Optica Applicata, Vol. XXXIV, No. 3, 2004

Creation and diagnostics of stable rainbow optical vortices

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An on-axis computer-synthesized hologram-based technique is introduced to create white-light "rainbow" optical vortices, which are stable with respect to environmental disturbances under long-distance propagation of singularity supporting beams. Regularities governing the radial alternation of colors at highly directed rainbow vortices are discussed. The original diffraction technique for detecting phase singularities is applied to reveal and diagnose the polychromatic vortices.

Keywords: singular optics, optical vortices, spatial coherence, white-light interference, mutual spectral purity, Young's interference experiment.

1. Introduction

Singular optics recognized as a new chapter of modern physics in the nineties of the last century [1], [2] has been developed until recently exclusively under approximation of complete coherence of light. In this framework, the phase singularities of common complex amplitude of completely spatially coherent, monochromatic waves were the subject of consideration alone. Vector generalization of the singular optical paradigm for completely coherent optical fields is discussed in [1]. Only at the threshold of the third millennium, this field of investigations was richly extended to partially coherent fields supporting phase singularities. In this context, two general cases are considered, namely, partially spatially coherent quasi-monochromatic beams supporting the phase singularities of spatial correlation functions [3], [4], and spatially coherent polychromatic fields supporting phase singularities of the spectral components [5]–[9].

It is shown in [5], [6] that the phase singularities manifest themselves at polychromatic field, while the spatial coherence of this field is high enough to provide amplitude zeroes via completely destructive interference for any spectral component. In this case, incomplete destructive interference takes place for spectral components close to the one of vanishing amplitude. As a result, relatively large spectral interval of the initial spectrum is considerably (though not completely) suppressed. This leads to noticeable coloring of initially "white" beam, and such coloring can be spatially non-uniform. Note that the local spectral modifications result from spatial non-coincidence of the phase singularities for different spectral components.

Several techniques for generation of polychromatic optical vortices have been proposed. Generation of the beams bearing a "white" optical vortex using a uniaxial crystal and a polarizer has been recently reported [10]. Another approach is based on diffraction of a femtosecond laser pulse with relatively narrow spectral band 10 nm at off-axis computer-synthesized hologram (CSH) computed for reconstruction of single -charged Laguerre–Gaussian (LG) doughnut modes at the first diffraction orders [11]. The pulse is decayed into spectrum, which impinges onto holographic grating. Then, after transformation into monochromatic vortices, such beams are spatially combined as a result of diffraction of spectrally decayed beam at the second grating with proper spacing that provides compensation of diffraction dispersion at the initial CSH. A disadvantage of this technique is that the spatial stability of the resulting polychromatic vortex depends considerably on mutual adjusting of two gratings (in period, orientation, *etc*.), so that a small misaligning of the arrangement results, under propagation, in decaying of the polychromatic vortex in spectral ones. Our previous experiments [12] with large-band polychromatic (virtually, white) light covering the visible range of electromagnetic radiation confirmed that polychromatic vortex might be obtained only at the plane where the singularity producing off-axis CSH is imaged, and even in this case one must operate with the gratings of low spatial frequency to minimize diffraction dispersion.

Here we introduce an on-axis CSH-based technique to create white-light (to judge from appearances, "rainbow") optical vortices, which are the co-axial superposition of the spectral vortices and are stable under their long-distance propagation. In this study, we essentially take into account the advantages of on-axis CSHs fruitfully used recently to solve another problem of singular optics [13]. Regularities governing the radial alternation of colors at highly directed rainbow vortices are discussed and demonstrated. The original diffraction technique for detecting phase singularities [4], [14]–[16] is for the first time successfully applied to reveal and diagnose the polychromatic vortices.

2. Experiment

The arrangement for generation and diagnostics of a rainbow polychromatic vortex beam using an on-axis CSH is shown in Fig. 1. As the primary source of a white-light radiation (1), we use a zirconium incandescent gas-lamp DATS-50 (Russian production) with argon filling with 0.3 mm-diameter circular luminous body (spectrum of radiation of the source is shown in Fig. 2). By a lens 2 (see Fig. 1), the source is imaged at 3.5×10^{-2} mm-diameter circular pinhole at an opaque screen 3. The size of a pinhole,

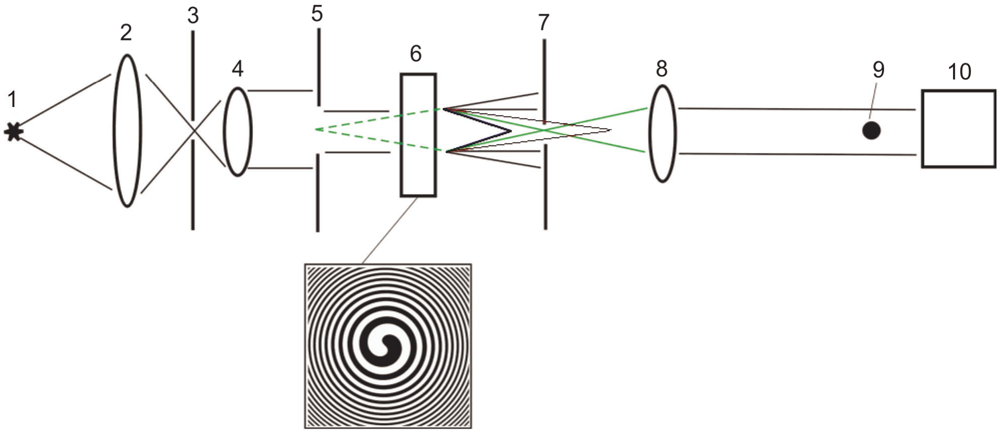

Fig. 1. On-axis arrangement for generation and diagnostics of rainbow polychromatic vortices: 1 – polychromatic 300 μm-diameter source, 2 – imaging lens, 3 – 35 μm-diameter pinhole, 4 – collimating lens ($f = 60$ mm), 5 – 0.8 mm-diameter aperture, 6 – on-axis CSH (LG01, $f_g = 70$ mm), 7 – 2 mm-diameter stop, 8 – collimating lens ($f_c = 180$ mm), 9 – needle, 10 – CCD-camera. Inserted: an on-axis CSH used for producing a polychromatic optical vortex.

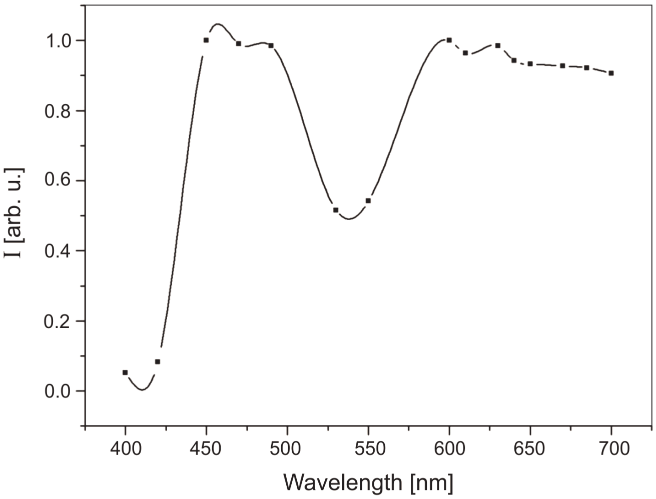

Fig. 2. Spectrum of radiation of the source.

which is virtually the secondary source of polychromatic light, is critical for generation of rainbow vortices. Namely, taking into account the Van-Cittert–Zernike theorem [17], it must be small enough to provide considerable spatial coherence of the field at the plane of a collimating lens 4 (and behind it) for all spectral components of the probing beam. Focal length of this lens in our experiment is $f = 60$ mm, thus the coherence area of the beam behind lens 4 estimated by the first zero of the first-order Bessel function of the first kind [18] varies in diameter $s = 1.22\lambda/\theta$, (θ being the angular dimension of the secondary source estimated from the center of the collimating lens), from $s_b \approx 0.8$ mm for blue spectral component ($\lambda_b = 380$ nm) to $s_r \approx 1.6$ mm for red one ($\lambda_r = 760$ nm). Diaphragm 5 behind a collimating lens 4 selects 0.8 mm-diameter central part of the beam. Then, the partially spatially coherent collimated polychromatic singularity-free beam impinges onto an on-axis CSH 6 (see insertion, Fig. 1) computed for reconstruction of the single-charged doughnut LG modes at the first diffraction orders. An opaque screen 7 with a small diaphragm passes the minus-first diffraction order of the radiation diffracted by a CSH, namely a polychromatic optical vortex.

Let us note the important differences of our experiment from ones described in [13] and in [18]. When one works with a quasi-monochromatic optical radiation [13], the diameter of the diaphragm 7 must be as small as possible to minimize the contributions from the 0th and the +1st diffraction orders into analyzed vortex beam. In contrast, one operates with enough large a diaphragm to generate a spatially incoherent source that is presumed into Van-Cittert–Zernike theorem [17], [18]. Our considerations are quite different. On the one hand, we also strive for excluding the background caused by the contributions from the 0th and the +1st diffraction orders, which can camouflage the central optical vortex. Hence, the diaphragm 7 cannot be large. On the other hand, we must provide for passing all spectral components of polychromatic vortex beam bearing considerable energy, which are focused at different distances behind a CSH due to diffraction dispersion. Hence, the diaphragm 7 cannot be too small, being adjusted for the central, conventionally “green”, spectral component of the probing radiation. As a compromise, we use 2 mm-diameter diaphragm 7 at opaque screen adjusted to let fully pass green, while blue and red are passed considerably, too. In our experiment, the focal length of a snail-like Fresnel grating (inserted in Fig. 1), $f_g = r^2/\lambda_g$ (r being the radius of the central Fresnel zone), for green ($\lambda_g = 550$ nm) is 70 mm.

As is known [2], paraxial free-space propagation of a monochromatic vortex beam of LG-mode is accompanied by diffraction spreading of the beam following the rule:

$$w_z = w_0\left[1 + \left(z^2/\pi^2 w_0^4\right)\lambda^2\right]^{1/2}$$

where w_0 being the waist parameter of the beam estimated by the e^{-1} intensity level for $z = 0$, and w_z – the width of the beam at the distance z from the caustics waist. It is clear that in the case of polychromatic vortex, *i.e.*, co-axial superposition of elementary spectral vortices, diffraction spreading must cause “rainbow” effect. Namely, the cross-section of the polychromatic vortex beam propagating behind a diaphragm 7 looks like a ring rainbow, whose periphery is red-colored, while violet and blue are concentrated close to the common axis.

However, observation of free-space propagating rainbow vortex is impracticable owing to rather fast geometric spreading of the beam. That is why we use a collimating length 8 (in our experiment, with a focal length f_c = 180 mm). The use of this lens causes the following peculiar transformation of the structure of the rainbow vortex. At free-space propagating vortex beam (as well as just behind the collimating lens 8), one really observes rainbow vortex with the above mentioned radial alternation of colors caused by diffraction dispersion. But the further propagation of the beam is accompanied by the inversion in the order of the radial alternation of colors. The reason for the color inversion lies in competition of diffraction (caused by a CSH 6) and refraction (caused by a lens 8) dispersion, which are of opposite signs. As a result, blue goes out to the periphery of the beam, while red is concentrated close to the beam axis (to the central optical vortex). What is important, despite color inversion the rainbow vortex occurs to be spatially stable at long-distance propagation. Namely, in our laboratory environment we observed stable (neither spatially nor spectrally decayed) rainbow vortices up to 80 m, even when the case of environmental disturbances kind of the combined influence of rapid heating and ventilator wind were applied. In the last case, the optical axis is fluctuated, but the central vortex is stable.

Further, due to incomplete spatial coherence of the beam and imperfect elimination of the contributions from the 0th and the +1st diffraction orders, the central vortex is observed at considerable incoherent background. It hampers direct visualization of the polychromatic vortex, as it is possible in the case described in [13]. Moreover, the standard interferometric technique for detection of phase singularities [2], which is generally accepted and highly efficient in coherent singular optics, is inapplicable in our case, while no any reference wave can be mutually coherent with all spectral components of the analyzed polychromatic beam simultaneously. That is why we apply the diffraction technique for revealing phase singularities introduced recently in [4], [14]–[16] for diagnostics of optical vortices in partially spatially coherent but monochromatic singular beams.

An opaque strip 9 (a 1 mm-diameter metallic needle) in Fig. 1 is placed in front of the vortex beam symmertically to its center. Behind the screen, within its geometrical shadow, one observes and registers with a CCD-camera 10 interference fringes arising from a superposition of wavelets from the screen edges. So, the fringes result from interference of wavelets from different points of the vortex beam itself, rather than from interference of this beam with a complementary reference wave. Rigorously speaking, in this way one obtains the data on the vortex of the spatial coherence function rather than on the vortex of ordinary complex amplitude of completely coherent singular beam tested using a reference wave. Being applied to polychromatic beams, this technique provides observation of white-light interference, while the requirement of mutual spectral purity of the disturbances at the probing points of the beam [17] is wittingly satisfied in the case of interest owing to the axial symmetry of the problem. Besides, due to very small diffraction angles of the interfering edge waves, chromatic blurring of white-light interference fringes is also small. Thus,

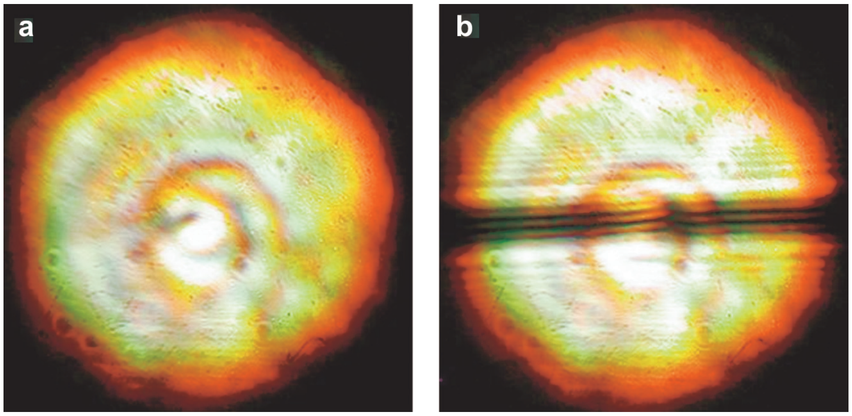

Fig. 3. Free-space propagating rainbow vortex (**a**), and its diffraction testing (**b**).

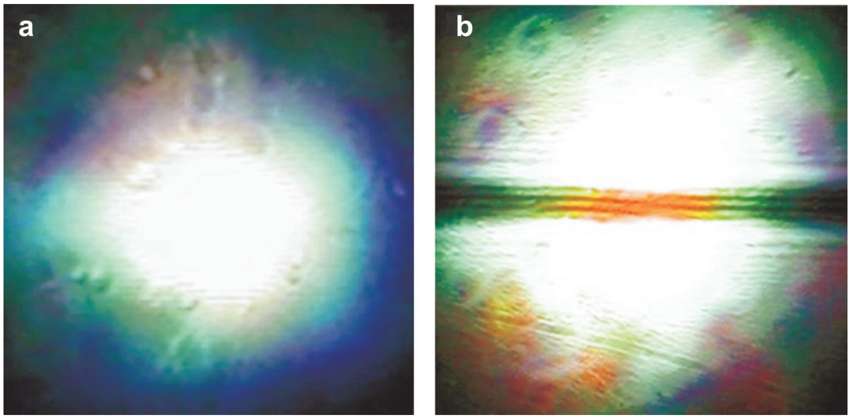

Fig. 4. Collimated rainbow vortex (**a**), and its diffraction testing (**b**).

specific bending of interference fringes following the arctan law [14] reflects helical phase of the spatial coherence function of polychromatic vortex beam and, indirectly, the vorticity of all spectral components of this beam.

Figure 3 illustrates the free-space propagating rainbow vortex originating from the diaphragm 7 in Fig. 1, (Fig. 3**a**) and the result of the diffraction diagnostics of the axial vortex (Fig. 3**b**). One can clearly see in Fig. 3**a** snail-like twirling of the beam near the core, as well as red periphery of the beam. As has been mentioned above, incoherent background camouflages the central vortex as well as the radial color distribution. Note that the central vortex can be put in evidence using a dark-field technique eliminating the regular background. But it is remarkable that even without applying a dark-field imaging technique, the use of an opaque strip at the beam of interest provides unambiguous confirmation of the presence of the central vortex (by the bending of interference fringes) as well as the radial alternation of colors governed by the diffraction dispersion, as is seen from Fig. 3**b**.

At last, in Fig. 4 we demonstrate the (spatially stable) rainbow polychromatic vortex with the inverted color alternation detected at the distance 5 m from the collimating lens 8 (see Fig. 1) and the result of its diffraction diagnostics. Bending of the interference fringes in Fig. 4**b** corresponds to right-hand (clockwise) twirling of the phase of the spatial coherence function of the single-charged LG mode and the same twirling of the phase of complex amplitudes of the spectral components of a polychromatic vortex beam. In Fig. 4**a**, one can see high spatial homogeneity of the stable vortex beam.

3. Conclusions

Summarizing, we have introduced a simple technique for creation of rainbow polychromatic optical vortices using a point-like white-light source and on-axis CSH technique. We have traced the transformations of the stable free-propagating rainbow vortices. The diffraction technique for revealing and diagnostics of vortices at partially coherent beams has been for the first time applied to polychromatic beams supporting phase singularities.

Considered here partially coherent singular beams are of interest, in part, in the problem of so-called optical traps and tweezers, as well as in the problem of optical telecommunications. In the first of the applications mentioned, it is attractive to use cheap non-laser, noninvasive sources for manipulating with microparticles. As for optical communications, it has been shown recently [19] that:

– a partially coherent beam may possess the directivity not conceding the directivity of any term of an expansion of the beam into the series of fully coherent (here, monochromatic) constituting modes, and

– some parameters of partially coherent beams occur more stable in respect of environmental disturbances than the corresponding parameters of completely coherent beams.

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Received February 9, 2004
in revised form May 15, 2004