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FILAMENTATION OF FEMTOSECOND VORTEX BEAM IN SAPPHIRE

Filamentation of powerful femtosecond beams with a vortex of the topological charge $l = 2$ in sapphire is studied. A method to control the azimuthal position of filaments by changing the phase difference between two coherent co-axial beams, vortex and vortex-free reference ones, is proposed and demonstrated. The observed misalignment between the paths of filaments generated by the vortex and vortex-free beams, when they cross at a small angle is explained in terms of the spiral propagation of filaments around the vortex optical axis.

Keywords: filamentation, femtosecond, vortex beams, topological charge.

1. Introduction

Since the basic work by Nye and Berry [1], the interest in screw dislocations of a wave front or optical vortices (OVs), as well as in other optical field singularities, is steadily growing. Researches in singular optics that were carried out at the Department of Optical Quantum Electronics of the Institute of Physics of the NAS of Ukraine [2–6] are widely known. Optical vortices have a phase singularity at the axis with zero intensity, and the instant phase of an OV wave depends on the azimuthal angle reckoned around the axis, changing by $2\pi l$ after every complete revolution. The topological charge $l = \pm 1, \pm 2, ...$ determines the orbital momentum transferred by the vortex. The interest in OVs is associated with their importance for the theory and numerous applications such as optical capture, optical micro-manipulation, quantum- and telecommunication [7, 8]. However, despite a considerable number of works dealing with nonlinear optical phenomena in OVs, those phenomena remain insufficiently studied else; in particular, this concerns the filamentation in OVs. The filamentation in OVs was observed for the first time in sodium vapors [10]; later, it was studied in various other media [10, 11]. The analysis of the azimuthal modulation instability in OVs in a Kerr medium was made in work [12]. In work [13], the azimuthal modulation was demonstrated to change the self-focusing dynamics, giving rise to the formation of a regular filament structure. The influence of the plasma formation inertia on the OV propagation stability was numerically studied in work [14]. In work [15], OV were proposed to be used to control the start of the multifilamentation in air.

In this work, we report the results of our calculations and experimental researches concerning the filamentation of a femtosecond vortex beam with the topological charge $l = 2$ in sapphire. We propose a method to control the azimuthal position of filaments by varying the phase shift between the vortex beam and the quasiplane vortex-free reference one; the both are collinear and mutually coherent. The method was confirmed by results of mathematical simulation and implemented experimentally. The observed misalignment of filaments formed at the mutual crossing of coherent quasiplanar and vortex beams can be explained by a spiral character of filament paths.

2. Experiment and Its Discussion

The schematic diagram of the experimental installation is shown in Fig. 1. As an excitation source, we used a femtosecond unit with a regenerative amplifier (RA) Legend F-1k-He. The unit generated

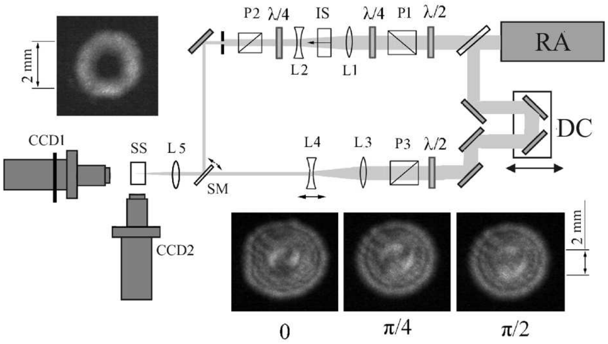

Fig. 1. Schematic diagram of the experimental installation

horizontally polarized laser pulses with the following parameters: a pulse energy of 2.5 mJ, the pulse duration τ_p = 160 fs, the wavelength at the pulse maximum $\lambda_{\max}$ = 800 nm, and a pulse recurrence rate of 1 kHz. Laser radiation was split into two components with an intensity ratio of 80:20. The more intensive beam passed through an intensity regulation unit composed of a half-wave plate $\lambda/2$ and a Glan prism P1, which transmitted vertically polarized light. Then, the vertically polarized beam arrived at a unit of OV generation. For this purpose, we used a modified scheme of dispersionless OV generation in a uniaxial crystal of Icelandic spar (IS) 1.5 cm in thickness, which was proposed for the first time in work [16]. As a result, we obtained a horizontally polarized OV 2 mm in diameter with a pulse energy up to 200 μJ and the topological charge l = 2 (see the photo in the upper inset in Fig. 1). After being reflected by a semireflecting mirror (SM), the OV was focused by lens L5 with a focal length of 8 cm on the front face of a polished high-quality specimen of single-crystalline sapphire (SS) with a 3×3-mm^2 rectangular cross-section fabricated at the Institute for Single Crystals of the NAS of Ukraine (Kharkiv). The self-focusing of femtosecond laser radiation took place in the specimen material, and filaments were formed [17]. Owing to the presence of Ti^{3+} impurity ions in the specimen, the recombination of the filament plasma channel invoked a bright luminescence radiation, which enabled the configurations of filamentation tracks to be registered with the help of a CCD-camera equipped with a microscopic objective (CCD2). The transverse cross-section of the radiation intensity distribution in the specimen was registered with the help of another CCD-camera with a microscopic objective (CCD1). To protect the CDD1 matrix from being damaged by direct laser radiation, a 5×10^3-fold attenuation filter was mounted between the objective and the matrix.

The formation of filaments in the specimen was studied both when focusing the OV beam separately and when it was focused simultaneously with a coherent vortex-free laser beam about 5 mm in diameter. For this purpose, the split part of the amplifier beam was directed to a delay line (DL). The latter was used to provide the time coincidence of both pulses in the specimen and to change the phase difference between them. After the delay line, the beam power was controlled with the help of a $\lambda/2$ phase plate and Glan prism P3 adjusted to transmit the horizontal polarization. The beam diameter was regulated with the use of telescope (L3, L4). The both beams were converged in space with the help of a semireflecting mirror (SM).

The lower inset in Fig. 1 demonstrates the interference patterns obtained for those two coaxial beams after they passed mirror SM for some positions of the delay line within the limits of pulse coincidence. The respective variations in the phase difference are also indicated. The observed rotation of two interference maxima about the beam axis is explained by a change of the phase difference between the OV and vortex-free beams at small delay line shifts. Unfortunately, the technical characteristics of the delay line did not allow the phase difference to be established with a satisfactory precision. Therefore, when the delay time was changed within the pulse duration interval (160 fs), the specific value of phase difference turned out to be random. Nevertheless, the azimuthal rotation of two interference maxima at the phase variation proves that we really obtained an OV with the topological charge $l = 2$.

When focusing the two coaxial beams into specimen SS, the generation of filaments was observed. The latter were registered by camera CCD2 in the form of two thin parallel tracks of luminescence, with the distance between them depending on the DL position (Fig. 2, *a*). Camera CCD1 registered the point localization of a transverse cross-section of the intensity distribution in the specimen, which was typical of the filamentation (Fig. 2, *b*). In this case, the azimuthal position of filaments also depended on the delay line position. The observed filamentation features, as well as the features in the interference pattern described above, are explained by a change in the phase shift between two beams. Really, the interference pattern maxima act as nucleation centers for the filament generation [18]; therefore, their azimuthal position is determined by the phase difference between two beams. Hence, by changing the phase difference between two interfering beams, one can manipulate the azimuthal position of filaments.

In our opinion, if two coherent beams, the OV and the vortex-free plane one, propagate at a small angle with respect to each other, an unordinary phenomenon such as the spiral tracks of filaments can be observed [19]. Really, the corresponding incursion of the phase difference between the OV and plane beams amounts to $\Delta\phi = 2\pi\theta^2 z/\lambda$, where θ is the angle between the beams, z the propagation distance along the OV axis, and λ the light wavelength in the medium. The phase difference incursion along the propagation length $z = \lambda/\theta^2$ equals 2π, i.e. the interference pattern and, hence, the filaments in its maxima make a complete revolution around the OV axis.

We execute a numerical simulation of the intensity distribution at the interference of two such beams in sapphire. The results obtained confirm the assumption concerning the spiral paths of interference maxima. The first beam was simulated as an annular one with the topological charge $l = 2$,

$$E_1(x, y) = Ar^l \exp\left[-\frac{r^2}{2a_0^2} + il \arctan(x, y)\right],$$

The nonlinear dynamics of filamentation, which is governed by the centers of filament nucleation at the local intensity maxima, can give rise, in this case, to the formation of spiral paths around the OV axis. Supposing the spirality of paths, the observed misalignment corresponds to their rotation by an angle of 13° around the OV axis after the propagation over a distance of 0.9 mm in sapphire.
where $r = (x^2 + y^2)^{1/2}$, $l = 2$, $A = 1$, and $a_0 = 20$ μm (the ring width is about 80 μm). The second wave was selected planar and crossed with the first one at an angle of 0.2°. The calculated dependences of the transverse intensity distribution on the propagation length z are depicted in Fig. 3. We also experimentally observed a nonparallel behavior of filament tracks in the case where the OV and vortex-free beams intersect at a small angle (Fig. 4).

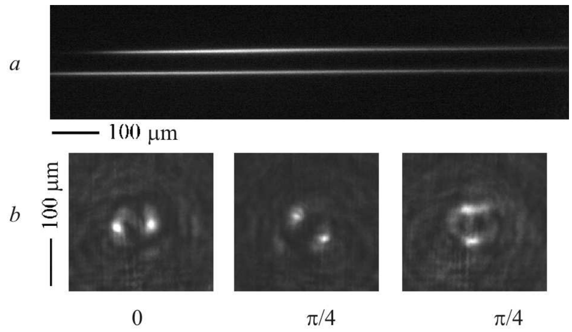

Fig. 2. Luminescent tracks and the transverse intensity distribution at a distance of 1.5 mm from the output face of the specimen excited with coaxial OV and vortex-free beams. The pulse energy in each beam equals 2 μJ

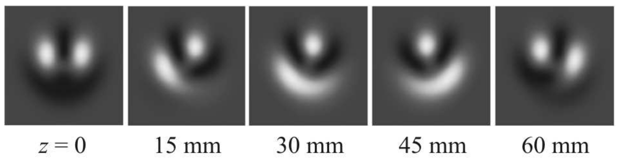

Fig. 3. Results of numerical simulation for the interference between an optical vortex with the topological charge $l = 2$ and a plane wave. The length of each fragment side equals 150 μm

Fig. 4. Nonparallel filamentation tracks obtained when the coherent OV and plane waves intersect each other at a small angle in sapphire. The photo length equals 1 mm

Hence, we have numerically and experimentally studied the filamentation of a powerful femtosecond optical vortex with the topological charge $l = 2$ in sapphire. A method to manipulate the azimuthal position of filaments by varying the phase difference between the optical vortex and the vortex-free planar reference wave, which are coherent and coaxial, is proposed and implemented. The misalignment between the paths of filaments observed when the optical vortex and the vortex-free plane beam intersect at a small angle can be explained as a spiral propagation of filaments around the OV axis.

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ФІЛАМЕНТАЦІЯ ФЕМТОСЕКУНДНОГО ВИХРОВОГО ПУЧКА В САПФІРІ

Р е з ю м е

Досліджено філаментацію потужного фемтосекундного пучка, який несе оптичний вихор з топологічним зарядом $l = 2$ в сапфірі. Запропоновано і продемонстровано спосіб контролю азимутального положення філаментів шляхом зміни різниці фаз між когерентними і співосними вихровим і референтним безвихровим пучками. Спостережена непаралельність траєкторій філаментів при перетині під невеликим кутом оптичного вихору і безвихрової плоскої хвилі пояснена з точки зору спірального поширення філаментів навколо осі оптичного вихору.