Comparative analysis of techniques for diagnostics of phase singularities

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ABSTRACT

The comparative analysis of several techniques for diagnostics of phase singularities in the optical vortex beams and fields is performed. Both advantages and disadvantages in the implementation and applications of different techniques are discussed.

Keywords: singular optics, wavefront dislocations, interference, diffraction, strip Young's interference experiment

1. INTRODUCTION

One of the urgent problems of a singular optics consists in the development of special techniques for detection and diagnostics (determining the magnitude and sign of the topological charge) of phase singularities in vortex-supporting beams in optical fields. Sometimes, namely for studying of partially spatially coherent combined singular beams, inhomogeneous in polarization or polychromatic beams, conventional interference techniques[1,2] are not efficient enough or even inapplicable. So, for diagnostics of partially spatially coherent singular beams resulting from mixing of mutually incoherent Laguerre-Gaussian modes applying the interference technique is impossible due to impossibility to form a reference wave, which would be coherent with all constituting modes simultaneously. Application of the classical interference techniques for diagnostics of phase singularities in polychromatic fields becomes extraordinary complicated due to the necessity of precise adjusting the optical arrangement.

Here we consider the main (both conventional and novel) techniques for detecting and diagnostics of phase singularities and analyze advantages and disadvantages of them in implementation and application of them as well as informativity and unambiguity of the provided result.

2. ANALYSIS

Interference technique

Conventional technique for diagnostics of phase singularities in optical fields is the interference one[1,3] presuming the use of the reference beam mutually coherent with singular beam and observation of an on-axis or off-axis interference pattern. Applying the interference technique to the analysis of "elementary", deterministic optical vortices kind of Laguerre-Gaussian modes one implements interference of the beam bearing one or several phase singularities with a plane or spherical reference beam. In practice, it is convenient to use for this purpose a spread Gaussian beam. Both off-axis and on-axis schemes are widely used. The fringes formed in such a manner can be straight with typical "bifurcations" or spiral depending on inclination and curvature of the reference beam's wavefront[3] as it is shown in Figs. 1 and 2. Let us note, that the number of dark fringes originating from the center (for an off-axis interference scheme, Fig. 1) equals the modulo of the topological change, $|m|$, and the sign if the vortex (the sign of the topological charge) is determined from the direction of

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bifurcation of interference “forklets” (up or down) taking into account the direction of propagation of the reference beam in respect to the interferogram axis. When one implements the on-axis technique, Fig. 2, for diagnostics of phase singularities, then the modulo and the sign of the topological charge of the vortex beam are determined from the number and direction of twirling of the blades in respect to the interferogram axis. In this case one must take into account relation between the curvature radii of the reference and tested beams[1,3,4]. It is clear that in both cases interference testing of vortex beams and fields presumes the use of complicate and precisely adjusted optical arrangement. So, according to the experimental estimations[4], the pattern of on-axis interference is observed if the angle between the axes of the reference and singular beams does not exceed $5 \cdot 10^{-4}$ rad, i.e. about 1.5 angular minutes, and the ratio of the curvature radii of the singular and the reference beams exceeds unity, $R_S / R_{ref} > 1$.

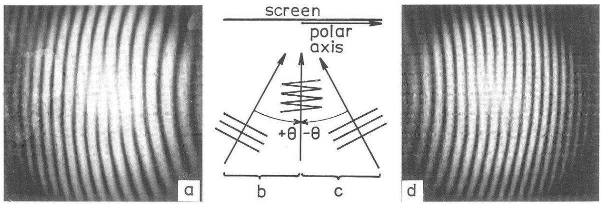

Fig. 1. Off-axis interferograms (**a**, **d**) of wavefront with a unity-charged screw dislocation ($m = 1$), and the corresponding interference schemes (**b**, **c**).

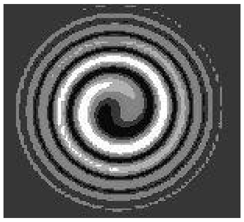

Fig. 2. On-axis interferogram for a single-charged optical vortex.

Thus, the use of interference techniques for diagnostics of phase singularities provides the data on the modulo and the sign of the topological charge of a vortex beam. However, unambiguous information is obtained if only one has *a priory* data on the arrangement and parameters of the tested and the reference beams. Besides, interpretation of the result (the sign of the topological charge of a vortex) obtained using an off-axis technique depends on the orientation of a pattern. So, rotating the pattern shown in Fig. 1 **a** or **d** at 180 deg results in interpretation of the vortex of the opposite sign.

Dove-prism technique

This approach consists in interference of the Laguerre-Gaussian mode with its mirror replica[5]. It is known[2] that mirror reflection results in changing of the sign of the topological charge on opposite one. That is why, when a vortex beam is divided into two partial beams and one additional reflection is provided in one of them, then two partial beams will be of the opposite signs of the topological charge. The Dove-prism technique is based on the summation and interference comparison of such modes. The idea of the technique is to compare the tested bean with its mirrored replica (“auto-reference technique”). It means that this technique does not presume application of additional reference beam. For that, while both partial beams are equal in rights, information of the sign of the topological charge of the initial vortex is lost.

Experimental arrangement is shown in Fig. 3. The Dove prism inserted into one leg of the Mach-Zehnder interferometer inverts the input Laguerre-Gaussian beam, which interfere coaxially with the initial (doubly mirrored) beam at the interferometer output that results in interference pattern as the fringes with $2m+1$ forklet at the center. Note, that using this technique one can obtain the information only on the modulo of the topological charge of the tested singularity on the number of interference fringes originating from the center of interference pattern. For that, it is impossible using this technique to determine the sign of the mode charge. Besides, this technique is applicable to diagnostics of the isolated vortices alone but not foe studying the phase singularities into speckle fields and into partially coherent singular beams.

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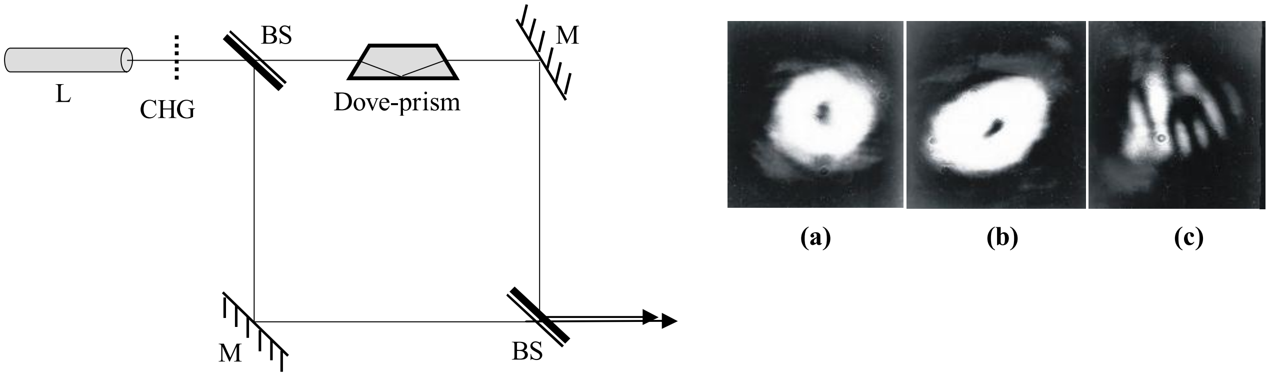

Fig. 3. Interference scheme with the Dove-prism for coherent superposition of two opposite-charged vortices (**a**) and (**b**), and the result of their superposition (**c**).

Diffraction technique

Another technique for diagnostics of optical vortices has been proposed in Ref. 6, which is based on a strip Young's interference experiment[6,7]. The idea of experimental investigation of vortex optical beams can be elucidated using the notations of Fig. 4. An opaque strip is placed at the tested beam symmertically to its center, and interference fringes arising at the geometrical shadow of the strip are observed. Following to the Young-Rubinowicz model of diffraction phenomena we consider these interference fringes as the result of superposition of the *edge diffraction waves*, which are thought as to be retransmitted by the strip edges. Accounting the stationary phase principle, we regard the fringes at any height r as being produced by the edge re-transmitters localized at this height alone.

In Fig. 5 one can see the interference pattern observed behind the diffraction strip positioned in front of a vortex-free beam and of a vortex-supporting one. In the first case (a vortex-free beam), see Fig. 5 **a**, the phases of the edge re-transmitters from both right and left sides are the same. So, one expects to observe the straight Young's interference fringes within the geometrical shadow produced by the superposition of the right- and left-sided wavelets, with the maximum along the mean line of the shadow. But if the tested beam supports the $m-$ charged vortex, one observes the bending interference fringes with the maximum (if m is even) or with zero (if m is odd) at the equator, Fig. 5 **b** and **c**. In general, the phase of the Young's interference fringes for the case under consideration obeys the rule:

$$\Delta\varphi(r,d) = m\left[\pi \pm \arctan\left(r/d\right)\right],$$

where d - is a half of the width of the diffraction strip.

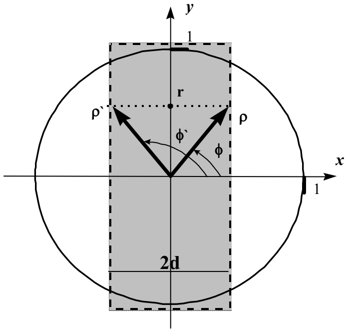

Fig. 4. Notations for analysis of the Young's strip interference experiment.

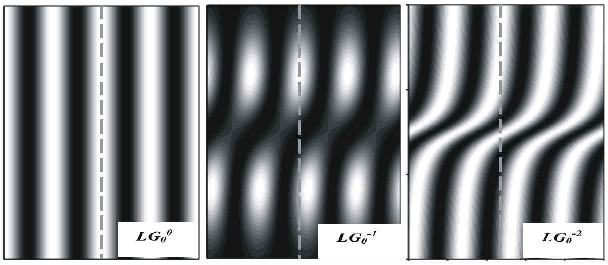

Fig. 5. Simulation of Young's interference fringes for vortexless, for singly-charged (*m*= *-1*) and for doubly-charged (*m*= *-2*) Laguerre-Gaussian modes.

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The basic experimental arrangement is shown in Fig. 6. A vortex-free He-Ne laser mode LG_0^0 illuminates a computer-generated hologram (CGH) computed to reconstruct the single-charged optical vortices of opposite signs at the plus-minus first diffraction orders. At the region where the diffraction spectra are separated, we introduce an opaque screen in front of the each diffraction order. We use a metallic needle as a diffraction screen. Fig. 7. illustrates diffraction testing of LG_0^{-1} −mode supporting a counterclockwise vortex (**a**), and right beam is LG_0^{+1} −mode supporting a clockwise vortex (**b**), respectively.

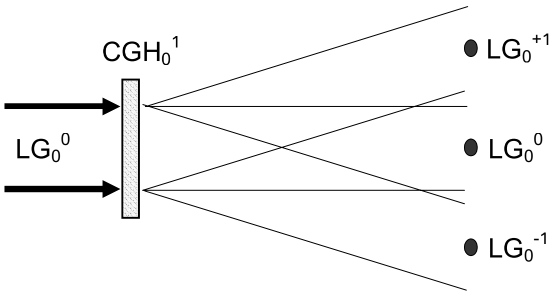
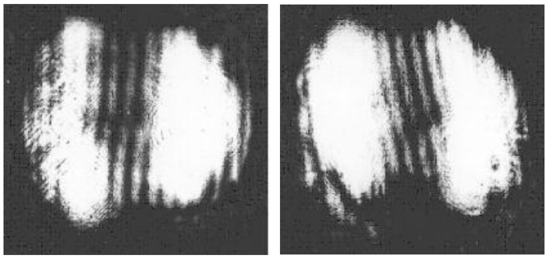


Fig. 6. Experimental arrangement for diffraction diagnostics of vortex-bearing optical beams.



(a) **(b)**

Fig.7. Diffraction testing opposite-charged vortex beams: LG_0^{-1} −mode (a) and LG_0^{+1} − mode (b).

So, one can note that the diffraction technique for diagnostics of phase singularities provides comprehensive information on the parameters of singularity of the beam, *viz.* information both on the modulo of the topological charge of the observed vortex and on its sign, respectively, on the magnitude and the direction of the Young's interference fringes at the geometrical shadow behind an opaque strip. This technique does not require neither additional reference beam what does it convenient for diagnostics of vortices in partially spatially coherent[7-9] and polychromatic[10] beams, where formation of the coherent reference wave is problematic or, sometimes, impossible nor complicate optical arrangement. In contrast to the interference *cross-correlation* techniques where one compares the phases of the singular and the reference beams, this technique is *autocorrelation* one. Namely, one compares the phases in different points of one singular beam. That is why, it is not needed to have any *a priory* information on the studied beam. In contrast to the interference technique, the result obtained by the diffraction technique (see Fig. 7) is objective in a sense that it is invariant in respect to the orientation of the pattern. Really, the direction of bending of the Young's interference fringes is always the same what enables unambiguous determination of the sign of the topological charge of the tested beam.

Wave-guide technique

Once more technique has been recently proposed for determination of the structure of optical vortices. This technique is based on the model of planar waveguide with a leaky mode[11]. Similarly to the Dove-prism technique and diffraction technique, the reference beam is not used here, but the principle of the detection of vortex is different. Due to multi-beam interference into planar waveguide causing high angular resolution such "interfreometer" can be used for diagnostics of phase singularities.

A planar waveguide with a leaky mode is a set of two equal side glass prisms with immersion liquid between them. Refraction index of an immersion is less than the refraction index of prisms. The sides of prisms between which immersion is inserted are parallel. As a result, narrow dark fringe appears in the cross-section of the reflected beam, which is observed both

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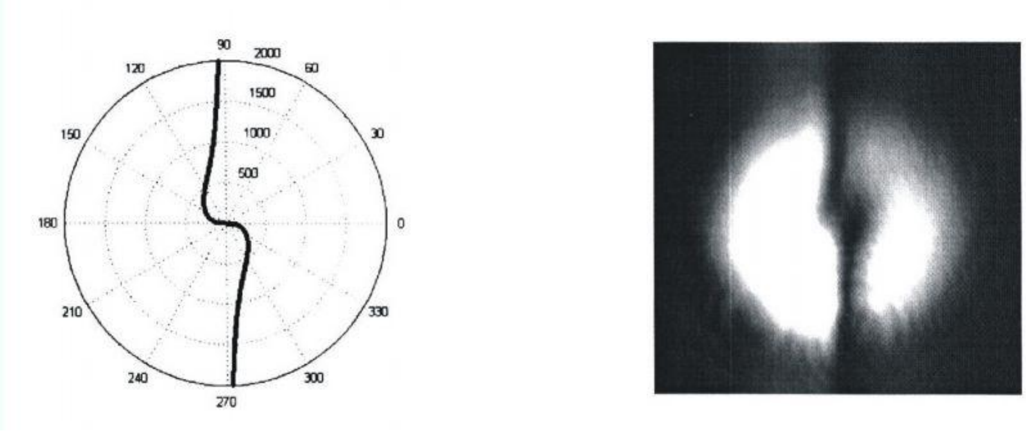
in near and in far field. It provides the possibility to observe the line of zero intensity crossed the beam that is non-localized (infinitely extended) wave dislocation. Scanning an optical beam by such a fringe of zero intensity one can determine on its form the wave front structure of the tested beam.

One can see from Fig. 8 that the presence of singularity its parameters (modulo and sign) of the vortex beam are determined on typical bending of the fringe of zero intensity. Similarly to the diffraction technique, the pattern is invariant in respect to rotation at 180 deg. Thus, the direction of bending of the fringe of zero intensity without *a priory* information.



(a) **(b)**

Fig. 8. Modulation of the dark line in the geometrical optics approximation, the beam waist is before waveguide (**a**); beam image reflected from the waveguide (**b**).

Thus, using the waveguide technique for diagnostics of phase singularities in optical beams one can determine the parameters of the tested vortex. This technique has been recently implemented foe white light vortices[12]. However, implementation of this approach is rather sophisticated. To provide multi-beam interference into thin layer of immersion liquid (glycerin) one must use precise goniometric equipment. Also, the tested beam must be of diffraction limited convergence. Besides, one must take into account that the uniquely high resolution ($6\cdot10^{-5}$ for He-Ne laser) is predicted by the geometrical theory of the technique alone (infinitely narrow dark line). At the same time, under the wave optics approximation and in the experiment such resolution is not realized while the infinitely narrow "black" line is surrounded by relatively broad area of non-zero but very low intensity, see Fig. 8 **b**.

Chromascope technique

Quite new technique for processing of phase singularities in the polychromatic speckle fields arises from the concept of a chromascope[13,14] intended for explanation of the universal color gamut seen by a human observer near an *isolated zero*, viz., within the area where the complex amplitude $\psi(R,k)$ varies linearly with position R over the spatial range considered, and linearly with wavenumber k over the visible range. In is remarkable that in this case "Approximately circular regions of colors, including intense blue, red and yellow, separated by a large white circle, merge into an unsaturated "asymptotic white"… the region in the total gamut of possible colors that the universal pattern occupies is rather

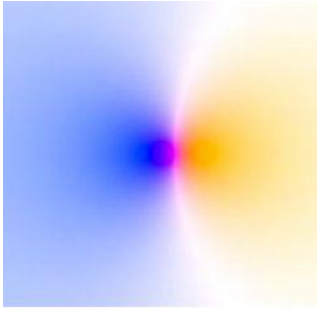


Fig. 9. Universal color pattern near an isolated phase singularity.

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small; most notably, there is no green", as it is seen in Fig 9. The concept of a chromascope is implemented using the following equation:

$$\begin{pmatrix} R \\ G \\ B \end{pmatrix}_{CR} = \begin{pmatrix} R \\ G \\ B \end{pmatrix} \Big/ \max(R, G, B),$$

Where we normalize the colors in each point of the field (ξ, η) based on the maximum intensity of any color in the RGB scale. This increases the brightness for points of low intensity, namely, in the vicinity of amplitude zeroes. Therefore, if all three spectral components are of low intensity, then these areas processed by a chromascope appear 'white'[15].

This technique is applicable only for detecting the vortices into polychromatic fields on the universal gamut of colors but not for determining the vortex parameters. Besides, this is software technique presumed just for polychromatic fields rather than universal experimental technique.

3. CONCLUSIONS

In this paper we have analyzed several different techniques for detection and diagnostics of phase singularities in optical beams and fields. We have argued the advantages and disadvantages of these diagnostic techniques. It has been shown that some techniques (in part, the Dove-prism technique, the chromascopic technique) are applicable for detection of a phase singularity alone but do not provide information on the parameters of singularity. Another class of techniques (interference) presumes some *a priory* information of the curvature radius of the reference beam (on-axis technique) or mutual orientation of the reference and singular beams (off-axis technique) for correct determination of the sign of the topological charge of a vortex. Having such information one obtains unambiguous and comprehensive result of diagnostics, and such techniques are the most popular among experimentalists elaborating completely spatially coherent monochromatic fields. At the same time, the use of interference techniques less convenient or even impossible in the domain of partially spatially coherent and polychromatic fields. Some techniques (the waveguide technique) require complicate and high-precision equipment and fine adjusting of the optical arrangement. Practical resolution provided by this technique occurs considerably less than it was predicted by the geometrical optical theory. Nevertheless, this technique is objective one and enables unambiguous diagnostics of optical vortices without any *a priory* information on the beam parameters and can be applied to white light vortices. In our opinion, the most flexible techniques for diagnostics of phase singularities is the diffraction technique based on the Young's model of diffraction phenomena (the model of the edge diffraction wave) and on the Young's interference experiment in its initial form, with an opaque strip. This technique does not require any *a priory* information on the tested beam and complicate optical arrangement and, at the same time gives unambiguous and comprehensive data on the parameters of singular beam, including the modulo and the sign of the topological charge. This technique has been successfully used for experimental elaboration of the phase singularities both in completely coherent and in partially spatially coherent, inhomogeneously polarized and polychromatic light beams.

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