2.4 Optical Correlation Diagnostics of Phase Singularities in Polychromatic Speckle Fields

2.4.1 Interferometric diagnostics of spectral phase singularities in polychromatic speckle fields

The diffraction (referenceless) technique for detection and diagnostics of phase singularities represented in Section 2.3 is rather suitable when one operates with a beam supporting an isolated singularity, such as the doughnut Laguerre-Gaussian mode. But in the case of polychromatic partially spatially coherent fields bearing singularities such as white-light speckle fields, this technique is less practicable. In reality, the use of the diffraction technique for this case illustrates the mechanical scanning procedure. Besides, the requirement of mutual spectral purity of radiation impinging onto two edges of an opaque strip is not generally compatible. Thus, following Ref. 3, one can specify the phase singularities considered in the previous section as *nongeneric*, in contrast to the amplitude zeros at a speckle field, implying that "generic means that the object in question occurs without special preparation or conditions; it is typical and *just happens*." Hence, following Ref. 29, we now present the interference technique for detection of phase singularities in the spectral components of a polychromatic random field, which provides obtaining a map of the phase singularities over the area of interest without scanning, in one step.

The interference technique that uses a separate reference wave, as in Ref. 8, provides an experimental diagnostic tool for white-light optical vortices by registration and analysis of interference forklets in free-space propagation of white light. The interference technique can be considered as the diagnostic instrument that provides (1) increased sensitivity and resolving power, especially for the control of film growths, in connection with spectral scanning, and (2) reducing the inverse problem of optics dealing with the correct determination of the average height of rough surface inhomogeneities (i.e., presuming a unique solution) based on the processing of partial solutions for the given set of spectral components.

The use of the interference technique for the analysis of polychromatic radiation provides new feasibilities for diagnostics of coinciding amplitude zeros for the discrete spectral components in white light. As a matter of fact, the coherence length of white light is extremely small (not exceeding a few wavelengths). The problem of diagnostics of singularity in such a case presumes calling for a precise interferometric experiment, in which one must provide (1) a high degree of spatial coherence of the radiation, (2) mutual spectral purity in both channels of an interferometer to obtain a coincident maximum in the interference pattern, (3) proper inclination of the reference beam with respect to the object beam by a unique system for fine adjustment, and (4) feasibility to monitor the field at arbitrary but well-defined distances from the object.

These complications are overcome in the arrangement shown in Fig. 2.10. A condenser lens C collects the radiation of a white-light source S at the diaphragm D placed at the focus of the objective O1. As a result, the 5-mm diameter beam

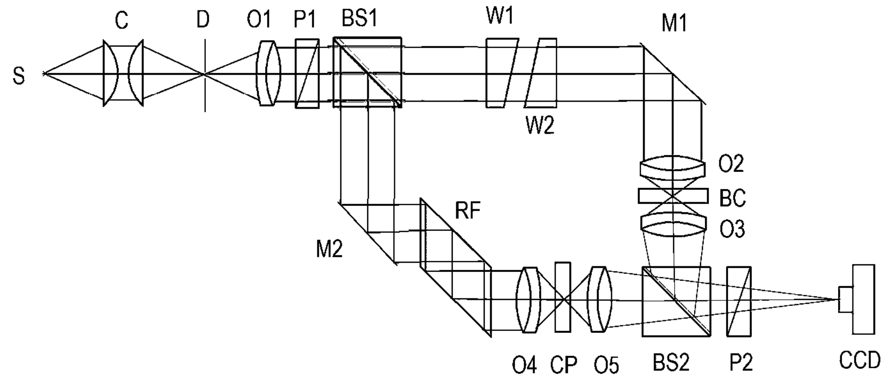
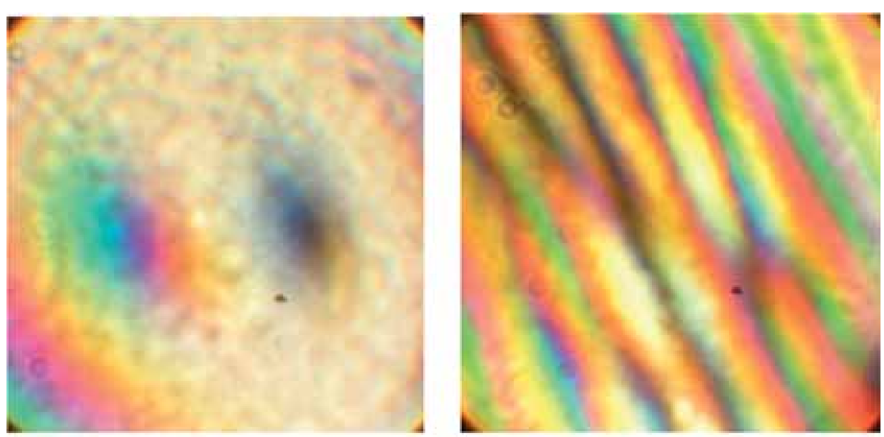


Figure 2.10 Experimental arrangement. S: white light source; C: condenser; D: 20 μm diameter diaphragm; O1 ($f = 200$ mm), O2, O3, and O4: objectives; P1 and P2: polarizer and analyzer; BS1 and BS2: beam-splitting cubes; M1 and M2: mirrors; BC: singularity-generating object; CP: compensating plate; RF: Fresnel rhombus; W1 and W2: moving and stationary optical wedges; CCD: camera.

behind the objective possesses a high degree of spatial coherence (∼90%). This beam passes a polarizer P1 and is divided by beamsplitter BS1 into two beams of equal intensities. Beamsplitters BS1 and BS2, and mirrors M1 and M2 (achromatic and nonselective in polarization) form a Mach-Zehnder interferometer, providing equal conditions for the beams in both legs of the interferometer. A singularity-generating object BC is placed in one leg. In the experiments,[29] this was a film of a polyethylenterephthallium (PETP) that has the properties of a double-axial crystal (a thickness of 74 μm, a difference of refraction indices of 0.085), or an object with an inhomogeneous phase, providing a large phase variance. The object is placed in the converging beam between the objectives O2 and O3. To facilitate identical chromatic and aberration conditions in the legs of an interferometer, the objectives O4 and O5 (which are identical to the objectives O2 and O3), with compensating plate CP in between, are placed in another leg of the interferometer. A Fresnel rhombus RF that provides circular polarization for all spectral components of white light is placed in the second leg. To geometrically compensate for the beams from the Fresnel rhombus, two optical wedges W1 and W2, forming a plane-parallel plate, are inserted in the other leg. The shift of the wedge W1 along its hypotenuse enables control of the thickness of the plate and, as a consequence, of the optical path difference in the legs of the interferometer. The interferometer output is followed by analyzer P2 and a CCD camera. Objectives O3 and O5 can synchronically be moved along the direction of the propagating beams, providing equal convergence. The angle of interference in the interferometer is controlled by transverse displacement of the objective O5.

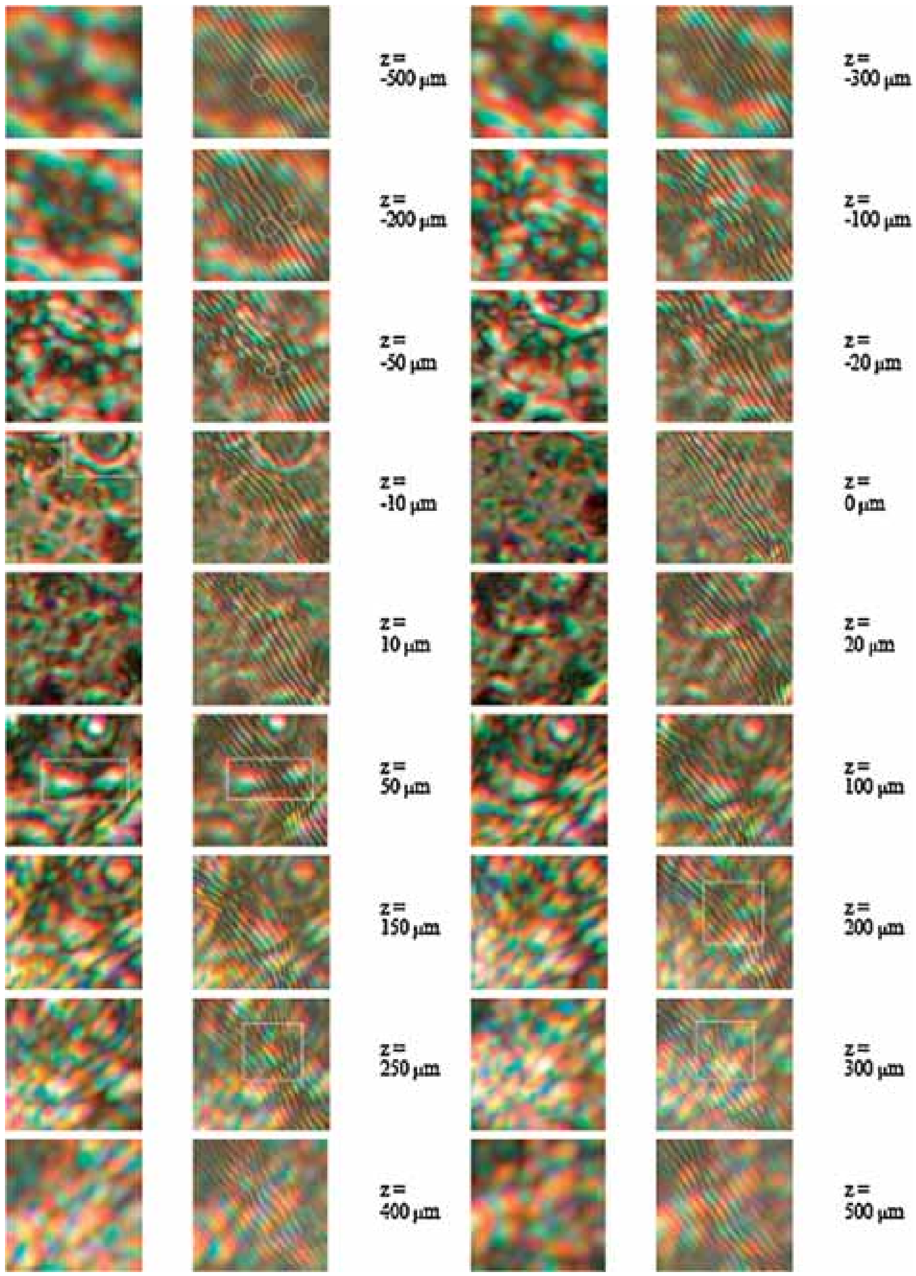
Figure 2.11 illustrates the feasibilities of the interference technique for detecting a singularity obtained under propagation of a white-light beam along any of the two axes of a double-axial crystal placed between the matched polarizer and the analyzer. Amplitude zeros for all spectral components of the beam are reliably diagnosed by interference [cf. Figs. 2.11(a) and (b)]. In this case, one observes a white-light vortex where amplitude zeros for all spectral components coincide, which results in an achromatic interference forklet. The form and orientation of the interference forklet facilitates the determination of both the charge of the dislocation and its sign if the direction of propagation of the reference wave is known.[2]

Figure 2.11(c) (left column) illustrates the intensity distributions for the field scattered by a deep phase screen at different distances. Zero distance corresponds to the exact image plane, and negative distances are toward the imaging lens. One can see pronounced caustics in the vicinity of which amplitude zeros (phase singularities) are expected (Fig. 2.11(c), left column, $z = -10$ μm). Indeed, imposing a reference beam results in detection of amplitude zeros in zones of partial focusing, as predicted in Ref. 39 (Fig. 2.11(c), right column, $z = 50$ μm). Passage from the areas of sharp focus through the nearest associated minimum is accompanied by a shift in the position of the interference fringes and the formation of forklets. The areas of particular interest in this respect are depicted in Fig. 2.11 by white rectangles ($z = 50$ μm). Interference probing of the field was carried out by interference comparison of various cross sections of the object field with the reference beam (cf. Fig. 2.11(c), right column). Different cross sections of the object field were projected onto the observation plane by shifting the objective O3. At each step, the visibility of the interference pattern was maximized to guarantee that each cross section of the field was compared interferometrically with the matched reference wave train (i.e., in all cases the path difference between the object and the reference beam approached zero). In such a way, longitudinal scanning of the studied field was performed.



(a) (b)

Figure 2.11 Singularity obtained in (a) white-light beam passing a double-axial crystal placed between matched polarizer and analyzer: (a) without a reference wave and (b) with a reference wave. (Figure continued on next page.)



(c)

Figure 2.11 (Continued). Left column illustrates an intensity distribution at the field scattered by a deep phase screen at different distances from it (from $z = -500$ µm to $z = 500$ µm). In the right column is an interference comparison of various cross sections of the object field with the reference beam.

One can observe the evolution of the distribution of amplitude zeros as the observation plane is moved away from the object. Therefore, one can look for various scenarios of the development of a speckle field, starting from the area just behind the object up to the caustic zone, etc., and diagnose the singularities of opposite signs (see Fig. 2.11, $z = -50$ μm). In this figure, interference forklets of the opposite directions associated with the oppositely charged vortices are depicted. As a result of such scanning, the birth, evolution, and annihilation of two close vortices were observed,[26] as is demonstrated in Fig. 2.11, $z = -50$ μm, -200 μm, and -500 μm. The mentioned events are shown at this chain of figures by white circles. Also, one observes a chain of vortices of different spectral components manifesting themselves by the coloring of the interference fringes (Fig. 2.11, $z = 200$, 250 μm, 300 μm, including a zone where a speckle field is formed). Amplitude zeros exist independently in the spectral components with no interaction and no annihilation during propagation of the polychromatic light, as is seen from their evolution in the figure (Fig. 2.11, $z = 200$ μm, 250 μm, and 300 μm). Thus, the possibility of interference diagnostics of amplitude zeros in a freely propagating polychromatic field, in arbitrary zones of registration (including zones where a speckle field is formed) has been shown. As a result, the applicability of this technique has been demonstrated for diagnostics of phase singularities both for separate spectral components and for white-light vortices, when amplitude zeros of all spectral components coincide.

2.4.2 Chromascopic processing of polychromatic speckle fields

A new technique for the processing of phase singularities in polychromatic speckle fields arises from the concept of a chromascope[9–11] intended as an explanation of the universal color gamut seen by a human observer near an *isolated zero*, namely, within the area where the complex amplitude $\psi(R, k)$ varying linearly with position R over the spatial range considered, and linearly with wave number k over the visible range. It 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 small; most notably, there is no green*," as is seen in Fig. 2.12. The concept of a chromascope is implemented using Eq. (2.3). The first experimental study using the concept of a chromascope dealt with chromatic effects near a white-light vortex generated holographically.[11] In Ref. 11, however, the amplitude zeros had not been diagnosed by any direct experimental technique.

The concept of a chromascope forms the basis of the technique for determining the points of amplitude zeros of a field. The technique of an inverted chromascope for determining the points of amplitude zeros for the spectral components of a random polychromatic radiation field, such as a speckle field, is presented here, as well as the applicability of this technique for the processing of experimentally obtained light distributions. Following Ref. 30, computer simulations and experimental modeling of passing polychromatic radiation through a phase object, such

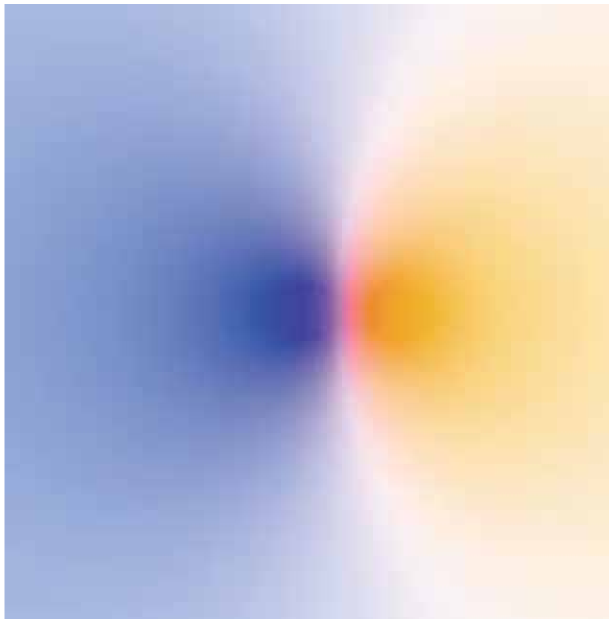


Figure 2.12 Universal color pattern near an isolated phase singularity.

as a frosted glass and crystals, are presented. The authors of Ref. 30 studied the structure of the field resulting from scattering of polychromatic radiation at such a surface.

In this consideration, the amplitude and phase of the field for each spectral component are computed using the Rayleigh-Sommerfeld diffraction integral.[7,35] Three spectral components are used with wavelengths of 633, 540, and 430 nm. Subsequently, the intensity distributions for the spectral components are added.

Let us consider the feasibility of determining spatially separated amplitude zeros of various monochromatic components. This technique is illustrated for an isolated fragment of a simulated speckle field with the intensity distribution shown in Fig. 2.13. The spatial phase distribution for each of the three spectral components reveals the presence of the amplitude zeros (cf. Fig. 2.14). Amplitude zeros are detected as the points where the equiphase lines are broken, which is followed by spatial blurring. "Blurring" is defined as the smooth changing of color intensity around the amplitude zero (even for circles of varying radii). One is interested in how the points of amplitude zeros for the separate spectral component can be determined from the intensity distribution of the complete polychromatic field. The technique for determining the points of amplitude zeros consists of three stages. In the first stage, the polychromatic field is processed by a chromascope.[10] Specifically, one normalizes the colors at each point of the field (ξ, η) based on the maximum intensity of any color in the RGB scale [see Eq. (2.3)]. This increases the brightness for points of low intensity, namely, in the vicinity of amplitude zeros.