Optics and Spectroscopy, 2025, Vol. 133, No. 3

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Excitation of optical vortices in a waveguide with a helical depressed cladding

© V.V. Likhov[1], P.I. Sadovskii[2], A.G. Okhrimchuk[1]

[1] Prokhorov Institute of General Physics of RAS, Dianov Fiber Optics Research Center, Moscow, Russia
[2] Fryazino Branch of Kotelnikov Institute of Radio Engineering and Electronics, Russian Academy of Sciences, Fryazino, Moscow region, Russia

e-mail: vladislavlikhov@gmail.com

Received December 26, 2024
Revised February 03, 2025
Accepted February 28, 2025

Helices with a pitch of the order of the wavelength of light in the IR range, in which the refractive index is depressed compared to unexposed glass, were inscribed in the volume of phosphate glass by a femtosecond laser beam. Thus, the written helices represent the cladding of a few-mode waveguide with a built-in Bragg grating. The reflection spectrum of the obtained Bragg structures is studied. It is shown that the beam reflected from the Bragg gratings has a helical wave front and carries an orbital angular momentum.

Keywords: Direct laser writing, Bragg grating, waveguide, optical vortex.

DOI: 10.61011/EOS.2025.03.61164.10-25

Introduction

Orbital angular momentum vortex beams (OAM) have received increased attention in the last decade. Such beams are characterized by a helicoidal wavefront, with the zero light intensity in the beam center (phase singularity). OAM beams are used in various fields due to their unique properties, the most important among which is the optical communication and microscopic particle manipulation [1].

Vortex light beams are used for multiplexing in experimental optical communication links for data transmission using multiple channels, each encoded using a different OAM [2,3]. This significantly increases the amount of transmitted information and improves the efficiency of spectrum utilization. Such systems are already being developed for long-distance, high-capacity data transmission [4–6].

The possibility of converting a Gaussian beam into waveguide vortex modes using Bragg helical structures written by a femtosecond laser beam was first shown in a Nd:YAG crystal [7]. This approach allows optical vortices to be produced directly in fiber light guides, eliminating the need for bulk optics typically used to produce vortex beams [8]. The excitation of vortex modes in a waveguide laser in which Bragg helical structures serve as resonator mirrors is even more attractive. It should be noted that writing of such structures was performed before, for example, in Ref. [9], but the helical geometry in this case was not used to obtain structured light, but it was used to increase the reflection coefficient of the grating by increasing the integral of the overlap, i.e., the fraction of power propagating through the modified part of the light guide.

Phosphate glasses activated by Er^{3+} ions are laser media that allow the development of efficient lasers in the telecommunication wavelength range. A waveguide laser with a positive change of the refractive index in the waveguide core was created on the basis of such a medium at the dawn of the development of direct laser writing [10]. Further studies showed that the refractive index change in phosphate glasses can be both positive and negative depending on the glass composition and laser writing parameters [11]. Subsequently, depressed cladding waveguides [12,13], including active waveguides [14], have also been written and studied. A waveguide laser that generates OAM modes requires a waveguide that supports multiple modes, which implies a significant change of the refractive index (at least 10^{-3}).

The aim of this paper is to study the laser writing of helical waveguide Bragg gratings in phosphate glass activated by Er^{3+} ions to find the optimal writing mode for the creation of small-mode waveguides supporting OAM modes, which can further serve as components of a waveguide vortex laser.

Writing of helical structures

Direct laser writing experiments were carried out in a sample of ytterbium-erbium phosphate glass synthesized at the Kotelnikov Institute of Radio Engineering and Electronics of the Russian Academy of Sciences, with the concentration of erbium ions of $8.5 \cdot 10^{19}\,cm^{-3}$ [15] and approximate composition (mol.%) of 16% Na_2O, 6% K_2O, 8% Al_2O_3, 8% Yb_2O_3, 60.8% P_2O_5, 1% Nb_2O_5. The refractive index of glass $n = 1.515$ at a wavelength of 1550 nm.

20× lens with a numerical aperture of 0.45 was used for waveguide writing. A spectroscopic slit with a lumen of 400 μm oriented along the waveguide axis was placed in front of the lens for achieving an azimuthally uniform

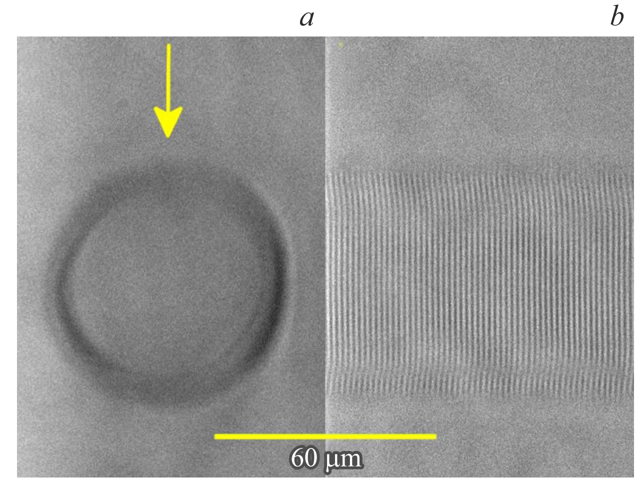

Figure 1. (*a*) Micrograph of WG1 from the end. The beam direction of the femtosecond laser is indicated by an arrow; (*b*) view of WG1 along the writing beam direction. The scale line refers to both views, highlighted from below.

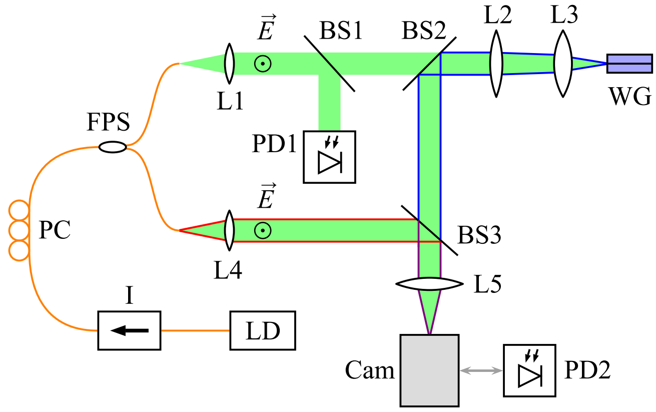

Figure 2. Optical scheme for waveguide characterization. LD — variable wavelength semiconductor laser; I — fiber optic isolator; PC — polarization controller; FPS — fiber optic splitter; L1, 2, 3, 4, 5 — lenses with focal lengths of 10, 500, 50, 20, 400 mm, respectively; BS1, 2, 3 — beam splitters; Cam — InGaAs camera; PD1, 2 — photodiodes; WG — phosphate glass sample with studied waveguides.

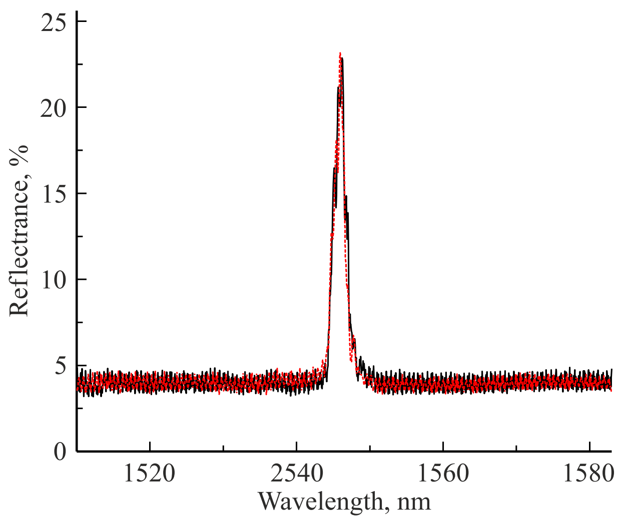

Figure 3. Waveguide reflection spectra. WG1 — black solid line, WG2 — red dashed line.

waveguide cladding thickness. This changed the shape of the writing beam waist, transforming the cigar-shaped waist into a lens-shaped waist [16].

To determine the optimal writing mode, a trial writing of helical structures with pulse energies ranging from 1.2 to 3 μJ was performed at a pulse repetition rate of 167 Hz and a writing rate of one turn per second, which corresponds to a tangential velocity of 0.2 mm/s and provided pulse overlap — approximately 9 pulses per point. The pulse duration was 180 fs, the wavelength was 1030 nm. The polarization of the writing beam is parallel to the axis of the waveguide. It was found that the energy of 1.8 μJ ensured the best quality of the created structures. The change of the sign of the refractive index is negative in glass of this composition with such a pulse energy, and the helical structure formed a cladding with a depressed refractive index.

Thus, in the volume of a rectangular plate made of this glass, two waveguide helical Bragg gratings with a helical pitch of 1.53 and 1.02 μm, corresponding to the Bragg order of 3 and 2 at a wavelength of 1550 nm, which represented the waveguide cladding (hereafter „waveguides“ or WG1 and WG2, respectively).

The length of each waveguide was 4.8 mm, the average diameter was 60 μm, and writing was performed at a depth of 200 μm. Micrographs of one of the waveguides are shown in Fig. 1.

Study of written structures

A wavelength-tunable semiconductor single-frequency laser was used to characterize the waveguides. The schematic setup for waveguide characterization is shown in Fig. 2.

The readings of the signal photodiode PD2 were divided by the readings of the reference photodiode PD1 for normalizing the spectra to the beam power driven into the waveguide. The L2 lens was used to adjust the beam diameter at the waveguide inlet. The path of the beam reflected from the waveguide is shown by the blue border. A fiber optic splitter was used to obtain the reference beam (indicated by the red border). The polarization of the beam is linear vertical.

The reflection spectra of waveguides 1 and 2 are shown in Fig. 3. The spectra were normalized by the magnitude of the Fresnel reflection from the sample face. The Bragg resonance is located at a wavelength of 1546 nm.

Experimental results and discussion

The profiles of the beam reflected from the waveguides in the near field are shown in Fig. 4.

The reflected mode has a ring-shape in contrast to the passing mode, which has a Gaussian profile. When the interferometer reference beam is superimposed, the ring is modulated in azimuth with the number of maxima corresponding to the Bragg order of the waveguides (three maxima for WG1 and two maxima for WG2).

The classical condition for Bragg resonance:

$$\beta_q + \beta_l = \frac{2\pi}{\Lambda} p,$$

where β_q and β_l are propagation constants of the backward and forward modes, respectively, Λ is the period of the structure, p is the order of Bragg resonance.

At the same time, it is also necessary to take into account the condition of azimuthal phase synchronism for helical structures. In the case of no modulation of the refractive index of the helical structure along the azimuth [16,17]

$$q - l = \alpha p, \tag{1}$$

where q and l are topological charges (or OAM) of the reflected and incident light beams, respectively, α is the chirality of the OAM beam ($+1$ or -1), p is the order of the Bragg resonance. Since a Gaussian beam was introduced into the waveguide, the topological charge of the incident beam l is zero.

The written waveguides had a right-hand helix structure. When the optical path length of the reference beam was increased (i.e., when the distance between the optical fiber end, lens L5, and beam splitter BS3 in Fig. 2 was increased), the rotation of the interference pattern (Fig. 4, c, d) was clockwise (i.e., $\alpha = 1$), which confirms that the chirality of the reflected beam's wavefront matches the chirality of the waveguides.

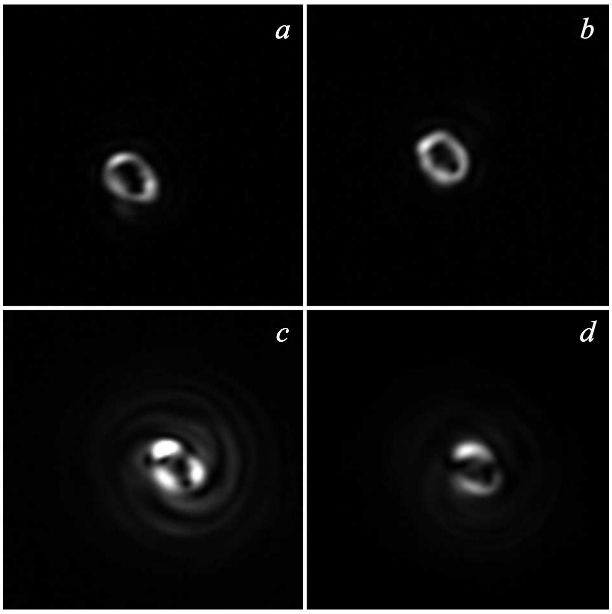

Figure 4. Profiles of the reflected beam from WG1 (a) and WG2 (b) in the near field at the resonance wavelength; c, d —-same with the reference beam superimposed.

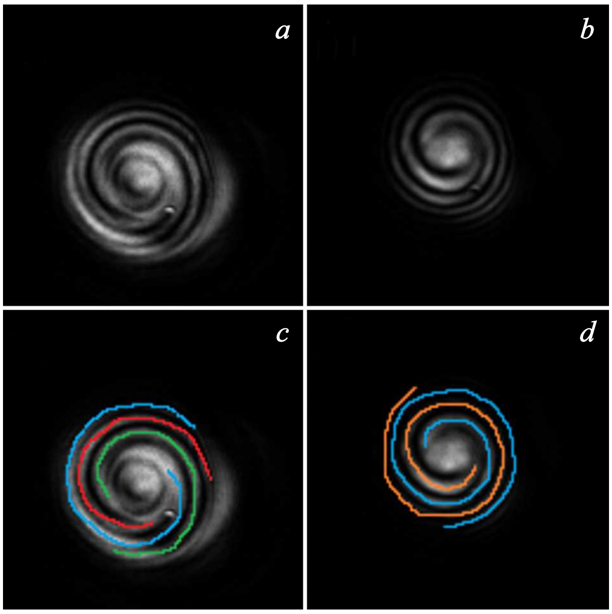

Figure 5. Profiles of the reflected beam from WG1 (a) and WG2 (b) in the far field. Same with overlapping helical sleeve pattern: 3 sleeves for WG1 (c), 2 sleeves for WG2 (d).

The profile of the beam reflected from the waveguides in the far field with the superimposed reference beam is shown in Fig. 5. The number of helical sleeves corresponds to the topological charge of the beam and the Bragg order of the waveguides according to equation (1).

Conclusion

In the volume of ytterbium-herbium phosphate glass, waveguides with helical cladding of reduced refractive index forming Bragg gratings of the second and third orders have been writtent by a femtosecond laser beam. It is shown that direct laser writing at a wavelength of 1030 nm allows writing Bragg structures in phosphate glass with a pitch of 1 μm or more. It is demonstrated that the beam resonantly reflected from the Bragg cladding has an orbital angular momentum, and its value corresponds to the Bragg order of the lattice at the resonance wavelength. The studied waveguide structure can be used to construct a compact vortex laser.

Funding

This work was supported by the Russian Science Foundation (№ 22-29-01187).

Conflict of interest

The authors declare that they have no conflict of interest.

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Translated by A.Akhtyamov