PROCEEDINGS OF SPIE

SPIEDigitalLibrary.org/conference-proceedings-of-spie

On important precursor of singular optics (tutorial)

Peter V. Polyanskii, Christina V. Felde, Halina V. Bogatyryova, Alexey V. Konovchuk

Peter V. Polyanskii, Christina V. Felde, Halina V. Bogatyryova, Alexey V. Konovchuk, "On important precursor of singular optics (tutorial)," Proc. SPIE 10612, Thirteenth International Conference on Correlation Optics, 1061209 (18 January 2018); doi: 10.1117/12.2304700

Event: Thirteenth International Conference on Correlation Optics, 2017, Chernivtsi, Ukraine

On important precursor of singular optics (Tutorial)

Peter V. Polyanskii*[a], Christina V. Felde[a], Halina V. Bogatyryova[b], Alexey V. Konovchuk[a]
[a]Correlation Optics Dept, Chernivtsy National University, 2 Kotsyubinsky Str., 52012 Chernivtsi, Ukraine; [b]Optical and Optical-Electronic Devices Dept, National Technical University of Ukraine "Kyiv Politechnic Institute", 37 Prospect Peremogy, 03056 Kyiv, Ukraine

ABSTRACT

The rise of singular optics is usually associated with the seminal paper by J. F. Nye and M. V. Berry [Proc. R. Soc. Lond. A, 336, 165-189 (1974)]. Intense development of this area of modern photonics has started since the early eighties of the XX century due to invention of the interfrence technique for detection and diagnostics of phase singularities, such as optical vortices in complex speckle-structured light fields. The next powerful incentive for formation of singular optics into separate area of the science on light was connectected with discovering of very practical technique for creation of singular optical beams of various kinds on the base of computer-generated holograms. In the eghties and ninetieth of the XX century, singular optics evolved, almost entirely, under the approximation of complete coherency of light field. Only at the threshold of the XXI century, it has been comprehended that the singular-optics approaches can be fruitfully expanded onto partially spatially coherent, partially polarized and polychromatic light fields supporting singularities of new kinds, that has been resulted in establishing of *correlation singular optics*. Here we show that correlation singular optics has much deeper roots, ascending to "pre-singular" and even pre-laser epoch and associated with the concept of partial coherence and polarization. It is remarcable that correlation singular optics in its present interpretation has forestalled the standard coherent singular optics. This paper is timed to the sixtieth anniversary of the most profound precursor of moderrn correlation singular optics [J. Opt. Soc. Am., 47, 895-902 (1957)].

Keywords: singular optics, correlation optics, partial coherence, edge diffraction wave

1. INTRODUCTION

It is generally and justly accepted[1-5] to take its rise of the modern scope of an inquiry referred to as Singular Optics in the seminal paper[6]. In the cited paper, the fundamental forming role of specific elements of EM field (in radio-frequency domain) associated with amplitude zeroes and undetermined phase has been revealed, and substantial kinematic analogy with *dislocations* in solids has been introduced. Avalanch-like coming-to-be just the singular optics was caused by two important interconnected factors. The first of them is the implementation of interference technique for detection and diagnostics (determination of the key parameters) of amplitude zeroes, such as screw dislocations of a wave front, into complex (speckle) light fields[7], in part, in connection with developing the optical phase conjugation by means of dynamic holography and adaptive optics techniques, as well as 3D holography of speckle fields bearing avast of wave front dislocations[8,9]. The second of them is the substantiation of practical method for "reconstruction" of optical beams with dislocations (both screw and edge) of a wave front from computer-generated holograms[10,11].

For the space of two decades[7,1], singular optics was developed exclusively within the framework of the strictly coherent approximation, being sometimes referred to as *coherent* singular optics[12-17]. The central subjects of the investigation was in this stage amplitude zeroes of scalar light fiels (ones with arbitrary but spatially homogeneous state of polarization)[1] and polarization singularities in vector light fields (with spatially inhomogeneously but locally completely polarized ones)[18] referred to as pseudo-depolarized[19,20] or globally unpolarized[21] fields. Established at this stage sign principles of coherent singular optics (both scalar[22,23] and vector[24]) have became the Ariadne's thread for the following investigations of phase singularities in partially coherent (in space and time) and polychromatic light fields (cf. the classification of optical singularities in Refs 25, 26). In accordance with the mentioned sign principles, subsequent phase singularities of any kind possess altering characteristics (topological charge, handedness etc.) and, as a consequence, form a singular

peterpolyanskii@gmail.com; phone +380372244730; fax +380372244730

Thirteenth International Conference on Correlation Optics, edited by Oleg V. Angelsky, Proc. of SPIE Vol. 10612, 1061209 · © 2018 SPIE
CCC code: 0277-786X/18/$18 · doi: 10.1117/12.2304700

sceleton of complex light fields, so that knowing the loci and signs of vortices, one can predict, at least in qualitative manner, behavior of the field parameters at all other regions, that provides significant (by several orders of magnitude[27]) reduction of the information content undergone encoding in the singular-optics parameters of a signal beam transmitted through optical telecommunication channel.

The present stage of progress of singular optics, started just at the beginning of the new Millenium, would-be retrospectively predicted, being connected with the generalization of the singular-optics concept on partially coherent (both in space and in time) light fields. This fruitful approach presumes recognizing well-known (but "slipping" in this context) or anew constructing complex parameters of light field, which just due to their *complexity* may possess their own specific phase singularities. There is the basic methodology of *correlation singular optics* as the singular optics of partially coherent, partially polarized and polychromating light fields[12,25] being one of the applications of the unified theory of coherence and polarization of random electromagnetic beams[28-30].

2. CHALLENGE OF THE CORRELATION PHASE SINGULARITIES

Observation of the singular structures at light fields (before establishing the coherent singular optics concept and even before invention of lasers) was connected with fundamental theoretical and experimental investigations in the field of partial coherence of optical fields. So, the authors[31,32] have developed the important consequence of the Van-Cittert – Zernike theorem concerning the analogy between diffraction of completely coherent, monochromatic light field at specified aperture, and origin of the spatial coherence and propagation of the spatial coherence function of a field from quasi-monochromatic, spatially incoherent (δ-correlated) source with the same form and size as ones of the mentioned aperture. These results are generally known, see in part[29,33]. Nevertheless, to our best knowledge, the cornerstone aspect of them as the important precursor of singular optics has not been discussed up to now.

The coherency function obeys the wave equation, so that coherence propagates in a free space like a wave, and the spatial coherency function at specified distance from quasi-monochromatic, spatially incoherent source is described (within the paraxial approximation) by the same integral, *viz*. Fourier, transform as a coherent diffraction field from an associated aperture. As so, the structure of the spatial coherency function must have the same peculiarities (≡ singularities, here) as the diffraction field from an associated aperture. In part, if an aperture (source) is circle-shaped, than the corresponding distribution of the normalized amplitude (the coherency coefficient that is the modulo of the complex degree of coherence) is described by the Bessel function[29]. At roots of the Bessel function, modulo of the complex coefficient of coherency, $j_{12} = |j_{12}|\exp(i\beta_{12})$, *viz*. the *factor of coherency,*

$$|j_{12}| \; (j_{12} = J_{12} / \left(\sqrt{J_{11}}\sqrt{J_{22}}\right),$$

$J_{kl} = \langle E_k E_l^* \rangle$ is the mutual intensity (the spatial coherence function) of the oscillations of electrical field at points $k, l = 1,2$ at the specified cross-section of a field, $\beta_{12} = \varphi_1 - \varphi_2$ is the phase difference of oscillations at the probing points of the tested field, being the phase of the complex degree of coherence[29,31-33], and $\langle \ldots \rangle$ denotes the time averaging), vanishes, so that β_{12}, by passing a root, changes its sign on opposite one, i.e. undergoes step-like changes by π, see Fig. 1. In terms of singular optics[1-4,34], it directly corresponds to the phase singularity, but for the complex coefficient of coherency of partially coherent field, rather than for the complex amplitude of completely coherent field. Moreover, as modulo of the complex coefficient of coherency equals the visibility of an interference pattern from disturbances of equal amplitudes in two probing points specified at cross-section of the analyzed field[29,31], then one can visualize the phase singularity of the complex coefficient of coherency by observing (*i*) zero visibility of interference fringe for corresponding distances between the probing points, and (*ii*) a half-period shift in interference fringes that accompanies crossing the root of the Bessel function, i.e. changing distance between probing points. Just this consequence of the Van-Cittert – Zernike theorem has been experimentally verified in the paper[31]. The conclusion (*i*) is proved by the graphs of the contrast of interference fringes obtained using the Young's interference arrangement: by crossings the visibility zeroes, just the phase singularities of the spatial coherency function, bright central interference fringe is changed by dark one and *vise versa*. The conclusion (*ii*) has been substantiated in paper[32], being directly and unambiguously proved in the arrangement of the Michelson's stellar interferometer providing, in contrast to the initial Young's interference scheme, constant period of interference fringes for changeble distance between the probing points at the field cross-section.

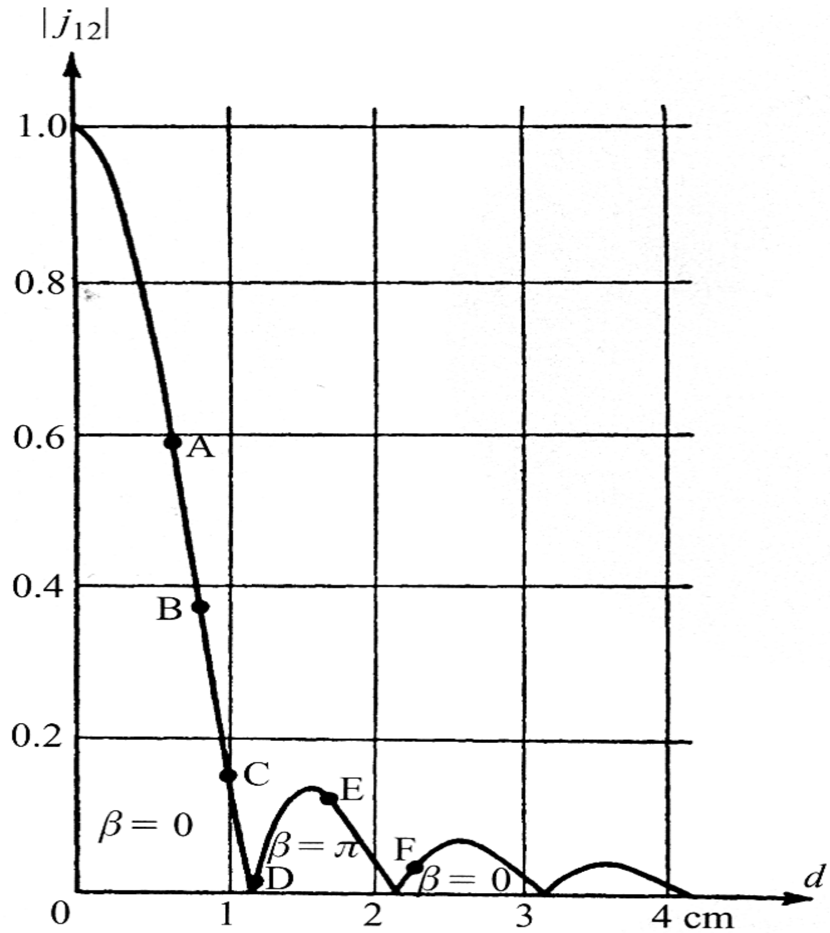


Figure 1[31] (see also Fig. 10.7 in Ref. 29). Two-beam interferece with partially coherent light. The degree of coherence as a function of the separation d of the two illuminated apertures in the diffractometer (see specifications in Ref. 31).

As so, performing the measurements for various orientations of the Michelson's stellar interferometer and determining the corresponding distances between the probing points when visibility vanishes, one reconstructs *the edge dislocation of the (complex) spatial coherency degree*. For that, for arbitrary shaped extended quasi-monochromatic, spatially incoherent source one reconstructs the closed curvilinear edge dislocation (while the spatial correlation length is in inverse proportion to the angular size of a source for the each specified orientation of an interferometer[29]), which is reduced to the *circle edge dislocation* for a circular source.

It is remarkable, in these early observations one can notice some intimate but nevertheless general peculiarity of a singular structure that have been quite comprehended only at the modern singular optics epoch[25,26,35] that is illustrated in Fig. 2. Let us discuss the mentioned peculiarity in more details. Any singularity, including optical one, is a certain local structure with a point or linear core with undetermined (singular) magnitude of some parameter for the threshold magnitude of other (control) parameter changing smoothly[26,35]. To say, in scalar coherent singular optics the field amplitude is the control parameter, while a phase is the singular parameter undergone π-magnitude jump at crossing zero amplitude. In general, the sets of such parameters are different for the beams of various kinds. However, all kinds of singularities are characterized by one common peculiarity, which is the criterial sign of the presence of singularity of the complex parameter of interest. This peculiarity consists in *conical* local structure of the control parameter in the nearest vicinity of the singularity core. The mentioned peculiarity enables, in part, to determine localization of phase singularities as well as differentiate them with local minima (may be deep, but not absolute) and saddle points of a field, what cannot be provided be direct measuring intensity distribution. For that, one can see in graphs of the paper[31] (cf. Fig. 1) the mentioned conical structure in the vicinity of the phase singularity of the coherency coefficient, *viz.* zero magnitude of modulo of the complex degree of coherency.

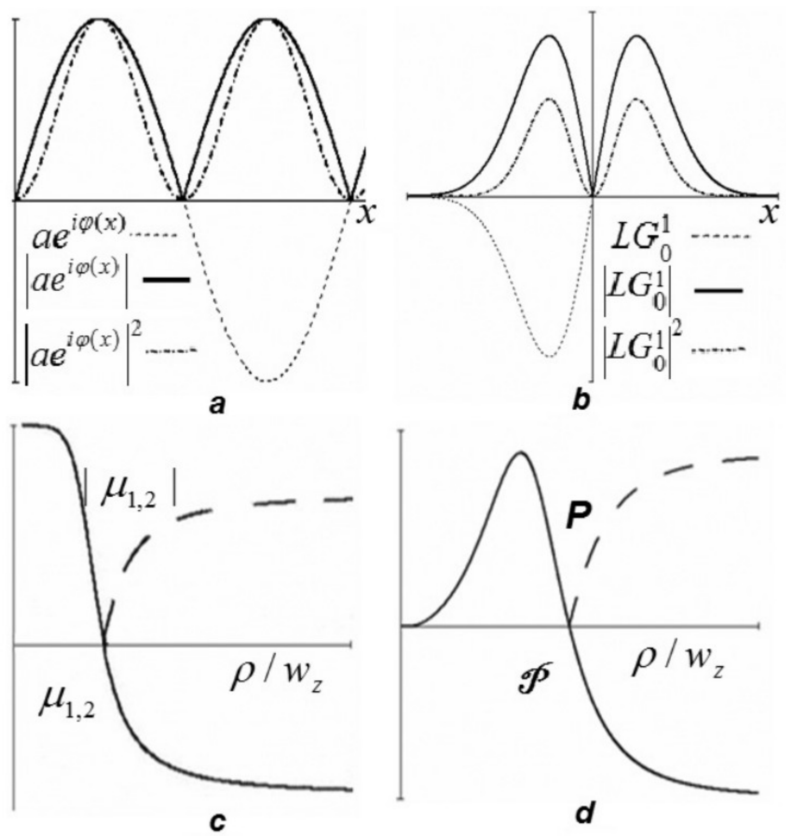
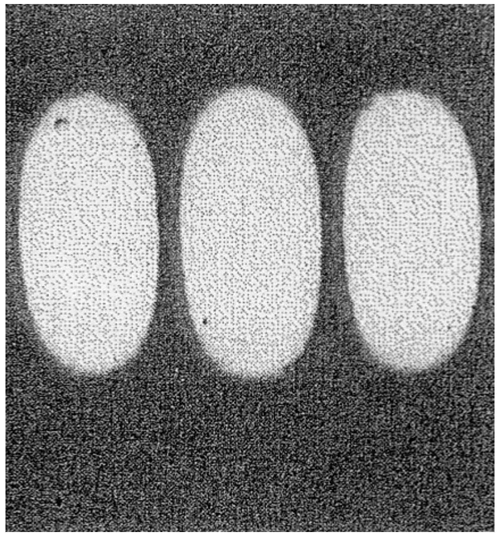


Fig. 2[35-37]. Conical vicinity of optical singularities for the modulo of complex amplitude of a harmonic signal (a), for the Laguerre-Gaussian mode LG01 with the central optical vortex (b), for the modulo of the complex degree of coherence of scalar (homogeneously polarized) combined beam (c) (in notations[35]), and for the complex degree of polarization[35-37] (d).
At left branches of the fragments I and (d) dashed and solid curves coincide.

Thus, emerging the theory of partial coherency has became one of the most important and direct precursors of subsequent formation of the singular optics concept. Note, the analogy between diffraction and propagating coherence[31,32] based on revealing theoretically and experimentally the edge dislocation of the spatial coherence function (though in other terms) is pronounced argument in favor of conceptual interconnectivity of the classical theory of partial coherence and polarization, and the modern concept of singular optics.

Note that similar approach (the Young's interference experiment and its modifications) has been later applied[39] (under coherent approximation) for proving physical reality of the Young-Rubinowitz edge diffraction wave, which also contains the edge dislocation (phase singularity) at the light-shadow boundary (see Fig. 3), as well for detection and diagnostics of screw and edge dislocations of the spatial coherency function at partially coherent Laguerre-Gaussian[34,38] and Hermite-Gaussian[37] combined beams.



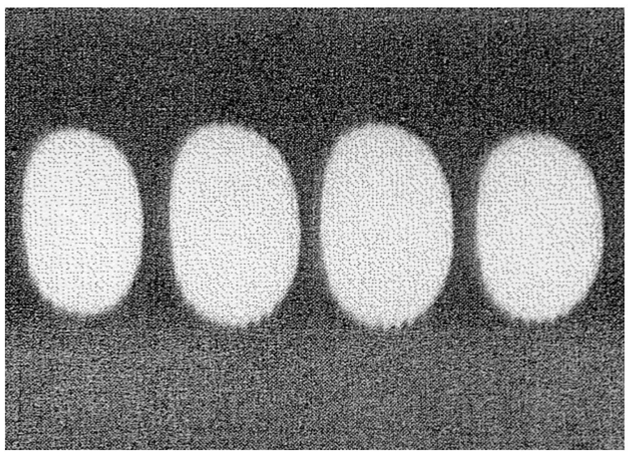


Fig. 3[39]. The Ganci's demonstration of physical reality of the edge diffraction wave. The upper fragment: a screen with two pinholes illuminated by undisturbed laser beam; one observes the central intensity maximum. The bottom fragment: an opaque half-phase screen is placed between the primary source and an opaque screen with two pinholes; one observes the central intensity zero, as it follows from the preredіction[40] (also in pre-singular optics paradigm) on the phase structure of the edge diffraction wave.

Note, the Ganci's demonstration experiment[39] has been performed following the prediction by Banerjee[40] that was concerned to opposite phases of the wings of the edge diffraction wave propagating from an opaque screen rim into the directly illuminated region and into geometrical shadow one (≡ the presence of the edge phase dislocation, in modern terminology), as it follows in its turn from the Rubinowicz's representation of the Kirchhoff's diffraction integral[41] finally confirmed validity of the Th. Young's model of diffrction phenomena (one more jubelee of singular optics manifestation within classical wave optics!), cf. Refs. 29,42.

3. CONCLUSIONS

Pronounced and influencial progress ternd of singular optics consists in expension/generalization of its approaches on the area of partially spatially coherent, partially polarized and polychromatic light fields, what was not typical for the initial stage of developing singular optics. Retrospective review of this field of modern photonics leads to quite obvious conclusion on precictability and even logical inevitability of this trend. It is of especial surprise that the correlation singular optics (as the *wave* singular optics of partially coherent, partially polarized light fields) has emerged much earlier than the traditional now coherent singular optics, *viz*. just sixty years before writing this paper[31,32]! This is the main (tutorial) finding of our consideration.

In this work, we have discussed one of the important precursors of modern singular optics taking account the Wolf's concept of the theory of partial coherency and partial polarization as the *optics of observable quantities*. Really, phase singularities of the spatial correlation functions are visualized and interpreted directry from bending or half-period shift on interference fringes, depending of the kind of singularity. It is remarkable that in the case of interest, the spatial correlation singularities occur even in the abcence of common singularities (wave-front dislocations) in any component of an analyzed beam, as in modern investigations of the combined singular beams[36-38], being in this sense of more general, *generic*[18] nature.

The newest results in singular optics of partially coherent light fields have been comprehensively accounted in Refs. 4, 5. Note, these references are in any case, inavoidably incomplete due to rapid development of this field of investigations. What is we would emphasize, the roots of modern (correlation) singular optics lie in the fundamental concepts of classical optics (interference, diffraction, coherence, polarization) and based on ground experimental results obtained before establishing singular optics as the separate branch of investigations. It is the edifying example that terminology and phraseology can change in the course of time, while physical phenomena leave unchanged though not always such associations are simple recognized. *The future of Optics is in its past*.

ACKNOWLEDGEMENT

This study was supported by the Ministry of Education and Science of Ukraine (grant No 0117U001152).

REFERENCES

[1] Soskin, M. S. And Vasnetsov, M. V., Singular Optics, in Progress in Optics, 42, 219–276 (2001).
[2] Vasnetsov, M. V., Bekshaev, A. Ya. And Soskin, M. S., [Paraxial Light Beams with Angular Momentum], Nova Science Publishers, NY (2008).
[3] Dennis, M. R., O'Holleran, K. And Padgett, M. J., Singular Optics: Optical Vortices and Polarization ingularities, in Progress in Optics, 53, 293–363 (2009).
[4] Gbur, G. and Visser, T. D., The Structure of Partially Coherent Fields, in Progress in Optics, 55C, 285-341(2010).
[5] Gbur, G. J., [Singular Optics], CRC Press, NY (2016).
[6] Nye, J. F. and Berry, M. V., "Dislocations in wave trains," Proc. R. Soc. Lond. A 336, 165-190, 1974.
[7] Baranova, N. B., Zel'dovich, B. Ya., Mamaev, A. V., Pilipetskii, N. F. and Shkunov, V. V., "Dislocations of the wave-front of a speckle-inhomogeneous field (theory and experiment)," JETP Lett. 33, 206-210 (1981).
[8] Zel'dovich, B. Ya., Pilipetsky, N. F. and Shkunov, V. V., [Principles of Phase Conjugation], Springer, Berlin (1985).
[9] Zel'dovich, B. Ya., Shkunov, V. V. And Yakovleva, T. V., "Holograms of speckle fields," Sov. Phys. Usp. 29, 678-702 (1986).
[10] Bazhenov, V. Yu., Vasnetsov, M. V. and Soskin M. S., "Laser beams with screw dislocations in their wave-fronts," JETP Lett. 52, 429-431 (1990).
[11] Heckenberg, N. R., McDuff, R., Smith, C. P. and White, A. G., "Generation of optical singularities by computer-generated holograms," Opt. Lett. 17, 221-223 (1992).
[12] Polyanskii, P. V., "Some current views on singular optics," Proc. SPIE 5477, 31-40 (2004).
[13] Polyanskii, P.V., Optical Correlation Diagnostics of Phase Singularities in Polychromatic Fields, in [Optical Correlation: Techniques and Applications, ed. O. Angelsky, 133-165], SPIE Press, Bellingham (2007).
[14] Angelsky, O. V., Polyanskii, P. V. and Felde, Ch. V., "Emerging the field of Correlation Optics," Opt. Phot. News 4, 25-29 (2012).
[15] Angelsky, O. V., Polyanskii, P. V., Mokhun, I. I., Zenkova, C. Yu., Bogatyryova, H. V., Felde, Ch. V., Bachinskiy, V. T., Boichuk, T. M. And Ushenko, A. G., Optical Measurements: Polarization and Coherence of Light Fields, in [Modern Metrology Concerns, ed. Luigi Cocco, Chapter 10, 263-317], InTech, (2012). ISBN: 978-953-51-0584-8

[16] Angelsky, O. V., Felde, Ch. V. and Polyanskii P.V., "Correlation optics paradigm in measuring coherence and polarization of light", Ann. Acad. Roman. Sci. 3, 5-32 (2013).
[17] Polyanskii, P. V., Felde, Ch. V., and Konovchuk, A. V., "On some prerequisites of correlation singular optics as a branch of information optics," Opt. Memory and Neural Networks 26, 207-215 (2017).
[18] Nye, J. F., [Natural Focusing and Fine Structure of Light: Caustics and Wave Dislocations], IOP Publ., Bristol and Philadelphia (1999).
[19] Schurcliff, W. A., [Polarized Light: Production and Use], Harvard Univ. Press, Cambridge, Massachusetts (1962).
[20] Polyanskii, V. K. And Kovalskii, L .V., "On fine structure of the scattered radiation field," Opt. Spectrosc., 35, 345-350 (1973).
[21] Ellis, J. And Dogariu, A., "Differentiation of globally unpolarized complex random fields," J. Opt. Soc. Am. 21, 988-993 (2004).
[22] Freund, I. and Shwartsman, N., "Wave-field singularities: the sign principle," Phys. Rev. 50, 5164-5172 (1994).
[23] Freund, I., Mokhun, A. I., Soskin, M. S., Angelsky, O. V. and Mokhun, I. I., "Stokes singularity relations," Opt. Lett. 27, 545-547 (2002).
[24] Mokhun, I. I., Introduction to Linear Singular Optics, in [Optical Correlation: Techniques and Applications, ed. O. Angelsky, 1-131], SPIE Press, Bellingham (2007).
[25] Polyanskii P. V., Felde Ch. V. and Chernyshov A. A. "Polarization degree singularities," Proc. SPIE 7388 0A, 1-13 (2009).
[26] Soskin, M. S. and Polyanskii, P. V., "New polarization singularities of partially coherent light beams", Proc. SPIE 7613 0G, 1-11 (2010).
[27] Angelsky, O. V., Gorsky, M. P., Hanson, S. G., Lukin, V. P., Mokhun I. I., Polyanskii, P. V. and Ryabiy, P. A., "Optical correlation algorithm for reconstructing phase skeleton of complex optical fields for solving the phase problem," Opt. Expr. 22, 6186-6193 (2014).
[28] Wolf, E., "Optics in terms of observable quantities," Nuovo Cimento 12, 884-888 (1954).
[29] Born, M. and Wolf, E., [Principles of Optics (7^{th} ed, expanded)], Cambridge U. Press, Cambridge (1999).
[30] Wolf, E., "Unified theory of coherence and polarization of random electromagnetic beams," Phys. Lett. A 312, 263–267 (2003).
[31] Wolf, E. and Thompson, B., "Two-beam interference with partially coherent light," J. Opt. Soc. Am. 47, 895-902 (1957).
[32] Thompson, B., "Illustration of the phase change in two-beam interference with partially coherent light," J. Opt. Soc. Am. 48, 95-97 (1958).
[33] Goodman, J. W., [Statistical Optics], Wiley, NY (2015).
[34] Bogatyryova, G. V., Felde, Ch. V., Polyanskii, P. V., Ponomarenko, S. A., Soskin, M. S. and Wolf, E., "Partially coherent vortex beams with a separable phase," Opt. Lett. 28, 878-880 (2003).
[35] Chernyshov, A. A., Felde, Ch. V., Bogatyryova, H. V., Polyanskii, P. V. and Soskin, M. S., "Vector singularities of the combined beams assembled from mutually incoherent orthogonally polarized components," J. Opt. A: Pure Appl. Opt. 11, 1-8 (2009).
[36] Felde, Ch. V., Chernyshov, A. A., Bogatyryova, H. V., Polyanskii, P. V. and Soskin, M. S., "Polarization singularities in partially coherent combined beams," JETP Lett. 88, 418-422 (2008).
[37] Felde, Ch. V., Polyanskii, P. V., Zelinskii, Ye. V. And Oleksyuk, M. V., "Young's diagnostics of the space correlation and polarization phase singularities inherent in combined Hermite-Gaussian beams," Proc. SPIE 9809 (980903), 1-10 (2015).
[38] Felde Ch. V., Bogatyryova H. V. and Polyanskii P. V., "Young's diagnostics of spatial coherence phase singularities," Proc. SPIE 6254, 104-110 (2006).
[39] Ganci, S., "An experiment on the physical reality of edge-diffracted waves," Am. J. Phys. 57, 370-373 (1989).
[40] Banerjee S., "On the radiation of light from the boundaries of diffracting apertures," Philos. Mag. Suppl. 37, 112 (1919).
[41] Rubinowicz A., "Die beugungswelle in der Kirchhoffschen theorie der beugungserscheinunger," Ann. der Physik 53, 257-278 (1917).
[42] Sommerfeld A., [Optics], Academic Press, NY (1954).