by changing the translation speed of the fiber, or by changing the pulse repetition rate. FBGs fabricated in a sapphire fiber by femtosecond laser radiation using point-by-point technique were demonstrated and they can operate up to 1400°C [5]. FBG inscribed using line-by-line technique is a set of parallel lines are written in the fiber core covering a distance defined by the length of the Bragg grating. Line-by-line technique is a less demanding on setting up the recording system as a whole, as compared with point-by-point recording, in which even small shifts in the position of optical fiber cause result in a pronounced asymmetry due to the small size of the modifiable region, which is unacceptable. Inscription of FBGs in a sapphire fiber by femtosecond laser using line-by-line technique was demonstrated and these FBGs can operate at
1612°C [6]. The main disadvantage of this technique is a rather long fabrication time, due to the fact that it is necessary to modify large areas in comparison with the point-by-point technique.

2. Experimental setup

In this work the source of laser radiation was femtosecond Yb:KGW-laser system (wavelength 1029 nm, pulse width 280 fs, pulse repetition rate of 10 kHz, pulse energy 180 μJ). As the focusing optics a high numeric aperture microobjective Mitutoyo Plan Apo NIR (100x, NA = 0.7) was used. Femtosecond laser radiation passing through the beam attenuation system is set up to the required value of pulse energy. The energy of the laser pulses was monitored using a highly sensitive photodetector. Further, the radiation passing the system of turning mirrors was reflected from a dichroic mirror and extends in the direction of the microobjective by which was focused in the region of a fiber core (sample). For position adjustment and moving of the sample during inscription high-precision 2-dimensional linear stage (Aerotech ANT130-110-XY Ultra) and motorized linear stage Standa 8MT167-25LS were used, flatness position of the sample was established by the tilt corrector system (Standa 8MKVDOM). For position adjustment of the focus area and visualization of the results were carried out with the aid of CCD-camera and backlight [7]. The experimental setup for inscription of FBG by femtosecond laser radiation presented in Figure 1.

![Experimental setup for inscription of FBG by femtosecond laser radiation](image)

Figure 1. Experimental setup for inscription of FBG by femtosecond laser radiation: 1 – Yb:KGW-laser system; 2 – beam attenuation system; 3, 4 – system of turning mirrors; 5 – dichroic mirror; 6 – focusing microobjective; 7 – tilt corrector system; 8 – X-Y-Z linear stage; 9 – sample; 10 – backlight; 11 – beam splitter; 12 – light filter; 13 – CCD-camera

FBGs in standard single mode telecom fiber Corning SMF-28e+ were fabricated without removing the polymer coating. The fiber is mounted on a three-axis translation stage in such a way that the desired FBG can be fabricated by translating the fiber regarding to the focused laser beam [8]. To overcome the fabrication limitation imposed by the intrinsic fiber geometry, the optical fiber was placed between slide and cover glass [3, 8], space between them filled with index-matching immersion liquid with a refractive index close to the refractive index of optical fiber so that the surface geometry presented to the path of the incident femtosecond laser beam is flat. Glycerin (C₃H₅(OH)₃) had been used as the immersion liquid, its refractive index is 1.4729. Schematic drawings of the processing area shown in Figure 2.
3. Results of FBG inscription

Several FBGs with different characteristics have been made using line-by-line technique. For inscription of FBGs the following parameters were selected: velocity during exposure to laser radiation $V_1 = 80 \, \mu m/s$, velocity without exposure laser radiation $V_2 = 400 \, \mu m/s$, pulse energy 150 nJ. Schematic image of the formation path of FBG and images of the FBGs shown in Figure 3.

Images of inscribed second order (period $\Lambda = 1.05 \, \mu m$) and fourth order (period $\Lambda = 2.14 \, \mu m$) FBGs is shown in Figure 4. Each inscribed line may be visualized as a cylinder with a diameter of ~800nm. In Figure 4, the modification area completely crosses of the fiber core (8.2 μm) that in turn fulfilled the necessary requirements.

Reflection spectra registration was performed with an optical interrogator module (OSI) NI PXIe-4844. The radiation of a tunable laser is introduced directly into the fiber in which the FBG is recorded. Measurement of spectral characteristics is performed in the reflection mode of the input signal, the wavelength range of 1510 nm to 1590 nm.
Figure 4. Images of inscribed FBGs: a, c – 2nd order FBG; b, d – 4th order FBG (c, d – perpendicular view)

Reflection spectrum of 2nd order FBG (period $\Lambda = 1.05 \, \mu m$, length of FBG $L = 2.1 \, mm$, grating period quantity $N = 2000$) is shown in Figure 5, period $\Lambda = 1.05 \, \mu m$, length of FBG $L = 2.1 \, mm$, grating period quantity $N = 2000$.

Figure 5 shows the presence of reflection peaks in the wavelength range 1518-1524 nm, at a previously theoretically calculated central Bragg wavelength at 1520 nm. It can be seen that the maximum reflection amplitude is 11 dB, the spectral width of an individual peak is about 1.2 nm. It is worth noting that due to the presence of several peaks, it is not possible to accurately determine the reflection coefficient of the FBG.
Figure 6 shows the reflection spectra of 4th order FBGs with a length of 4.28 mm (a) and 6.42 mm (b), period $\Lambda = 2.14 \, \mu m$, grating period quantity $N = 2000$ and 3000.

Figure 6 shows the presence of reflection peaks in the wavelength range 1546-1550 nm, at a previously theoretically calculated central Bragg wavelength at 1550 nm. The reflection spectrum of 4th order FBG with length 4.28 mm (Fig. 6, a) is distinguished from the reflection spectrum depicted above (Figure 5) much smaller peak amplitude. However, with increasing of grating period quantity the reflection amplitude of FBG has increased as shown in Fig. 5 (b). Also it should be noted that in each of the reflection spectra there was a set of pronounced peaks, which indicates the heterogeneity of the inscribed FBGs, this in turn can be associated with a number of factors. More specifically, the main factors here are instability of the energy of laser pulses, non-uniform displacement of the optical fiber, non-uniform modification of the medium along the z-axis.

Insufficient pulse-to-pulse energy stability leads to leads to the fact that even with slight change of the pulse energy, modification of the material by the action of laser radiation will be uneven. If the value of the pulse energy has decreased so much so that it has not reached the modification threshold value, then the changes in the medium will not occur at all, in this case, areas not subjected to modification may appear.

Non-uniform displacement of the optical fiber along the XY-axis during recording can have a significant impact on the quality of inscribed FBG. In this case, even small deviations from the specified motion parameters will lead to a violation of the period of the recorded FBG, and, consequently, the appearance of additional reflection peaks. This problem can be solved by calibrating high-precision linear stage, thereby eliminating the probability of error and inconsistency of the value of the displacement to the initially specified parameters.

Also, do not exclude the option of setting the position of the sample plane during recording. Even taking into account the fact that a tilt corrector system is used in the recording setup, this may not be enough to effect a uniform modification of the medium along the z coordinate over the entire length of FBG.

In light of the above we can conclude that to improve the quality of recorded FBGs necessary eliminate the negative impact of these factors, or to get rid of them completely, by improving the system using software or by equipping it with additional technical means.
4. Conclusion

The results of inscription of second order and fourth order FBGs in standard single mode telecom fiber through the polymer coating using a femtosecond laser line-by-line technique are presented. For inscription of FBGs the following parameters were selected: pulse energy 150 nJ, period for second order FBG $\Lambda = 1.05 \mu m$ (length 2.1 mm), period for fourth order FBGs $\Lambda = 2.14 \mu m$ (length 4.28 mm and 6.42 mm).

This work was performed as a part of the state task VLSU 3.5531.2017/8.9 GB-1106/17 and a grant of the RFBR number 16-08-01226.

References

[1] Hill K O, Fujii Y, Johnson D C and Kawasaki B S 1978 Applied physics letters 32
[2] Schaffer C B, Brodeur A and Mazur E 2001 Measurement Science Technology 12
[3] Dostovalov A V, Wolf A A and Babin S A. 2015 Quantum Electronics 45
[4] Vasil’ev S A, Medvedkov O I, Korolev I G et al. 2005 Quantum Electronics 35
[5] Yang S., Hu D., Wang A. 2017 Optics Letters, 42
[6] Xu X, He J, Liao C, Yang K et al. 2018 Optics Letters, 43
[7] Chkalov R, Khorkov K, Kochuev D et al. 2018 International Conferences WWW/Internet and Applied Computing, 395-399
[8] Chernikov A S, Khorkov K S, Kochuev D A and Chkalov R V 2017 INTERMATIC, International Scientific and Technical Conference, 176-179