Computer-synthesized hologram-based rainbow optical vortices

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Abstract. An on-axis computer-synthesized hologram-based technique is introduced to create long-distance stable white-light ‘rainbow’ optical vortices. Regularities governing the radial alternation of colours at highly directed rainbow vortices are established. The original diffraction technique for detecting phase singularities is applied to reveal and diagnose the polychromatic vortices.

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1. Introduction

Phase singularities have been recognized to be ubiquitous features of spatially coherent optical fields of various origin such as developed scalar speckle-fields [1], edge diffraction waves [2] and so on [3]–[5]. They became the subject of singular optics, which is of importance both for fundamentals and applications of optics [6]–[8]. Most of the published papers deal with monochromatic spatially coherent light fields. Recently, singular optics of polychromatic radiation have attracted much attention [9]–[18]. It has been shown both theoretically [13, 14] and experimentally [18] that phase singularities on some wavelengths in the white spectrum are
accompanied by considerable changes over the whole spectrum, which are the direct consequence of the famous diffraction-induced spectral changes (Wolf’s ‘spectral effect’) [19, 20]. A general polychromatic theory of the optical singularities of birefringent dichroic chiral crystals was built recently [21].

Generation of white-light optical vortices is of importance both for fundamentals and applications. Indeed, white stimulated supercontinuum spectra of very high field strength with vortex structure promises the realization of new interesting phenomena. On the other hand, the actual practical applications of optical vortices are optical tweezers and spanners [22] due to the existence of orbital angular momentum given by $\hbar m$ per photon ($m$ is the topological charge of an optical vortex) [23]. Therefore, the mechanical momentum of a white-light vortex is proportional to the intensity of the light beam and would be high enough for light sources with broad spectra. Therefore, power polychromatic optical vortices are very promising for non-invasive (non-destructing) manipulations with biological microparticles owing to the low probability of multi-photon reactions. Besides, polychromatic vortices can be of special interest for optical telecommunication applications.

In this paper, we elaborate a practicable algorithm for synthesizing long-distance stable white-light ‘rainbow’ optical vortices that are of importance to many applications. It is clear that diffraction of each spectral component during propagation depends on its wavelength. Therefore, one can expect that a white-light vortex beam has to possess a rainbow colour distribution in its cross-section. The possibility of managing this colour structure of the polychromatic vortex was substantiated and experimentally argued in our paper. Preliminary results were reported recently [24].

2. Experimental setup

The arrangement for the generation of a rainbow white-light vortex by an on-axis computer-synthesized hologram (CSH) and its diagnostics is shown in figure 1. As the primary source of a white-light radiation (figure 1, 1) we use a zirconium incandescent gas-lamp with argon filling and 0.3 mm diameter circular luminous body. The spectrum of radiation of the source is shown in figure 2. The broken line shows a relevant part of the normalized initial spectrum of the source used and the solid line demonstrates the spectrum of radiation after all transformations into the optical system (i.e., one actually involved in rainbow vortex formation) normalized by sensitivity of the CCD camera limited on about 760 nm. By lens 2 (see figure 1), the source is imaged on a $3.5 \times 10^{-2}$ mm diameter circular pinhole of an opaque screen 3. The size of the pinhole, the virtual secondary source of polychromatic light, is critical for the generation of polychromatic vortices. According to the Van-Cittert–Zernike theorem [25], it must be small enough to provide considerable spatial coherence of the field at the plane of the collimating lens 4 (and behind it) for all spectral components of the probing beam. The focal length of this lens in our experiment was $f = 60$ mm. The coherence area of a beam behind lens 4 can be estimated by the diameter of the first zero ring of the first-order Bessel function of the first kind $s = 1.22 \lambda / \theta$ ($\theta$ is the angular dimension of the secondary source seen from the centre of the collimating lens) [26]. It varies from $S_b \approx 0.8$ mm for the blue spectral component ($\lambda_b = 380$ nm) to $s_r \approx 1.6$ mm for the red one ($\lambda_r = 760$ nm). Diaphragm 5 behind the collimating lens 4 selects 0.8 mm diameter central part of the beam. Then the partially spatially coherent collimated polychromatic singularity-free beam with the estimated degree of coherence $\sim 0.8$ impinges onto an on-axis CSH [27] 6 (see insertion)
Figure 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 diaphragm; 8, collimating lens ($f_c = 180$ mm); 9, 1 mm-diameter metallic needle; and 10, CCD camera.

Figure 2. Optical domain of the spectrum of radiation of the source: (a) a relevant part of the normalized initial spectrum of the source used and (b) the spectrum of radiation actually involved in the rainbow vortex formation normalized by the sensitivity of the CCD camera.
computed for reconstruction of the single-charged doughnut Laguerre–Gaussian modes at the first diffraction orders [5]. In contrast to an off-axis CSH (such as the one used in [18]), where the diffraction orders spread out transverse to the propagation direction, in the case of an on-axis CSH the diffraction orders differ in their focus positions, as in a Fresnel zone plate. So, the virtual +1st diffraction order is focused before a CSH (shown in figure 1 by broken lines), while the real −1st diffraction order is focused behind a CSH. An opaque screen 7 with a small diaphragm passes mainly the −1st diffraction order of the radiation, namely a polychromatic optical vortex.

Let us note the important differences between our experiment and those described in [28] and [26]. When one works with a quasi-monochromatic optical radiation [28], the diameter of the diaphragm 7 must be as small as possible to minimize the contributions from the 0th and the +1st diffraction orders to the analysed vortex beam. In contrast, one operates with a sufficiently large diaphragm to generate a spatially incoherent source that is assumed for the Van-Cittert–Zernike theorem [25, 26]. Our reasons are quite different. On the one hand, we strive hard to exclude 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, all spectral components of a polychromatic vortex beam bearing considerable energy and focused at different distances behind a CSH due to diffraction dispersion must be passed. 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 the 2 mm-diameter diaphragm 7 at an opaque screen adjusted to pass green light fully, while blue and red are also passed considerably. In our experiment, the focal length of a snail-like Fresnel grating (inserted in figure 1), \( f_g = \frac{r^2}{\lambda_g} \) (r is the radius of the central Fresnel zone), equals 70 mm for green light \( (\lambda_g = 550 \text{ nm}) \).

As is known [5], paraxial free-space propagation of a monochromatic vortex beam of the kind of Laguerre–Gaussian mode is accompanied by diffraction spreading of the beam following the rule \( w_z = w_0[1 + (z^2/\pi^2 w_0^4)\lambda^2]^{1/2} \), where \( w_0 \) is the waist parameter of the beam estimated by the \( e^{-2} \) intensity level for \( z=0 \) and \( w_z \) is the width of the beam at the distance \( z \) from the caustics waist. It is clear that, in the case of a polychromatic vortex with coaxial superposition of elementary spectral vortices, diffraction spreading must cause the rainbow effect, i.e. the cross-section of the polychromatic vortex beam propagating behind a diaphragm 7 looks like a ring rainbow, whose periphery is red-coloured, while violet and blue are concentrated close to the common axis.

However, observation of the free-space propagating rainbow vortex is impracticable owing to a rather fast geometric spreading of the beam. Hence, we use a collimating lens 8 with a focal length \( f_c = 180 \text{ mm} \). This lens causes the peculiar transformation of the structure of the rainbow vortex. Indeed, for a free propagating vortex beam (as well as just behind the collimating lens 8), one really observes the rainbow vortex with the above-mentioned radial alternation of colours caused by diffraction dispersion. But further propagation of the beam is accompanied by the ‘inversion’ in the order of the radial alternation of colours. The reason for the colour inversion is in the competition of diffraction (caused by a CSH 6) and refraction caused by dispersion of the lens 8, 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. What is important is that the rainbow vortex appears to be spatially stable for long-distance propagation despite colour inversion. In our laboratory environment, we observed stable (neither spatially nor spectrally decayed) rainbow vortices up to 80 m even in the case when environmental disturbances such as the combined influence of
rapid heating and ventilator wind were applied. In this case, the optical axis is fluctuated, but the central vortex is stable.

Furthermore, 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 with considerable incoherent background. It hampers direct visualization of the polychromatic vortex, as it is possible for the case mentioned above [28]. Note that the lens 8 in figure 1 collimates only the −1st diffraction order supporting the vortex, while the 0th and the +1st orders (and all other ones) are focused by this lens at distances of 180 and 411 mm, respectively, behind this lens. On propagation, the 0th and the +1st diffraction orders undergo rapid geometrical spreading. As a result, the effect of these orders on the highly directed vortex, associated with the −1st diffraction order, becomes negligibly small. For this reason, we associate low visibility of the pattern only with an incomplete spatial coherence of a polychromatic vortex of the −1st order rather than with the influence of ‘foreign’ diffraction orders. Besides, the standard interferometric technique for detecting phase singularities [1], which is generally accepted and highly efficient for coherent singular optics, is inapplicable in our case, while no reference wave can be mutually simultaneously coherent with all the spectral components of the analysed polychromatic beam. That is why we apply the diffraction technique for revealing phase singularities introduced recently [29]–[32] to the diagnostics of optical vortices in partially spatially coherent but quasi-monochromatic singular beams.

An opaque strip (a 1 mm-diameter metallic needle; 9 in figure 1) is placed in front of the vortex beam symmetric about its centre. Behind the needle within its geometrical shadow, one observes and registers with a CCD camera (10) the interference fringes arising from a superposition of wavelets from the needle 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, one obtains in this way data on the vortex of the spatial coherence function rather than data on the vortex of an ordinary complex amplitude of the completely coherent singular beam tested using a reference wave. When 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 [25] 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, specific bending of interference fringes according to the arctan law [29]–[32] reflects the helical phase of the spatial coherence function of polychromatic vortex beam and, indirectly, the vorticity of all spectral components of this beam.

Figure 3(a) illustrates the free-space propagating rainbow vortex originating from diaphragm 7 in figure 1, and the result of diffraction diagnostics of the axial vortex is shown in figure 3(b). One can clearly see in figure 3(a) snail-like twirling of the beam near the core, as well as a red periphery of the beam. As has been mentioned above, incoherent background camouflages the central vortex as well as the radial colour 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 colours governed by the diffraction dispersion, as seen in figure 3(b).
Finally, we demonstrate in figure 4 the spatially stable rainbow polychromatic vortex with the inverted colour alternation detected at a distance of 5 m from the collimating lens 8 (see figure 1) and the result of its diffraction diagnostics. Bending of the interference fringes in figure 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 figure 4(a), one can see high spatial homogeneity of the stable vortex beam.

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

Figure 4. (a) Collimated rainbow vortex and (b) its diffraction testing.
Note that in figures 3 and 4 the central parts of the patterns are considerably saturated. Proper choice of an exposure time enables us to visualize the central (co-axial) polychromatic vortex and the rainbow effect. But in this paper we just ensure high visibility of the low-intensity colour of Young’s interference fringes confirming the presence of the central vortex. For comparison, we show the patterns saturated in their central parts.

3. Conclusions

Summarizing, we have introduced a simple and practicable technique for the creation of rainbow polychromatic optical vortices using a point-like white-light source and an on-axis CSH. 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 applied for the first time, to the best of our knowledge, to polychromatic beams supporting phase singularities.

Partially coherent singular beams considered here, are of interest, in part, in the problem of the so-called optical traps and tweezers, as well as in the problem of optical telecommunications. In the first of the mentioned applications, it is attractive to use cheap non-laser, non-invasive sources for manipulating with microparticles. As for optical communications, it has been shown recently [33] that (a) a partially coherent beam may possess directivity without conceding the directivity of any term of an expansion of the beam into the series of fully coherent (here, monochromatic) constituting modes, and (b) 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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