YOUNG'S DIAGNOSTICS OF PHASE SINGULARITIES OF THE SPATIAL COHERENCE FUNCTION AT PARTIALLY COHERENT SINGULAR BEAMS

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A complex experimental technique for the separate determination of the azimuthal and radial dependences of a phase of the spatial coherence function of partially spatially coherent singular beams is introduced and demonstrated by the example of combined beams with a separable phase of the spatial coherence function. Beside of the diagnostics of the central vortex of the spatial coherence function, the presence of the ring singularity of the complex degree of coherence supported by a partially spatially coherent singular beam is showed experimentally for the first time.

Introduction

Singular optics is the chapter of modern physics dealing with light fields, any parameter of which degenerates [1]. So, in fully coherent monochromatic and uniformly (in general, elliptically) polarized fields, the phase of the wave's complex amplitude becomes undetermined at points (or lines, or surfaces), where the wave amplitude vanishes [2]. In fully coherent monochromatic but spatially nonuniformly polarized electromagnetic fields, in the plane perpendicular to the mean direction of propagation of a paraxial beam, one observes the vector singularities, such as disclinations (temporal singularities), C-points (points where the field is circularly polarized), and L-contours (lines where the field is linearly polarized) [3], as well as so-called Stokes singularities [4].

It has been realized only at the threshold of the third millennium that phase singularities can be supported by not the wave's complex amplitude alone, but also by any complex parameter of a light field, including correlation functions of the field, which is not without fail fully coherent. This statement has been for the first time formulated explicitly by Prof P. Polyanskii [5, 6]. Investigations of phase singularities of the correlation functions of partially coherent vortex beams constitute a new direction of singular optics, namely correlation singular optics. It is worth to be noted that early considered Stokes singularities [4] are non-intrinsic singularities of real optical fields, being rather the singularities determined in the artificially constructed analytical complex Stokes space. In contrast, the phase singularities of correlation functions are intrinsic in real optical fields, being connected with observables in optics [7].

Coming into being of correlation singular optics presumes not only the generalization of the conceptual basis of singular optics, but also the development of adequate theoretical and experimental instrumentations. In part, the use of a separate reference wave to detect and diagnose phase singularities, regularly and efficiently implemented in singular optics of fully coherent fields [1, 8], becomes inappropriate into a space of partial coherence. To all appearance, the "referenceless" (or auto-reference, or autocorrelation) experimental methodology introduced early in optical holography [9—11] is the most promising approach in this context. The key idea of this methodology consists in the correlation comparison of disturbances at two different probing points of the tested beam, rather than in the determination of the relative phase difference between the vortex beam of interest and a separate reference wave. It is clear that an implementation of this methodology must be based on any version of the Young's interference experiment.

One of the initial implementations of the Young's diagnostics of phase singularities of the spatial coherence function supported by partially spatially coherent vortex beams has been recently reported in paper [12]. (A close approach, though without adequate substantiation, has been realized in X-ray optics [13]). Following the theoretical background [14], in paper [12], we have synthesized partially spatially coherent singular beams with a separable phase of the spatial coherence function (or cross-spectral density) by the incoherent coaxial superposition of two weighed one-charged Laguerre—

Gaussian modes with different radial mode indices. (The notion of a separable phase is explained in Section 1.) In the same paper, we have introduced a new diffraction technique for the diagnostics of phase singularities at optical fields, which is applicable for the experimental analysis of dislocations of a spatial coherence function in both fully coherent and partially coherent fields. This technique, substantiated in details in [15, 16], has been developed by us proceeding from the Thomas Young's interference experiment in its initial version [17, 18], when the analysis of spatial coherence is performed using an opaque diffraction strip, rather than using the generally accepted now technique with two pinholes (or two slits) in an opaque screen.

Carrying out the study [12, 15, 16], we essentially used the statements [19, 20] that (a) the phase of the spatial coherence function is *directly* observed as the phase (specific spatial localization) of interference fringes in the Young's interference experiment, and (b) under some general assumptions, the modulus of the complex degree of coherence is *directly* connected with a visibility of the interference pattern.

However, the success of the study [12] was not complete. So, the diffraction Young's technique has provided revealing the central vortex of the spatial coherence function, but it has no provided the visualization of the ring dislocation of the complex degree of coherence (that is, the analog of a non-localized dark interference fringe [2] in the space of partial coherence) predicted by theory [14].

Here, we propose and implement, for the first time, a complex technique based on the Young's interference experiment in its various versions, which provides the comprehensive experimental analysis of a singular structure of partially spatially coherent beams bearing phase singularities of the spatial coherence function. Let us emphasize that *any* Young's interference experiment gives us the data on the spatial autocorrelation function of a singular beam, rather than on the mutual correlation function of a tested singular beam and a separate reference wave. It is true also in the case of applying the presented technique to fully coherent dislocation-bearing optical fields [15, 16].

Despite our consideration concerns to the partial case of the beams with a separable phase of the spatial coherence function, we believe that the technique introduced here is of general applicability for the investigation of partially coherent combined singular beams of arbitrary nature.

1. Basic Definitions

An instructive example of singular optical beams is the Laguerre—Gaussian modes, LG_n^m, where the subscript n refers to the order of a Laguerre polynomial, and the superscript m refers to the azimuthal mode index (the topological charge) of a singular optical beam. The former indicates the number of nodes (non-localized dark interference fringes [2]) along the radial distribution of wave amplitudes at the "doughnut" mode, and the later indicates the value of a phase change in a closed loop around the circumference of the beam axis in 2π measure. It is known [14] that LG_n^m-modes are the singularity-supporting beams with a separable phase. Namely, in polar coordinates (ρ, ϕ), the phase of a beam is represented by the product

$$f_l\left(\rho/w_z\right)\exp\left[im\phi\right], \tag{1}$$

where ρ/w_z is the dimensionless radial variable equal to the ratio of the radial coordinate, ρ, to the beam width, $w_z = \left(w_0^2 + 4z^2/k^2w_0^2\right)^{1/2}$, w_0 being a spot-size at the beam waist, z being the distance from the beam waist to the plane of observation, and $k = 2\pi/\lambda$. In Eq. (1), the first (radius-dependent) factor is determined as $f_l(\rho/w_z) = (l-1)\pi$, l being the number of the bright ring, and the second (azimuth-dependent) factor is explained above.

The simplest partially spatially coherent singular beam [12] is constructed by the co-axial mixing of two weighed statistically independent (mutually incoherent) Laguerre—Gaussian modes LG_n^m with the same $m = \pm 1$ but with different $n = 0, 1$. If the ratio of integral powers of the modes with $m = 0, |1|$ is $P_0/P_1 = 1.45$, then the combined beam has the radial intensity distribution resembling such a distribution for the isolated $\mathrm{LG}_0^{|1|}$-mode, see Fig. 1. The partial spatial coherence of such a combined beam results from the variable intensity ratio of the constituting modes along the beam radius. As shown in [14], the phase of the cross-spectral density of the combined beam (as well as the phase of the associated spatial coherence function [7]) is also separable, being represented as the product

$$f_{lj}\left(\frac{\rho_l - \rho_j'}{w_z}\right)\exp\left[im\left(\phi - \phi'\right)\right], \tag{2}$$

where the radius-dependent factor is determined as $f_{lj}\left(\frac{\rho_l-\rho_j'}{w_z}\right) = (l-j)\,\pi$ [$\rho = (\rho, \phi)$ and $\rho' = (\rho', \phi')$ are the position vectors of the probing points of the combined partially spatially coherent singular beam].

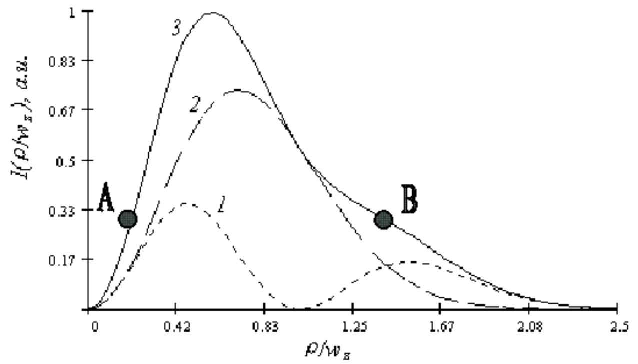

Fig. 1. Radial distributions of Laguerre—Gaussian modes $\mathrm{LG}_1^{|1|}$ and $\mathrm{LG}_0^{|1|}$ (curves *1* and *2*, respectively) and of the combined partially coherent beam (curve *3*) vs dimensionless variable $^{\rho}/_{w_z}$. Ratio of integral powers of the constituting modes is $P_0/P_1 = 1.45$. A and B are the probing points for the revealing of a ring phase singularity of the complex degree of coherence

Thus, the phase of the spatial coherence function and the phase of the associated normalized value, namely the complex degree of coherence, are altered at the crossing of each radial node of these functions. At the ring, where the modulus of the complex degree of coherence vanishes, the phase of this function undergoes a singularity.

2. Diffraction Diagnostics of the Vorticity of the Spatial Coherence Function

The idea of experimental investigation of the azimuthal dependence of the phase of a spatial coherence function at the combined partially coherent singular beam and the diagnostics of the vorticity of this function [12] is clear from Fig. 2. An opaque strip of width $2d$ is placed at the tested beam symmertically to its center, and interference fringes arising at the geometric shadow of the strip are observed. Following to the Young—Rubinowicz model of diffraction phenomena [7, 11, 17, 18, 21—24], we consider these interference fringes as a result of the superposition of edge diffraction waves which are thought as to be re-transmitted by the strip edges. The formal description of such an interference pattern is based on so-called Rubinowicz's representation of the Kirchhoff's diffraction integral [7, 23]. Accounting the stationary phase principle [24], we regard the fringes at any height r as being produced by the edge re-transmitters localized at this height alone.

As shown in [15], the structures of the interference patterns at the geometric shadow of an opaque strip illuminated by a simple wave (such as plane wave or Laguerre—Gaussian mode) and by an m-charged optical vortex are distinctly different. So, if a singularity-free beam impinges upon an opaque strip, then the phase difference among wavelets from the edge re-transmitters, $\Delta\varphi = \varphi - \varphi'$, equals zero for every r and, consequently, for every difference of azimuthal coordinates $\Delta\phi = \phi - \phi'$, as far as $\Delta\rho = \rho - \rho' \equiv 0$. As a result, one observes straight interference fringes with a maximum at the center of the geometric shadow, see Fig. 3,a. In contrast, if an m-charged vortex beam impinges upon opaque strip, then the phases of the wavelets from "equatorial"

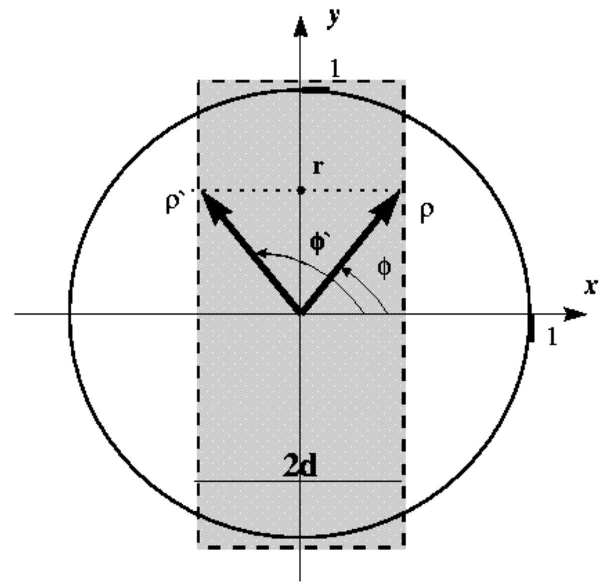

Fig. 2. Notations for analysis of the strip Young's interference experiment for testing of the azimuthal dependence of the vortex spatial coherence function: $2d$ is the strip width, $\rho = (\rho, \phi)$ and $\rho' = (\rho', \phi')$ are the position vectors of the edge re-transmitters forming an interference pattern at height r

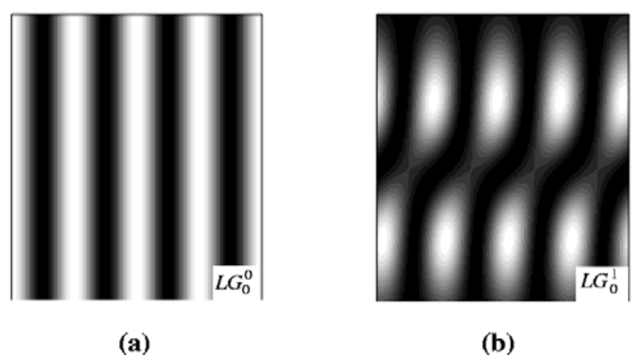

Fig. 3. Simulated Young's interference fringes behind an opaque strip illuminated by a vortex-free mode LG_0^0 (a), and by a doughnut mode LG_0^{-1} (b); $d/w_z = 0.4$

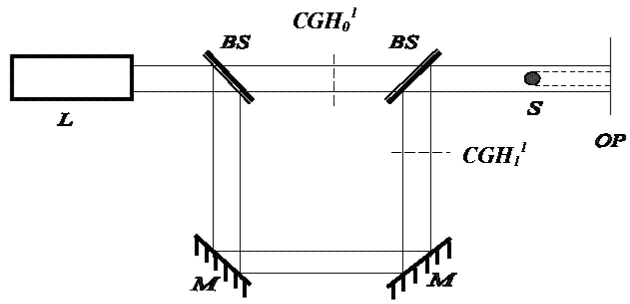

Fig. 4. Experimental arrangement for diagnostics of the central vortex of the spatial coherence function of partially coherent singular beam: L — laser, BS — beam-splitters, M — mirrors, CGH_0^1 and CGH_1^1 - computer-generated holograms reconstructing the modes LG_0^1 and LG_1^1, respectively, S — an opaque screen, OP — observation plane

edge re-transmitters ($r = 0$, $\Delta\phi = \pi$) differ in phase by $m\pi$, while $\Delta\varphi$ approaches zero as $\Delta\phi$ (asymptotically) approaches zero (at "poles"). Generally, the interference fringes corresponding to the m-charged optical vortex are bent following to the rule [15]:

$$\Delta\varphi(d,r) = m\pi \pm \mathrm{arctg}^{r}/_{d}, \tag{3}$$

where the signs plus-minus correspond to the right-hand and left-right phase twirlings, respectively. In other words, this sign coincides with the sign of the topological charge, m. Thus, the magnitude and the direction of bending of Young's interference fringes are unambiguously associated, respectively, with the modulus and the sign of the topological charge of an optical vortex. The result of simulation of an interference pattern for the doughnut mode LG_0^{-1} is shown in Fig. 3,*b*.

The experimental arrangement for the creation of the simplest partially spatially coherent vortex beam kind of one shown in Fig. 1 and for testing the azimuthal dependence of the phase of the spatial coherence function of such a beam is shown in Fig. 4. The beam from a He—Ne laser (mode LG_0^0) is splitted into two beams, and an optical path delay is provided in one leg of the mismatched Mach—Zehnder interferometer, which exceeds the considerably preliminarily measured coherence length of the used laser. So, in our experiment, the coherence length of the laser radiation is about 27 cm, and the optical delay path is about 80 cm. (We also checked that the provided optical delay path was much less than the doubled length of the laser resonator to avoid the coincidence with the secondary maximum of the longitudinal coherence function of the emitted radiation.) Thus, two partial beams mixed at the output of the interferometer are virtually mutually incoherent.

To create desirable Laguerre—Gaussian modes, we have implemented the computer-generated hologram technique, the remarkable instrument of singular optics introduced by Prof. M. Soskin [25] and widely used now. In two legs of the interferometer, at equal distances from the mixing output beam-splitter, we place off-axis computer-generated holograms calculated for the reconstruction of the modes $\mathrm{LG}_0^{\pm1}$ and $\mathrm{LG}_1^{\pm1}$ at the first diffraction orders. Further, using spatial filters (not shown in Fig. 4) we select the orders, in which the mentioned one-charged Laguerre—Gaussian modes with equal signs of the topological charge (in our case, $m = +1$) are reconstructed. In addition, using neutral attenuators at the legs of an interferometer (not shown in Fig. 4), we provide the desirable ratio of the integral powers of the mixed modes, $P_0/P_1 = 1.45$. At the combined beam, we place a metallic needle as an opaque screen. In our experiment, $d/w_Z \approx 0.25$. An interference pattern is observed within the geometric shadow region behind the needle restricted in Fig. 4 by dashed lines. The distance from an opaque screen to the plane of observation of interference fringes is not critical for the diagnostics of phase singularities. It is chosen from the consideration of convenience, with regard for that the spatial frequency of the Young's interference fringes and the number of the observed fringes are, approximately, in the inverse proportion to this distance.

The main experimental result is shown in Fig. 5. Fragments Fig. 5,*a* and *b* demonstrate, respectively, the diffraction diagnostics of the central vortex of the spatial coherence function supported by the completely coherent isolated partial modes LG_0^{+1} and LG_1^{+1}. The bending of interference fringes following rule (3) is quite evident in both fragments. In addition, in fragment Fig. 5,*b*, one can see a half-period shift of interference fringes in the vicinity of the ring node of an amplitude distribution in the LG_1^{+1}-mode ($\rho/w_z = 1$). On this shift, one diagnoses an envelope-like (two-dimensional) phase singularity kind of a non-localized dark interference fringe [2]. Fragment Fig. 5,*c* demonstrates the diffraction diagnostics of the central vortex of the spatial coherence function supported by a partially spatially coherent combined beam. The bending of interference fringes is the same as at the isolated constituting modes LG_0^{+1} and LG_1^{+1}.

Let us discuss here both advantages and disadvantages of the introduced experimental approach. First of all, the diffraction diagnostics of phase singularities at optical beams is quite universal, being

(a) (b) (c)

Fig. 5. Experimental results: diffraction diagnostics of the phase singularities at isolated modes LG_0^1 (a) and LG_1^1 (b), and of the central vortex of the spatial coherence function of the combined partially spatially coherent singular beam (c)

applied both to completely coherent and partially coherent vortex beams. Beside of partially spatially coherent monochromatic vortices considered here, the same technique has been recently successfully extended to the case of spatially coherent polychromatic singular beams [26]. Secondly, this technique is the only applicable one for the diagnostics of phase singularities at partially coherent vortex beams, and it possesses undoubted advantages in the diagnostics of polarization singularities [27]. Further, an implementation of the diffraction technique does not presume a fine adjusting of cumbersome interferometric arrangements as well as having any a priori information on the parameters of a reference wave such as the curvature radius of this wave or the sign of the interference angle [8]. At last, the strip Young's experiment provides a direct and complete information on the azimuthal dependence on a phase of the spatial coherence function "in one frame" rather than that as a result of the processing of numerous two-pinhole Young's interference experiments.

However, one meets some difficulties in applying this technique to the revealing of the ring singularities of the spatial coherence function with a complex degree of coherence predicted by theory. The nature of these difficulties and the means of overcoming them are elucidated in the following section.

3. Young's Diagnostics of the Ring Singularity of the Complex Degree of Coherence

It follows from the theoretical consideration [14] that the combined beam resulting from an incoherent superposition of the weighed Laguerre—Gaussian modes $LG_0^{|1|}$ and $LG_1^{|1|}$, beside of the central vortex of the spatial coherence function, supports the ring singularity of the complex degree of coherence, which is an analog of the non-localized dark interference fringe at the isolated mode $LG_1^{|1|}$ at $\rho/w_z = 1$, see Fig. 5,b. So, if the combined beam is generated with $P_0/P_1 = 1.45$, then such a singularity takes place at the ring $\rho/w_z \approx 1.45$ [12]. However, it is hardly to reveal such a ring singularity of a complex degree of coherence using the strip Young's experiment applied successfully for the diagnostics of the central vortex of the spatial coherence function.

First of all, the node at the radial intensity distribution of the combined beam at the ring $\rho/w_z \approx 1.45$ is absent, as seen from Fig. 1 and Fig. 5,c. As so, one cannot observe a half-period shift of interference fringes in the vicinity of the ring singularity kind of one shown in Fig. 5,b.

What is more important, the field of the combined beam of interest does not obey the requirement of statistical homogeneity and isotropy [28, 29], which is generally accepted in studies of partially coherent fields [19, 20]. It means that the statistical moments of the field, including the complex degree of coherence, are dependent on a specific choice of the probing points within the beam cross-section, ρ and ρ', rather than on the difference $|\rho - \rho'|$ alone.

Moreover, the intensity distribution at a beam's cross-section is also nonuniform. As a consequence, the visibility of interference fringes, V, obtained, to say, in a two-pinhole Young's experiment is not connected unambiguously with the modulus of the complex degree of coherence, $|\mu_{AB}|$, being obeying the more complicated

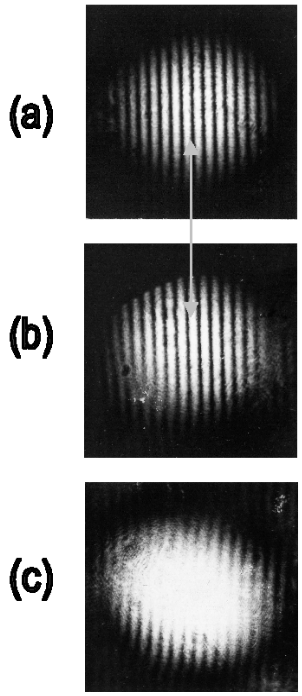

Fig. 6. Revealing the ring singularity of the complex degree of coherence of the combined partially spatially coherent singular beam via two-pinhole Young's interference experiment: interference fringes of unity visibility produced by the isolated modes LG_1^1 (a) and LG_0^1 (b), respectively (arrows show a half-period shift of two interference pattern); a pattern produced by both mutually incoherent modes (c), vanishing visibility confirms the presence of the ring phase singularity of the complex degree of coherence at $\rho/w_z \approx 1.45$

law [19]:

$$V = \frac{ab}{a^2 + b^2}|\mu_{AB}|, \tag{4}$$

where a and b are the amplitudes of the disturbances at the probing points of the beam, A and B, respectively. It follows from Eq. (4) that the visibility of interference fringes depends both on the correlation of two disturbances and on the amplitude ratio of these disturbances.

Three mentioned circumstances dramatically hamper obtaining a complete map of the coherence function of the combined beam. In this context, the success of the study described in Section 2 is caused mainly by the axial symmetry of the problem and a specific location of an opaque strip at the combined beam, which evidently excludes all mentioned problems.

Let us note the fundamental difference among the azimuthal and radial dependences of the spatial coherence function of the combined beam. The former is generically two-dimensional, while the latter is one-dimensional, being determined for $\Delta\rho = \rho - \rho' \neq 0$, but $\Delta\phi = \phi - \phi' \equiv 0$. Proceeding from this difference, we implement the diagnostics of the ring phase singularity of the complex degree of coherence by performing a two-pinhole Young's interference experiment. Really, in contrast to the problem considered in the previous section, a single two-pinhole Young's experiment occurs to be now sufficient. In this study, we essentially use the classical approach of B. Thompson [20] (see also [7, 29]) to determine a phase of the complex degree of coherence in connection of the Van Cittert—Zernike theorem.

The experimental revealing of the ring singularity of the complex degree of coherence of a combined beam has been performed by us using the arrangement of a star Michelson interferometer [19, 20]. Namely, the strip S in Fig. 4 is replaced by a plane opaque screen with two pinholes positioned at the radius of the beam. Just behind this screen, one places an objective and observes an interference pattern at the back focal plane of this objective. The key point in carrying out this experiment consists in a proper choice of probing points at the radius of the combined beam. As has been found, one can specify the probing points, A and B, in such a manner that the main mentioned problems disappear. If the probing points are chosen as shown in Fig. 1, point A at $\rho/w_z \approx 0.18$ and point B at $\rho/w_z \approx 1.45$, then the resulting pattern at the back focal plane of the objective can be considered as the superposition of two independent interference patterns from mutually incoherent modes LG_1^1 and LG_0^1.

Both partial patterns are of the same spatial frequency owing to the equal interference angles. Fortunately, as seen from Fig. 1, both resulting disturbances (curve *3*) are of equal intensity, and the same is true for four partial disturbances (see the corresponding points at curves *1* and *2*) at pinholes A and B. As a result, the amplitude factor in Eq. (4) is equal to unity, and the visibility of *every* interference pattern (both partial, produced by isolated constituting modes, and the resulting, produced by the combined beam) is directly connected with the modulus of the complex degree of coherence.

Two partial patterns produced by isolated modes LG_1^1 and LG_0^1 are shown in Fig. 6,a and b, respectively. Both patterns are of unity visibility that corresponds to the complete coherence of disturbances of equal intensities produced by the each partial mode. The only difference of two patterns (shown by arrows) consists in a half-period shift of interference fringes that reflects different phases of the complex degree of coherence. So, a dark interference fringes arises at the center of the pattern for the mode LG_1^1, while the phase of this mode is changed by π at the ring $\rho/w_z = 1$. At the same time, a bright interference fringe arises at the center of the pattern for the mode LG_0^1. Illuminating an opaque screen with the combined beam, one obtains the result shown in Fig. 6,*c*. Superposition of two shifted interference patterns of unity visibility and equal average intensity results in the vanishing visibility of a pattern. It just means that the complex degree of coherence of the combined disturbances at points A and B is equal zero.

Let us note that the same conclusion can be obtained for another specification of the probing points at the radius of the combined singular beam. However, our choice is preferable as it provides a straightforward confirmation of the presence of a ring singularity of the complex degree of coherence based on the concepts of classical optics.

Conclusions

In this paper, we have implemented, for the first time, a complete diagnostics of phase singularities of the spatial coherence function of partially coherent singular beams.

Both azimuthal and radial behaviors of the spatial coherence function have been determined *via* two versions of the Young's interference experiment, without using a separate reference wave. Taking the combined beams with a separable phase of the spatial coherence function as an example, we have realized the conditions when one can detect both the central vortex of the spatial coherence function (on the bending of interference fringes at the shadow of the diffracting strip), and the ring singularity of the complex degree of coherence (on the vanishing of the visibility of resulting interference fringes in a two-pinhole Young's experiment).

Thus, a new powerful experimental tool of correlation singular optics has been introduced, and the comprehensive solution of the problem of experimental analysis of phase singularities intrinsic to the spatial coherence function of partially coherent singular beams has been obtained.

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ЗАСТОСУВАННЯ ДІАГНОСТИКИ ЮНГА ДО ВИВЧЕННЯ ФАЗОВИХ СИНГУЛЯРНОСТЕЙ ПРОСТОРОВОЇ ФУНКЦІЇ КОГЕРЕНТНОСТІ ЧАСТКОВО КОГЕРЕНТНИХ СИНГУЛЯРНИХ ПУЧКІВ

Х.В. Фельде

Р е з ю м е

Розроблено комплексний експериментальний метод роздільного визначення азимутальної та радіальної залежностей фази просторової функції когерентності частково когерентних сингулярних пучків. Метод проілюстровано на прикладі комбінованих пучків із сепарабельною фазою просторової функції когерентності. Окрім діагностики центрального вихора просторової функції когерентності, вперше експериментально показано наявність кільцевої сингулярності комплексного степеня когерентності частково когерентного сингулярного пучка.