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Laboratory setup for fiber Bragg gratings inscription based on Talbot interferometer

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Abstract An experimental setup for the fiber Bragg gratings (FBGs) inscription by use of Talbot interferometer has been described in this paper. A KrF excimer laser system Master Oscillator–Power Amplifier CL-7550 (Optosystems Ltd, Russia) was used as the UV radiation source in the experimental setup. In order to control laser beam quality, thus to provide FBGs effective writing, the laboratory setup includes: spectral width control system, based on Fabry–Perot interferometer; laser beam energy distribution control system; monitoring system of laser pulse energy density on the optical fiber; and control system of optical fiber to the laser beam relative position. FBGs of type I inscription results in a single-pulse and multi-pulse modes are presented.

Keywords Talbot interferometer · Fiber Bragg grating · KrF excimer laser system · Coherence · Phase mask

1 Introduction

Nowadays there has been continual growth of interest in the Bragg gratings production technologies and its application in fiber-optical sensors (Köppe et al. 2016; Lawson et al. 2016), laser technologies (Fortin et al. 2016; Huang et al. 2016) and telecommunication (Liaw et al. 2016; Shanker et al. 2016). There are three basic fiber Bragg grating (FBG) inscription methods which are widely presented in modern literature: phase mask method (Hill et al. 1993; Varzhel' et al. 2012), point-by-point (Martinez et al. 2004; Arkhipov et al.

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2015) and interferometric ones (Meltz et al. 1989). The method to produce an FBG presented in the (Meltz et al. 1989) was first observed in 1989 and was called interferometric. The photoinduced refractive index change was produced in germanium-doped fiber through the side surface by two intersecting coherent beams of UV-light. Described technique revealed new opportunities for fabrication of the FBGs with different wavelength of Bragg resonance, used to create a distributed sensors systems (Rao 1999), Fabry–Perot interferometers (Wada et al. 2012), and systems with wavelength division multiplexers (Koo et al. 1999).

The most advanced realization of interferometric technique used today is the one based on Talbot interferometer comprising a phase mask as beam splitter (Bartelt et al. 2007). This method has several advantages as compared with the phase mask technique: the possibility of FBGs inscription with different Bragg wavelengths by using the same phase mask; the absence of direct contact of optical fiber with phase mask and reduced laser beam energy density on it in case of using cylindrical lens.

Interferometric technique has enhanced requirements for temporal (>10 mm) and spatial (>1 mm) coherence of UV-light source (Mayer et al. 1999). To provide possibility for FBG fabrication during fiber drawing process, laser source must also have energy over 100 mJ. As such UV-light sources for single-pulse mode writing the oscillator/amplifier KrF excimer lasers are the most applicable (Askins et al. 1992; Rothhardt et al. 2004).

2 FBG writing scheme

The development of high-power excimer lasers with enhanced spatial and temporal coherence has been performing on industrial laser samples designed at Physics Instrumentation Center at Prokhorov General Physics Institute of the Russian Academy of Sciences (PIC GPI RAS) (Atezhev et al. 2003). As a result of this development the KrF excimer laser system MOPA CL-7550 (Optosystems Ltd, Russia) was designed. This system is used as the UV laser source in the experimental setup. MOPA CL-7550 is a Master Oscillator–Power Amplifier laser system, which provides high temporal (>10 mm) and spatial (>5 mm) coherence with beam aperture $6 \times 20\ mm^2$, operating at 248 nm with a pulse repetition rate up to 50 Hz and pulse energy up to 250 mJ.

FBG writing functional scheme based on Talbot interferometer is shown in Fig. 1.

High reflection dielectric mirrors for 248 nm wavelength are used in laser beam transportation optical system and Talbot interferometer. There is a motorized attenuator module (Coherent Inc.) in the experimental setup for smooth adjustment of laser beam energy, and optical shutter is used for required amount of laser pulses to pass through. Removable rectangular diaphragm allows varying the gratings length up to 14 mm.

The laser beam is focused onto the optical fiber by a cylindrical lens with a focal length of 500 mm, which is installed on a linear stage. Beam splitting in Talbot interferometer is performed by phase mask (Ibsen Photonics) with a grating period of 1000 nm. The deflecting mirrors in the interferometer setup is placed on rotary stages Thorlabs NR360S/M having accuracy of 2″. The phase mask and rotators with interferometer mirrors are situated on the same plate, mounted on the linear stage. Incline angle of the mirrors defines the period of the interference pattern and therefore also the period of the Bragg grating and its reflection wavelength according to Bragg's condition. Thus the experimental setup allows FBG inscription with Bragg wavelength over a wide range by varying the angle between the two interfering beams and using the same phase mask.

To provide tuning and stable operation during a long runtime the experimental setup includes the control systems that are described below.

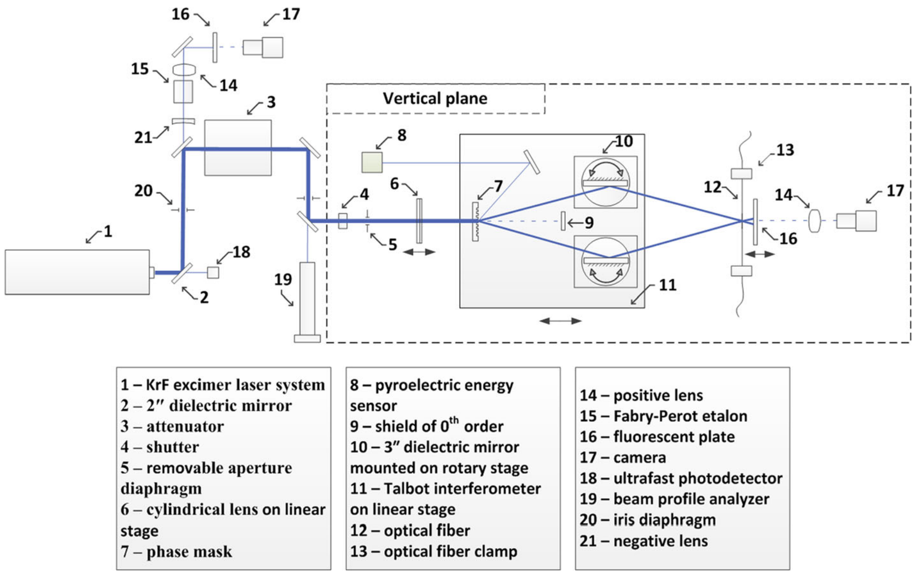


Fig. 1 FBG writing functional scheme

Laser beam energy distribution control system, based on beam profile analyzer Ophir Optronics SP 620, provides initial adjustment of intensity distribution and its registration during the FBG writing process. Figure 2 shows beam energy distribution of our excimer laser system passed through an aperture diaphragm 6 × 14 mm^2. Deviation of the pulse energy density in FBG writing area remained below 15%.

Spectral width control system, based on 5 mm Fabry–Perot etalon, allows visual monitoring of interference rings stability on PC screen. A picture of the interference rings is produced on fluorescent plate and is registered by TV camera (Fig. 3a). For auxiliary control of the laser system synchronization an ultrafast photodetector Alphalas UPD-200 is used.

Energy monitoring system allows to determine the laser pulse energy on the interference area in real time, by measuring the energy of third diffraction order of the phase mask.

Optical fiber to the laser radiation relative position control system provides fine adjustment of fiber position in the middle of the beam accurate to 50 μm and also complete interfering beams overlap in fiber position. Figure 3b shows the shadow picture registered on fluorescent plate by synchronized camera.

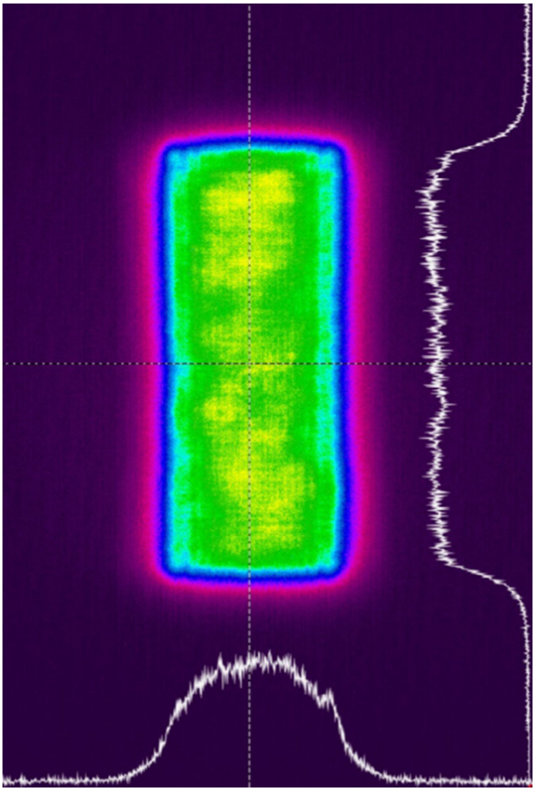
Presented control systems allows to operatively monitor laser radiation characteristics and fiber to the beam relative position, that provides efficient fabrication of the FBG with required spectral parameters.

3 Results

Figure 4 shows the reflection spectrum of type I Bragg grating with the reflectivity of 26%, written in the birefringent optical fiber with an elliptical stress cladding and 18 mol% GeO_2 concentrations in its core, manufactured on technology described in paper (Bureev et al. 2007).

The inscription was produced for single-pulse mode and energy density of 0.6 J/cm^2 for 10 mm long grating, and therefore the grating bandwidth (FWMH) of 0.09 nm was

Fig. 2 Laser beam energy distribution



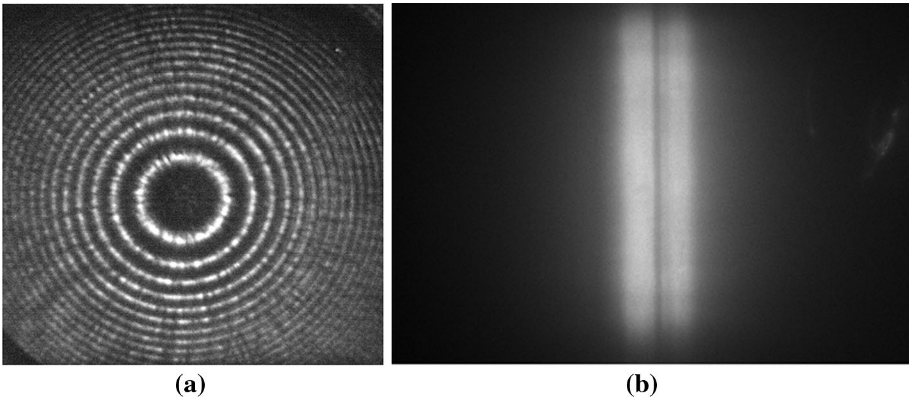


Fig. 3 Imaging on PC screen: **a** interferometric patterns obtained using a Fabry–Perot etalon; **b** the fiber position relative to the laser beam

achieved. The presence of two peaks in the FBG spectrum is due to the difference between effective refractive indices of "fast" and "slow" anisotropic optical fiber axes (Varzhel' et al. 2016).

In order to prove the precision in achievable Bragg reflection wavelengths, the reflection spectrum of an array of 4 different FBGs of type I is shown in Fig. 5. By tilting mirrors, the

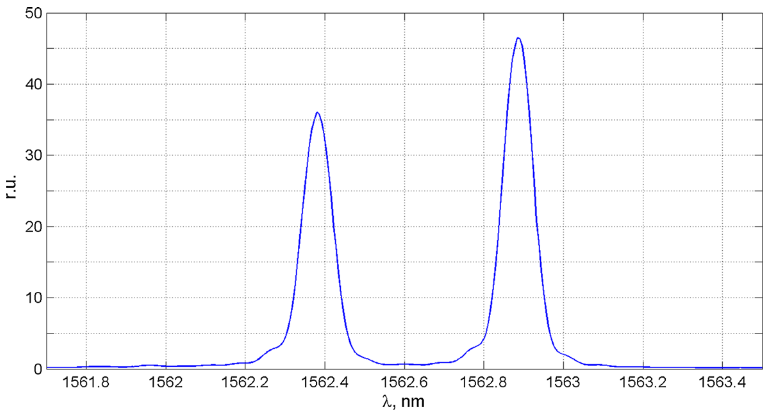


Fig. 4 FBG reflection spectrum (*r.u.* relative units, λ wavelength)

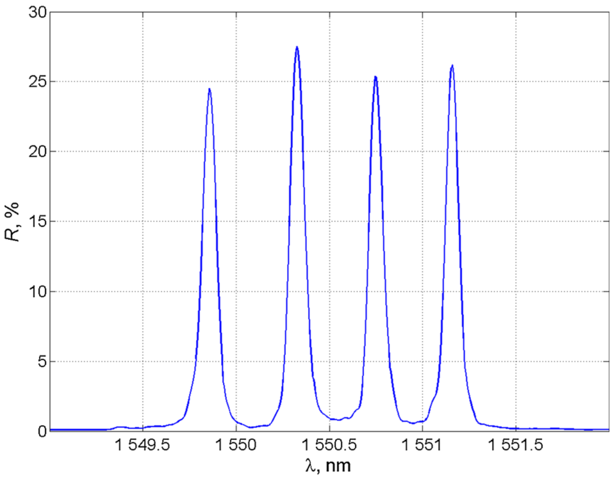


Fig. 5 FBGs array reflection spectrum (*R* reflectivity, λ wavelength)

period of the interference pattern was being altered in order to shift Bragg resonance wavelength of 0.4 nm. FBGs were written for multi-pulse mode in isotropic optical fiber with the high concentration of GeO_2 at a repetition rate of 10 Hz and pulse energy density of 200 mJ/cm^2. The experimental spectrum for 14 mm long gratings obtained with the use of precise optical spectrum analyzer Yokogawa AQ6370C with 20 pm resolution.

Demonstrated FBGs array has potential applicability to band-pass filters and wavelength division multiplexers.

4 Conclusion

An experimental setup for the FBGs writing by use of Talbot interferometer has been developed. The operational control systems for monitoring of laser beam energy distribution, temporal coherence, laser pulse energy and optical fiber positioning have been designed. Laboratory setup allows FBGs inscription in the wide range of wavelength, covering the second (1310 nm) and the third (1550 nm) GeO_2 optical fiber transmission window. Variation of laser beam height using removable diaphragms over the range between 1 and 14 mm gives possibility to change FBGs bandwidths (FWHM) from 0.07 to 0.7 nm. Developed laboratory setup provides stable FBG inscription for single-pulse and multi-pulse modes. The developed setup is applicable for Bragg gratings fabrication during the fiber drawing process.

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