Chapter 1
Introduction: From Coherent Singular Optics to Correlation Optics

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1.1 Classical (Coherent) Singular Optics: Applying Solid State Physics to Optics—Wavefront Dislocations

The term *singular optics* emerged after the publication of a seminal paper by Nye and Berry[1] in 1974. Nye and Berry noticed a remarkable kinematic analogy among the peculiar/singular regions of structured electromagnetic waves and the structure of real crystals having various defects, including *edge and screw dislocations* defined by the Burgers vectors.[2] This analogy was of great interest and at the same time was quite predictable, as John Nye came to the field of Optics from Solid State Physics, where he was disciple of

W. L. Bragg. The approach of applying solid state physics to optics has turned out to be highly fruitful as applied to the problem of laser (coherent) phase conjugation,[3] as well as to the theory of volume holograms of speckle fields.[4] Additionally, Zel'dovich et al. proposed an excellent interference technique for detection and diagnostics of wavefront screw dislocations by typical bifurcations of interference fringes when an off-axis reference wave is added to the speckle field having 'one amplitude zero per speckle' on average.[5] Similar results were obtained and illustrated a little later by the authors of this book.[6] Since the mid-1990s, the term 'singular optics' has been propagated by Soskin, and since the publication of the review chapter, "Singular Optics"[7] in *Progress in Optics* at the beginning of the third millennium, this term has become generally accepted.[8]

The central theme of singular optics involves investigation of so-called phase singularities that arise at given elements of a light field (e.g., points of lines—contours that are closed within the region of observation, at infinity, or at a cross-section of a beamlike (or paraxial) wave; lines or surfaces; or envelopes in three dimensions), where the amplitude of a field vanishes and a phase becomes undefined, i.e., singular (see Fig. 1.1). The origin of such singular elements of a field is a completely destructive interference accompanied by the peculiar behavior of the phase in the vicinity of singular elements. In the course of establishing singular optics as a field of research, various terms were used for designating the same subject; phase singularities, amplitude zeroes, wavefront dislocations, and optical vortices are all synonymous with each other. (The Laguerre–Gaussian laser mode[7,9] is a widespread example of a beam supporting a central optical vortex.) In the context of this book, all of these terms convey the same essential condition: the impossibility of determining a phase when the amplitude of a disturbance vanishes.

What fuels our interest in phase singularities in light fields? Why do we (including the reader) aspire to elucidate phase singularities as an attractive subject of modern photonics? Besides being of purely theoretical interest in

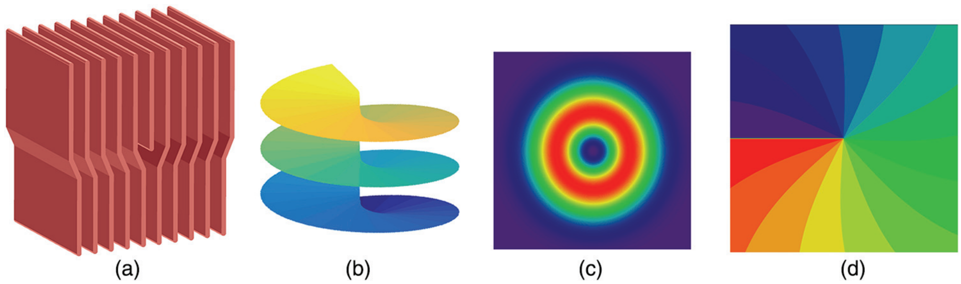

Figure 1.1 (a) Edge and (b) screw dislocations of a wavefront. In both cases, the field amplitude equals zero at the dislocation axis, and the phase changes by 2π under the circumference of the dislocation line. (c) Amplitude and (d) phase structures of a singly-charged screw dislocation in Laguerre–Gaussian mode shown in fragments.

the context of classical optics and, specifically, of structured light, we are highly intrigued by the possible applications of optical beams supporting phase singularities in manipulating the minute quantities of a matter, which is of vital importance for modern nanophysics, crystal growth, problems of nanodots, metamaterials, nano-optics, near-field optics and super-resolution, precision chemistry and pharmacology, etc. It has been reported that various kinds of singularities are able to 'captivate' small particles (of micro- and nanoscales) and provide fine mechanical action, such as ordered motion, rotation with controlled direction and velocity, and convergence and divergence of such particles. A wide variety of optical traps, optical tweezers, and optical manipulators[10–13] exploiting phase singularities have been proposed.

On the other hand, detection and diagnostics (where appropriate, as is for screw dislocations) of the singular elements of an optical field enable the reconstruction of its 'singular skeleton,' which is of interest in two respects. Firstly, if one knows the loci and characteristics of phase singularities at the analyzed field, then, due partially to well-established sign principles (see Section 1.3[14,15]), by alternating the signs of chirality of the neighboring vortices, one can predict the behavior of the optical field parameters at all other regions of a beam, at least in a qualitative manner, to within the accuracy of the phase, for instance, $\pi/2$. Secondly, if one wishes to realize telecommunications with singular-optical coding, one must use the mentioned sign principles. Namely, one must take into account not only the loci of optical vortices, but also their signs (topological charges),[7,8] which determine the angular optical momentum of a beam and correspond to the direction of phase twirling (clockwise or counterclockwise) under the circumference of the amplitude zero. Owing to the translation of the singular elements alone, data compression by several orders of magnitude can be achieved, allowing the optimal use of the channel capacity.

Additionally, reconstruction of the singular skeleton of an optical field facilitates solving other problems in optics, including the inverse phase problem.[16–21] The phase problem involves revealing spatial (coordinate) phase distribution in complex (speckle-type) fields. This problem has been successfully solved within the framework of the singular optics approach based on the following concepts:[15]

1. the field skeleton having "reference" structure-forming elements, i.e., the field amplitude zeros;
2. the sign principle in the spatial distribution of the amplitude zeros: In correspondence with the sign principle, one can predict the behavior of the optical field parameters at any region of a beam, at least in a qualitative manner, within the accuracy of phase to, e.g., $\pi/2$; and
3. the interconnection of the intensity spatial distribution and the field phase distribution.

By all appearances, vortexlike (or spiral-like) motion is among the universal types of motion found in both classical and quantum[22] physics. Therefore, the investigation of phase singularities *per se* is important and has unequivocal validity.

1.2 Problems of Scalar Coherent Singular Optics: Light Fields with Phase Singularities—Control and Diagnostics of their Parameters

The notion of coherence is among the most fundamental concepts of modern optics, being intrinsically connected to the characteristics of light that create the foundation for classical wave optics, such as intensity, phase, and polarization.[23,24] For didactic purposes, one might attempt to distinguish between intensity, polarization, and coherence of a light field. However, every practical experiment involves the problem of the inseparable interconnection among them. Therefore, one cannot define coherence by aspiring to associate it with the visibility of an interference pattern, ignoring the states of polarization of the superposed beams. Note that attempts to explain the Young's interference experiment for "completely unpolarized" light sometimes lead to questionable conclusions.[25] At the same time, the most fundamental definition of polarized light is given simply by the measure of mutual coherence of the orthogonally polarized components of a beam. Finally, all three of these characteristics of a light beam (intensity, coherence, and polarization) are not entirely separable, being comprehensively expressed through known combinations of Wolf's coherency matrix elements.[26] In 2003, Wolf determined the fundamental role of interference for analysis of partially polarized light based on the unified theory of coherence and polarization of random EM fields.[23,24] The coherency matrix introduced by Wolf,

$$W(\mathbf{r}_1,\mathbf{r}_2) = \begin{bmatrix} W_{xx}(\mathbf{r}_1,\mathbf{r}_2) & W_{xy}(\mathbf{r}_1,\mathbf{r}_2) \\ W_{yx}(\mathbf{r}_1,\mathbf{r}_2) & W_{yy}(\mathbf{r},\mathbf{r}_2) \end{bmatrix},$$

where $W_{ij}(\mathbf{r}_1,\mathbf{r}_2) = \langle E_i^*(\mathbf{r}_1)E_j(\mathbf{r}_2)\rangle$, $(i, j = x, y)$, ensures a transition from the optical field parameters to the correlation functions, i.e., some "abstract" constructions that can be directly determined from measurements of the field intensity for properly specified conditions of the interference experiment. Note that the coherency matrix can be represented by using the Stokes parameters that contain the data on correlation among the Cartesian components of the fluctuations of the electric field vector at a specified spatial point and a specified instant of time. For this reason, the Stokes parameters do not describe the changes in the state of polarization of a light beam that accompany its propagation.

During its initial establishment (1981–2001) as a stand-alone topic of research, singular optics was developed as a study of coherence. So, in the simplest case, one considers the only complex amplitude of a scalar monochromatic, homogeneously and completely polarized EM field, $a\exp(i\varphi)$, a and φ being the amplitude and phase of the disturbance, respectively. In the case of screw dislocation (a vortex), $\varphi = l2\pi$ under the circumference of the point of zero amplitude at the observation plane perpendicular to the mean direction of propagation of the paraxial optical beam. The notation l represents the integer designating the order of singularity and generically equals ± 1 (clockwise–counterclockwise). In three dimensions, there is a 'snakelike' trajectory.[3,4] Amplitude zero at the specified point results from complete destructive interference of the disturbances going to this point from all possible pairs of oppositely located wavelets. These wavelets are associated with the Huygens–Fresnel secondary sources lying at the vanishingly small circle around amplitude zero. This means that, crossing an amplitude zero, the field undergoes a steplike change of phase by π. This peculiarity (just singularity) may be directly observed in the radiowave domain of EM radiation.[1] Due to a large difference in the scale of frequencies, a similar observation is quite impossible within the visible range of EM radiation. In this case, the natural solution for detection and diagnostics of phase singularities involves (as has been previously mentioned) the use of a reference beam (axial or nonaxial) that is correlated with a tested singular beam. Typical structures of the resulting interference patterns (an example of which will be provided in Section 1.3) provide efficient diagnostics of phase singularities if an observer has *a priori* information on the experimental conditions, including geometrical provisions, such as the direction and/or curvature radius of a reference beam with respect to the tested singular beam.

Another problem of coherent singular optics arises in the formation of light beams with controlled phase singularities. Many experimental studies offer solutions to this problem, including, e.g., the review in Ref. 7. By all appearances, the most practicable and popular approach is the use of computer-generated holograms.[27,28] To obtain the beams with elementary phase singularities, one computes a wave structure having a kind of Laguerre–Gaussian [(LG) for screw dislocations] or Hermite–Gaussian [(HG) for edge dislocations] mode[8] with the imposed coherent reference beam. Such a pattern is printed using a high-resolution printer and then photographically diminished to a desirable scale. When such a computer-generated and photographically implemented hologram is illuminated with a laser beam, high-quality singular beams with well-established and simply controlled properties are reconstructed in nonzero diffraction orders.

Recently, crystalline media have been used for engineering light beams with phase singularities, where a combination of anisotropy, absorption, and chirality is involved in both demonstration of singularity generation as well as possible transformation of phase singularities into polarization singularities (see Section 1.3). Knowing the mechanisms of the origin and annihilation of singularities, one can identify which crystals can be used as a tool for investigating polarization singularities.[29]

Studies in coherent scalar singular optics have been successfully used for development of a new generation of devices for optical trapping and control of the motion of micro- and nanoparticles, in optical telecommunications and imaging devices, as well as for defectoscopy of media, including photonic crystals.[30]

Another issue related to coherent scalar singular optics [i.e., singular optics of a completely coherent, homogeneously polarized (in space) light field, for which the specific state of polarization can be neglected] is its anticipated applications. As previously mentioned, the most promising of such applications is, very likely, development of a new generation of devices for optical trapping and control of the motion of micro- and nanoparticles. Another foreseen application involves use of the sign principles that connect all phase singularities in the singular skeleton for exploiting in optical telecommunications.

Of great importance here is the following: It appears that if a light beam is not completely coherent, completely monochromatic, and completely and homogeneously polarized (in space), then completely destructive interference with the occurring amplitude zeroes is impossible. What can be done in this case?

As is noted in Ref. 31, "… each singularity disappears at a deeper level of description… it is true for perhaps all singularities in physics," and further on, "Scalar optics has its own singularities, in the form of nodal lines in space (that is, phase singularities, or optical vortices), and these in turn disappear in polarization (i.e., vector wave) optics, whose singularities are loci of pure linear or purely circular polarization" (see Section 1.3). This methodological concept is the *Ariadne's thread* for elaborating on the topic of our book.

An additional problem arises: One cannot form a reference wave that is simultaneously correlated with all components of a partially spatially coherent field, as is possible in the typical case, where such a field is assembled from a set of uncorrelated components. If even one foresees new kinds of optical singularities, what experimental tools must be applied to detect such singularities? The answer is currently not obvious. Undoubtedly, one must seek out new experimental techniques for detection of singularities inherent in partially coherent light fields (see Chapters 2 and 3).

1.3 From Optical Vortices to Coherent Polarization Singularities: Sign Principle of Vector Singular Optics

In the late 1980s, the research area of singular optics was considerably extended[32–36] to the domain of completely coherent but so-called pseudo-depolarized fields, i.e., optical fields that are completely polarized but with the state of polarization changing gradually from point to point. These fields are the same as those referred to by Crawford[37] (see also Ref. 38) as being *polarized in small scale, but estimated as unpolarized in large scale*. The state of pseudo-depolarization is also sometimes called global depolarization.[25] Pseudo-depolarized fields arise, in part, from stationary, multiple coherent (laser) light scattering,[39] as in light scattering in a glass of milk, or in multimode optical fibers, or in most types of natural matter in which volume scattering occurs. In contrast to scalar singular optics, an explanation of the vector (polarization) structure of a light field now becomes unavoidable. Note that the description of pseudo-depolarized fields is possible within the Stokes polarimetry approach, although the Stokes polarimetric analysis leads to considerably different results for local and "global" (space-averaged) measurements.

The disappearance of scalar phase singularities into an inhomogeneously polarized field is evident. When obtaining absolute amplitude zero in such a field, one must expect precise spatial coincidence (not closeness!) of amplitude zeros for two arbitrarily orthogonally polarized field components, but the probability of such an event occurring vanishes. On the other hand, the conditions are well known for forming a linearly or circularly polarized field from the superposition of two correlated, orthogonally linearly (but not necessarily) polarized components. So, to obtain a linearly polarized field from such components, the two components must have a phase difference of zero or π. In either case, for an arbitrary amplitude ratio of the orthogonal components, one obtains a linearly polarized beam; the amplitude ratio will determine only the azimuth of polarization.[38,40] Thus, operating with a tiny-structured, pseudo-depolarized light field, one can expect the presence of *lines* (closed contours or contours closing at infinity) at the beam cross-section, where the mentioned phase difference is conserved, but changing amplitude ratio of the orthogonal components causes a gradual change in the azimuth of polarization. At the same time, when obtaining circular polarization as a result of superposition of orthogonally linearly polarized mutually coherent components, one must satisfy *two* conditions simultaneously: (1) phase difference $\pm\pi/2$ and (2) equal amplitudes of the components (see Fig. 1.2). This means that the conditions for obtaining circular polarization are much stricter than those for obtaining linear polarization. It follows from this consideration that one must seek isolated points where the pseudo-depolarized field is circularly polarized.

As a result, one can image a coherent paraxial pseudo-depolarized field (at its cross-section) as the set of isolated C (circularly polarized) points demarcated by L (linearly polarized) lines. As in the case of a scalar field, the system of stable polarization singularities forms the skeleton of a vector field, determining its behavior at each point. For that, a new (with respect to scalar singular optics) sign principle[14] is valid.[15,41,42] So, the handedness (clockwise or counterclockwise rotation of the electrical vector of a light beam) is the

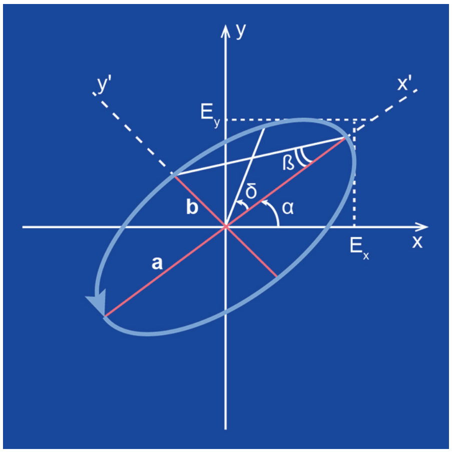

Figure 1.2 Ellipsometric parameters of a beamlike optical field: α is the azimuth of polarization in arbitrarily chosen but fixed Cartesian coordinates; $\beta = \tan^{-1}(b/a)$ is the angle of ellipticity; δ is the vibration (initial) phase; $I = E_x^2 + E_y^2$ is the intensity of a beam (E_x and E_y being x and y components of the electrical vector).

same in the vicinity of a C point, alternating in a steplike manner by crossing the nearest L line. In other words, the azimuth of polarization is undetermined at C points, where the polarization ellipse degenerates to a circle, while the handedness is undetermined at L lines, where the ellipse of polarization degenerates to the intercept.

It can be shown[43] that the sign principle for C points (as the phase-difference vortices) is analogous to the sign principle for phase vortices in a scalar field; i.e., the even numbers of C points are found at closed equi-azimuthal lines, and adjacent C points at one equi-azimuthal line are characterized by the topological charges of the azimuth singularity of opposite sign.

Note that this singular-optical concept has a remarkable forerunner from classical optics (in addition to those discussed in Section 1.5). In 1892, when developing the principles of the mathematical theory of light, Poincaré introduced the refined notion of the circular complex polarization variable represented at the circular complex polarization plane.[40] Poincaré proposed the idea of imaging left-handed circular polarization at the center of a complex plane (see Fig. 1.3). Then, he proposed imaging linear polarization with all possible (within $\pm\pi/2$) smoothly changing azimuths of polarization at the unit circle radius. Continuing this construction, one finds that all states of polarization of any *completely polarized* beam can be represented at this plane, so that right-handed circular polarization is imaged at infinity in any direction from the center of coordinates.

The situation is described as a whole using the circular complex polarization variable:[40]

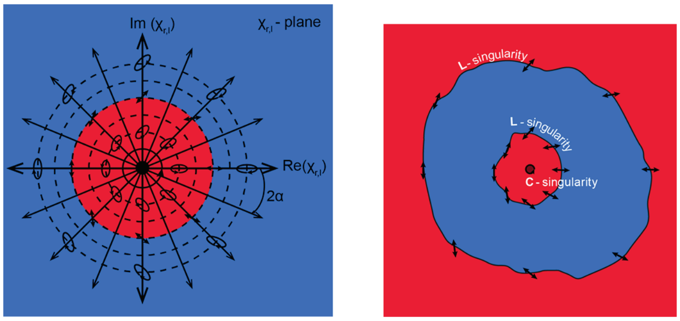

Figure 1.3 (a) The Poincaré complex polarization plane reflecting the complex circular polarization variable χ_{rl} and (b) the singular-optical incarnation of this model[44] for a completely polarized beam of the LG_0^1 mode.

$$\chi_{r,l} = E_r/E_l = (|E_r|/|E_l|)\exp(\delta_r - \delta_l), \tag{1.1}$$

where E_r and E_l are the complex amplitudes of right-handed and left-handed circularly polarized components of a beam, respectively, and $\delta_r - \delta_l$ is the phase difference of these components. The situation can also be described in terms of ellipsometric parameters:

$$\chi_{r,l} = \tan(\beta + \pi/4)\exp(-i2\alpha), \tag{1.2}$$

where α is the azimuth of polarization, and β is the ellipticity angle (see Fig. 1.2), and both are functions of the spatial coordinates at the cross-section of a paraxial pseudo-depolarized beam. Note that the representation in Eqs. (1.1) and (1.2) leads to one-to-one correspondence among the points of an unbounded circular complex polarization plane and the state of polarization.

This representation of polarization is exhaustive for the case of completely polarized light beams and, undergoing stereographic projection, leads to a generally accepted current description of polarized light fields using the Poincaré sphere. The physical meaning of this description is rooted in its direct connection to the set of the Stokes parameters[45] (see Fig 1.4).

Meanwhile, this representation suffers from at least two restrictions. Firstly, the measure of 'closeness' or 'remoteness' of two states of polarization is nonuniform over the complex plane. So, going from left-circular polarization to the L contour (see Fig. 1.3) means traveling from the center of the coordinates to the unit circle radius. In contrast, going from the L contour to the right-circular polarization means traveling from the unit circle radius to infinity. Secondly, this representation is limited by the case of completely polarized beams. The approximation of completely polarized beams is a far-fetched idealization, as only a completely monochromatic field

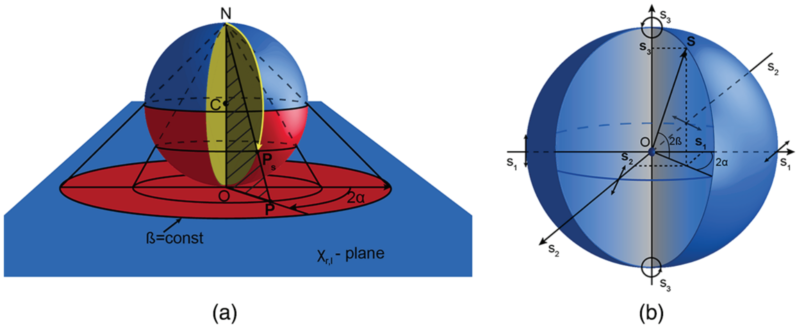

Figure 1.4 (a) Stereographic projection of the complex circular polarization plane to the Poincaré sphere with a uniform measure for 'closeness' of the states of polarization and (b) correspondence of the Cartesian coordinates of the point at the Poincaré sphere to the Stokes parameters.

would be completely polarized.[46] A realistic case of partially polarized light beams is not covered by the method that uses the circular complex polarization plane nor by the standard method that uses the Poincaré sphere, as partially polarized beams are not represented within the framework of these approaches. It is remarkable that both mentioned problems are solved by applying stereographic projection of the complex polarization plane to the Poincaré sphere or, more generally, to the Poincaré ball[47,48] (see Fig. 1.4).

This problem will be considered in detail and solved in Chapter 4. Here we note only that no devices exist that separate a partially polarized beam into completely polarized and completely unpolarized components. This is in accordance with the classical definition of the degree of polarization[38,40] as a share of the intensity of the completely polarized component of a partially polarized beam in its total intensity, $P = I_p/(I_p + I_u)$, where the subscript letters p and u denote completely polarized and completely unpolarized components, respectively. Nevertheless, one can introduce the generalized definition of the complex degree of polarization[44] and, applying 2D Stokes polarimetry, detect and diagnose the phase singularities of this new complex parameter of an optical field (see Chapter 4).

There are some relevant considerations. As has been pointed out by Freund,[49] we are not to the point where we can experimentally investigate the problem of coherence and polarization of optical light in the general 3D case, when the paraxial approximation is violated and one cannot neglect any of the three Cartesian coordinates for describing the behavior of the electric vector. In this context, another problem has been discussed, i.e., so-called *optical currents* (*flows*).[50–55] These studies[50–55] are essentially substantiated by the fact that micro- or nanoparticles (serving to identify inhomogeneously polarized and partially coherent optical fields) affect this field as absorbing and retransmitting particles with their own characteristics, such that the state of a field, in general, changes under the influence of such secondary radiators.[11–13,56–58] Investigations in this domain have been actually stimulated, in part, by the studies reported in Refs. 59–63, where the classical approaches of the theory of coherence are complemented by the parameters describing partially coherent fields in both space and in time, the so-called intrinsic degrees of coherence. At the same time, typical as well as new results based on the theory of partial coherence and partial polarization have become critical in their application to the concept of singular optics.

1.4 Polychromatic Singular Optics

Progressing from coherent scalar singular optics to vector singularities in inhomogeneously polarized coherent fields, including phase singularities of the complex degree of coherence and the complex degree of polarization, the next step becomes quite predictable, namely, extending the singular optics approach to polychromatic light fields. It might seem at first that a polychromatic field does not possess the coherence necessary for completely destructive interference, which results in the appearance of amplitude zeros. Nevertheless, phase-singularity-type optical vortices *can* arise in some spectral components of a wave with rich spectral content. A requirement for such an event to occur is the presence of spatial (rather than temporal) coherence. It is intuitively clear that subtraction of any spectral component from 'white' light (typically accompanied by considerable, although not perfect, suppressing neighboring components) results in complementary coloring. Note that investigation of phase singularities in polychromatic optical fields has been accompanied by the introduction of new experimental techniques and data processing algorithms, resulting (in part) in the concept of chromascopy.[64,65] Diagnostics of optical vortices in polychromatic[66] (and even in polyphonic[67]) fields as well as some interesting manifestations of the singular-optical phenomena in such fields are considered in Chapter 5.

1.5 Forerunners of Correlation Singular Optics

One can see from the above concise historical outlook that since the beginning of the third millennium (approximately), the second stage of singular optics has been underway. Namely, coherent (both scalar and vector) singular optics has evolved to *correlation singular optics*, defined as the wave singular optics of partially coherent (both in space and in time) and/or inhomogeneously partially polarized structured light fields.[68–70] The importance of this approach is supported by the fact that the concept of partial coherence is the most fundamental and influencing concept of modern optics and photonics. Born and Wolf[45] wrote:

> "An attractive feature of the theory of partial coherence is the fact that it operates with quantities (namely with correlation functions and with

> some averaged intensities that may, in principle, be determined from experiment. This is in contrast with the elementary optical wave theory, where the basic quantity is not measurable because of the very high rapidity of optical vibrations... The mathematical techniques employed in connection with partial coherence are also very suitable for the analysis of partial polarization. Here one is concerned with phenomena which can be interpreted in terms of correlation between orthogonal components of the electromagnetic field vectors."[45]

On the other hand, it is understood that *any* parameter of an optical field that can be generalized to the complex form (even to the form traditionally defined as real and non-negative visibility of an interference pattern) may possess its own phase singularities.[71] Elaboration of these intrinsically correlational singularities leads to a deeper understanding of the structure of complex optical fields, as well as to new promising applications of singular beams with a controlled degree of spatial and temporal coherence, a controlled degree of polarization, and broad spectral content.

It is of interest to emphasize in this context that, strictly speaking, singular optics was conceived initially simply as correlation optics. So, considering a structured optical field assembled from a few (only six) planewave components slightly differing in wavenumbers and in orientation of wave vectors, Sommerfeld theoretically predicted in 1950 the presence of peculiar zones[46] (see Fig. 1.5), where the amplitude of such a *structured* resulting field vanishes, and the wavefront becomes so complicated that even the definition of a wavelength (in the classical sense) becomes problematic.

Further, the pioneering investigation of Nye and Berry[1] has been also carried out just for *signals* (for *wave trains*, which are time-bounded and by definition cannot be strictly monochromatic), rather than for an idealized, perfectly monochromatic wave (which is, by definition, time-unbounded).[72]

One additional important observation preceded the emergence of the field of correlation singular optics in the sense applied here: the enigmatic coloring of white-light radiation diffracted at rough surfaces with intermediate parameters of roughness when the surface cannot be specified as slightly rough,[73] but rather is specified as a scattered field, yet it contains a considerable number of regular components.[74] A definitive explanation of this observation was provided within the singular-optical concept:[75] it is a result of the singularity of the complex amplitude transmission coefficient for some spectral component of polychromatic probing beam (see Chapter 5).

It worth noting also that, even before the creation of lasers, one of the first examples of the singular optics phenomenon was elaborated on both theoretically and experimentally for spatially incoherent sources of light—without the use of singular-optical terminology. In Refs. 76 and 77, E. Wolf and B. Thompson develop the consequence of the Van Cittert–Zernike theorem concerning the analogy between diffraction of a strictly coherent,

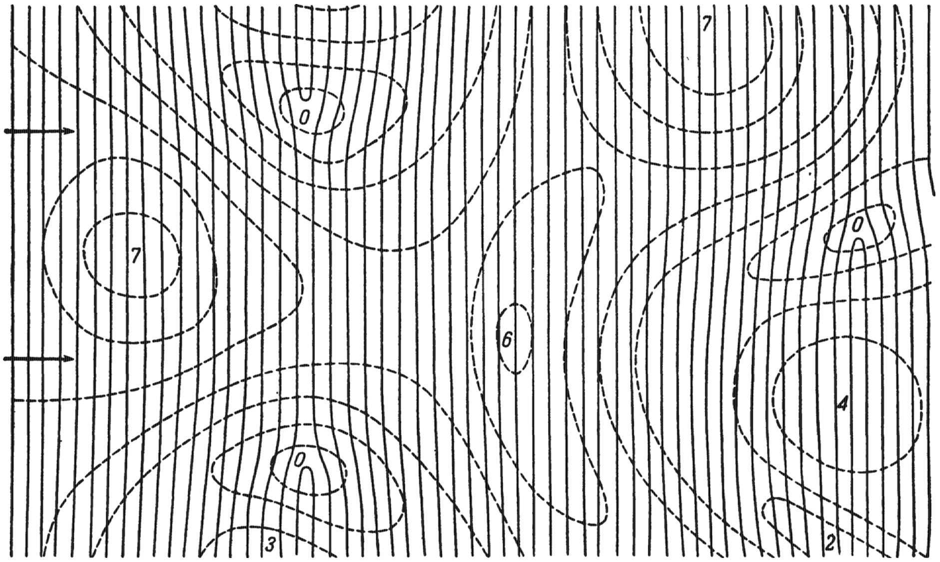

Figure 1.5 Instantaneous pattern of a "wave train" consisting of six independent plane waves; the solid lines are the isophases, and dashed lines are isoamplitudes. Frequency ratio: 95:97:99:101:103:105; directions of propagation (in radians): +1/20, +1/20, 0, 0, −1/20, −1/20. Solid (in general, straight) lines show *instantaneous* zeros of the resulting oscillating process. Dashed lines (similar to the horizontals on a topographic map) show the wave amplitudes. The regular row of waves is broken at the points of zero amplitude. A new wave period is thought to be arising at these points. An entire wave field propagates with light velocity from left to right, and its form gradually changes. Three points labeled 0 are directly computed (i.e., computed without explicitly using the singular-optical concept), being typical zero-crossings of singular optics, and points labeled 4, 6, and 7 are the points of the maximal amplitudes of the polychromatic field [reprinted from Ref. 46 with permission; © (1954) Elsevier].

monochromatic light field at a specified aperture and propagation of light from a quasi-monochromatic spatially incoherent source with the same form and size as those of the mentioned aperture. These results were formulated in terms of the theory of partial coherence alone, and are so well known that they do not need to be included here, appearing in detail in many books [see Ref. 45 (Section 10.4.4)]. We will discuss in an intuitive manner only the singular-optical aspect of these results.

The coherency function obeys the wave equation, so that coherence propagates in free space like a wave, and the spatial coherency function at specified distance from quasi-monochromatic, spatially incoherent source is described by the same integral transformations as a coherent diffraction field from an associated aperture. As such, the structure of the spatial coherency function must have the same peculiarities as the diffraction pattern from an associated aperture. In part, if an aperture (source) is circular, then the corresponding distribution of the normalized amplitude (the coherency coefficient) is described by the Bessel function.[45] At the root of the Bessel function, the modulo of the complex coefficient of coherency (the *factor of coherency*) vanishes, and the phase of this coefficient, by passing a root of the Bessel function, changes its sign to the opposite sign, i.e., undergoes steplike changes by π. (Mathematical definitions of this consideration will be provided in Chapter 3.) In terms of singular optics,[7] the modulo of the complex coefficient of coherency directly corresponds to the phase singularity, but for the complex coefficient of coherency of a partially coherent field, rather than for the complex amplitude of a completely coherent field. Furthermore, since the modulo of the complex coefficient of coherency equals the visibility of an interference pattern from disturbances in two probing points specified at a cross-section of the analyzed field,[45] one can visualize the phase singularity (nothing but edge dislocation) of the complex coefficient of coherency by observing (1) zero visibility of the interference fringe for corresponding distances between the probing beams, and (2) a half-period shift in interference fringes that occurs when the phase crosses the root of the Bessel function, i.e., changes the distance between probing points. This consequence of the Van Cittert–Zernike theorem has been experimentally verified in Ref. 47.

It is worth noting that in these early observations one can detect some peculiarities in a singular structure that was not understood until the modern era of singular optics.[33,78] Any singularity, including an optical one, can be considered as a certain local structure with a point or linear core having an undetermined (singular) magnitude of some parameter for the threshold magnitude of the other (control) parameter as it gradually changes. In scalar coherent singular optics, the field amplitude is the control parameter, while the phase is the singular parameter that has undergone a π-magnitude jump at the zero-crossing amplitude. Generally speaking, the sets of such parameters are different for various kinds of beams. However, all kinds of singularities are characterized by one common peculiarity that signals the presence of singularity in the complex parameter of interest. This peculiarity involves the *conical* local structure of the control parameter at the nearest vicinity of the singularity core. The mentioned peculiarity, in part, enables one to determine the localization of phase singularities as well as to differentiate them from the local minima (which may be deep but are not necessarily so) of a field, neither of which can be achieved by simply measuring the intensity distribution. To that end, the graphs of Ref. 77 show the mentioned conical structure in the vicinity of the phase singularity of the coherency coefficient, i.e., the zero magnitude of the modulo of the complex degree of coherency.[79,80] We will address this classical result again in proper context in Chapters 3 and 4.

To sum up, the emerging theory of partial coherency has become one of the most important and direct prerequisites to the subsequent formation of the singular optics concept. Note that the above-considered diffraction–coherence analogy based on theoretical and experimental elaboration of the ring-edge dislocation of the spatial coherence function (though in other terms) has not been discussed to this point. Nevertheless, it is obvious that this analogy is a strong argument in support of the conceptual interconnectivity of the classical theory of partial coherence and the modern concept of singular optics.

1.6 Organization of the Book

This book is organized as follows. Chapter 2 is devoted to the Young–Rubinowitz model of diffraction, i.e., the concept of an edge diffraction wave.[45,81,82] Although the consideration is carried out under the assumption of completely coherent fields (as such, it might seem that this topic is outside the context of the book), this concept will be essentially used in the chapters that follow for substantiating and implementing new tools for experimental detection and diagnostics of phase singularities in partially spatially coherent and polychromatic singular-optical beams. Phase singularities of the coherency functions and the complex degree of coherence[83–85] are elaborated on in Chapter 3. New kinds of vector phase singularities inherent to partially coherent and partially inhomogeneously polarized structured optical fields[85–88] are described in Chapter 4. These include the corresponding sign principles, as well as the means for practical assembly of such fields and application of 2D Stokes polarimetry for detection and diagnostics of the corresponding singular structures. An additional branch of correlation singular optics, i.e., singular optics of polychromatic light fields, is highlighted in Chapter 5.[64,65,75,86] Chapter 6 is devoted to crystal singular optics, which is rapidly developing in both conceptual and engineering aspects.[30] Applications of singular optics, including those pertaining to partially coherent, partially polarized, and polychromatic light fields are presented in Chapter 7.

Note that the list of references given in the next section is not comprehensive. Its purpose is to orient the reader in priority publications or publications most suitable to gaining basic knowledge of the mentioned topics.

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