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A technique for simultaneous detection of individual vortex states of Laguerre–Gaussian beams transmitted through an aqueous suspension of microparticles

S.N. Khonina [a,b,*], S.V. Karpeev [a,b], V.D. Paranin [b]

[a] Image Processing Systems Institute, Branch of the Federal Scientific Research Centre "Crystallography and Photonics", Russian Academy of Sciences, Molodogvardeyskaya st. 151, Samara 443001, Russia

[b] Samara National Research University, Moskovskoe Shosse 34, Samara, Russia

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ABSTRACT

A technique for simultaneous detection of individual vortex states of the beams propagating in a randomly inhomogeneous medium is proposed. The developed optical system relies on the correlation method that is invariant to the beam wandering. The intensity distribution formed at the optical system output does not require digital processing. The proposed technique based on a multi-order phase diffractive optical element (DOE) is studied numerically and experimentally. The developed detection technique is used for the analysis of Laguerre–Gaussian vortex beams propagating under conditions of intense absorption, reflection, and scattering in transparent and opaque microparticles in aqueous suspensions. The performed experimental studies confirm the relevance of the vortex phase dependence of a laser beam under conditions of significant absorption, reflection, and scattering of the light.

1. Introduction

The problems of optical transmission of information in randomly inhomogeneous media are usually solved by using pulsed radiation sources, as well as aperture, spectral and polarization matching in the receiving and transmitting units. However, the intensive influence of random factors of a propagation medium stipulates the search for new distinguishing signs of signals [1–3]. One of these features in the case of laser beams can be a vortex dependence of the phase front of a beam [4–7]. Note that beams carrying an orbital angular momentum and having an infinite number of possible quantum states are of particular interest for increasing the information capacity of transmission channels [4]. Significant progress has already been made in applying the method of division multiplexing both in fiber communication systems [5] and in free space [6,7] and in the ocean [8,9]. Encoding symbols by the order of the vortex dependence, it is possible to optically transmit information [10].

The stability of vortex beams to random effects was investigated in experimental studies [9,11–15]. Gbur and Tyson [11] showed that high-order vortex beams are preserved in a turbulent medium at a considerable distance (several kilometers), but then split into first-order vortices. In the same paper the authors asserted that a bundle of vortex beams can split, deflect and wander outside the detector region, but it never disappears, i.e. the total angular momentum of the field is conserved. Porfirev et al. [14] showed that beams with a higher-order optical vortex are more prone to the action of random fluctuations, although with further propagation (after distortion) in free space, they demonstrate a better recovery ability. This effect was explained by the phase structure of the beam. Similar studies for Laguerre–Gaussian (LG) beams were carried out in work [16]. Note that the above-mentioned works consider, as a rule, single-ring LG beams. Given a greater stability of sets of individual vortex beams, it makes sense to consider, as an alternative, multi-ring LG beams.

A separate issue is the detection of optical vortices under conditions of beam distortion by random fluctuations. A general approach to designing phase filters for encoding and decoding images distorted by random noise involves the use of the double random phase encoding (DRPE) method [17,18]. However, in the problem of detecting optical vortices during the information transmission with the help of free space optics (FSO), detection and measurement of the contribution of individual vortex beams rather than complete image reconstruction are required.

The stability of the detection methods to random distortions of the beam is achieved by averaging over the largest possible area [11]. But the averaging area must be such that only one vortex is captured. In ad-

* Corresponding author at: Image Processing Systems Institute, Branch of the Federal Scientific Research Centre "Crystallography and Photonics", Russian Academy of Sciences, Molodogvardeyskaya st. 151, Samara 443001, Russia.

E-mail address: khonina@smr.ru (S.N. Khonina).

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dition, under conditions of the beam wandering, the method should be stable to a shift of the beam center. In paper [12], the total angular momentum was defined with the help of Young's double-slit interferometer. This method is the simplest one; however, its main drawback consists in the fact that it requires digital processing of the interferogram, that is, a two-dimensional array of data. There is no averaging of the data, and a decrease in the contrast of the interference fringes under distortion conditions makes it difficult to detect vortices. A more complex method [19] used in paper [13] is based on the use of special refractive elements. The method allows one to work with individual photons and perform measurements by a single-element photodetector. However, the developed elements are very difficult to produce by free-form diamond turning techniques. The methods for vortex detection (see, e.g. [20]) are based on a mathematical treatment of the field of gradients or local slopes of the wavefront of a vortex beam. To this end, the gradients of the transverse phase distribution are calculated in the analysis plane and their reorientation is found by integrating various sizes, phase gradient rotor and other radiation characteristics along the perimeter of contours. The hardware implementation of the method is carried out in a nonlinear ring interferometer. Its use as a dislocation detector makes it possible to accurately register the presence and order of an optical vortex even in the presence of an additive 'white' phase noise or an amplitude noise. For detection, it suffices to analyze the nonlinear phase shift averaged over the cross section or the averaged intensity of the beam. However, studies show a significant dependence of the result, especially for high-order vortices, on the size of the integration contour because of the high probability of additional dislocations falling into the integration region. It is difficult to change the contour dimensions in real time. Similar problems arise when using the slopes measured by the Shack–Hartmann sensor for calculating the wavefront gradients. All currently available Shack–Hartman sensors do not allow the microlens raster size to be changed in real time. In addition, the resulting array of experimental data needs to be digitally processed.

The best method for detecting vortices under distortion conditions is a simple and reliable approach based on consistent correlation filtration. This approach is implemented using a phase diffractive optical element (DOE), which decomposes the field along the angular momenta at different points of the output plane [21,22]. Using this approach, Mair et al. [23] studied the entanglement of different angular momenta of photons in different optical fibers. The integration over the area of the analyzed beam was implemented in the Fourier cascade. The method permits the simultaneous detection of the incidence of several beams with the same or different orbital angular momenta in different regions of the output plane into the integration region; at the same time, the correlation maxima do not vanish during the beam wandering, but only move within the corresponding region. The method makes it possible to simultaneously measure the individual contribution of a vortex by the value of the intensity in the center of the correlation maximum and to assess the contribution of several vortices of different orders, which improves the stability of the detection technique to amplitude and phase noises. In the optical system, the corresponding contributions of optical vortices are measured by recording the intensity in one CDD pixel. When the beams travel, leading to the displacement of the correlation peak by more than one pixel, the areas of the measured intensity pattern should be processed using a thresholding procedure to find the maxima. In this case, no transformation of the measured intensity pattern is required.

The propagation of optical radiation in natural aqueous media is accompanied by intense processes of light absorption, reflection and scattering [24], which are caused by mineral and organic polydisperse particles of different shape and chemical composition. Absorption of radiation is also due to chemical substances dissolved in water. In this case, the concentration of particles, their type and size depend significantly on the depth of the water layer and remoteness from the shoreline [25]. The particle parameters are also determined by the type of a water reservoir, the type of surrounding soils and the presence of artificial objects [24]. Moreover, the granulometric composition of the aqueous suspension of a sea and an ocean includes microparticles and microorganisms measuring from 0.25 μm to 50 μm and larger [26]. Thus, an aqueous medium is characterized by random parameters and determines active absorption, reflection and scattering of light.

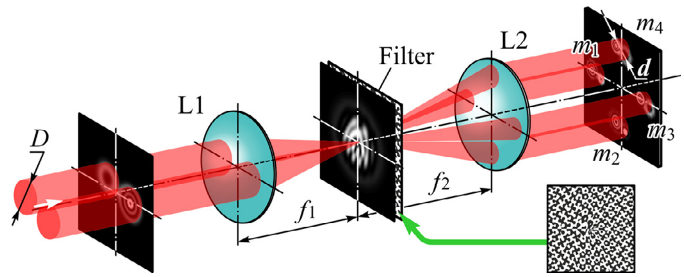

Fig. 1. A multi-channel DOE in the correlation system.

The aim of this work was the experimental approbation of the developed detection technique for the case of propagation of Laguerre–Gaussian vortex beams under conditions of intense absorption, reflection, and scattering of transparent and opaque microparticles in an aqueous suspension.

2. Principles and modeling of the technique for detecting the vortex state of a beam

The principle of the detection technique described in this paper is based on the correlation filtering in the Fourier region using a correlation filter. The correlation filter has a transmission function $\Psi^*_m(x,y)$ that is complex conjugate with the spectrum of the signal $\Psi_m(x,y) = \Im[\psi_m(x,y)]$ to be detected. The input field containing the signal in the form of the superposition $\sum\limits_m \psi_m(x,y)$ is Fourier transformed by means of lens L1 and is incident on the correlation filter (see Fig. 1).

After passing the correlation filter, one more Fourier transformation occurs with the help of lens L2 and correlation maxima are produced at the points of the output plane with coordinates that coincide with the coordinates of the centers of the detected signals in the input plane. The implementation of the described principle of correlation filtration with the help of the DOE allows several different signals to be simultaneously detected by a single filter.

Consider a multi-order DOE, whose transmission function is represented as a linear combination of a limited number of optical vortices $\Psi_m(x,y) = \exp(im\varphi) = \exp(im\tan^{-1}(y/x))$ with different spatial carrier frequencies (α, β):

$$\tau(x,y) = \sum_{p=1}^{P} \Psi^*_{m_p}(x,y)\exp\left[i\left(\alpha_p x + \beta_p y\right)\right]. \quad (1)$$

Note that DOE (1) is consistent with complex conjugate functions $\Psi^*_m(x,y) = \exp(-im\varphi)$. A separation of different functions in superposition (1) is carried out using the principle of superimposed holograms. Optical vortices are invariant to the passage in free space and lens systems, i.e. invariant to the Fourier transform.

Let DOE (1) be supplemented by a spherical lens and illuminated by a light wave $w(x,y)$. The distribution in the focal plane is described by the Fourier transform:

$$\begin{aligned} F(u,v) &= \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} w(x,y)\tau(x,y)\exp\left[-i\frac{2\pi}{\lambda f}(ux+vy)\right]dx\,dy \\ &= \frac{k}{f}\sum_{p=1}^{P}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} w(x,y)\Psi^*_{m_p}(x,y)\exp\left[i\left(\alpha_p x+\beta_p y\right)\right]\exp\left[-i\frac{2\pi}{\lambda f}(ux+vy)\right]dx\,dy \\ &\approx \frac{k}{f}\sum_{p=1}^{P} C_{m_p}\delta\left(u-\frac{\lambda f}{2\pi}\alpha_p,\, v-\frac{\lambda f}{2\pi}\beta_p\right) \end{aligned} \quad (2)$$