On the feasibility for determining the amplitude zeroes in polychromatic fields

Oleg V. Angelsky,[1] Steen G. Hanson,[2] Alexander P. Maksimyak[1] and Peter P. Maksimyak[1]

[1] *Correlation Optics Dept, Chernivtsi University, 2 Kotsyubinsky Str., Chernivtsi, 58012 Ukraine*
[2] *Optics and Plasma Research Dept., RISØ National Laboratory, P.O. Box 49, DK-4000 Roskilde, Denmark*
oleg@optical.chernovtsy.ua

Abstract: The technique of an inverted chromascope is introduced for determining the points of amplitude zeroes for the spectral components of a polychromatic radiation field. Applications of this technique for processing of experimentally obtained light distributions are demonstrated, both arising from birefringence and from speckle fields.

OCIS codes: (240.5770) Roughness, (290.5820) Scattering measurements, (120.3180) Interferometry, (120.4630) Optical inspection, and (180.1790) Confocal microscopy.

References

1. H. He, N.R. Heckenberg, and H. Rubinsztein-Dunlop, "Optical particle trapping with higher-order doughnut beams produced using high efficiency computer generated holograms," J. Mod. Opt. **42**, 217-223 (1995).
2. N.B. Simpson, J.L. Allen, and M.J. Padgett, "Optical tweezers and optical spanners with Laguerre-Gaussian modes," J. Mod. Opt. **43**, 2485-2491 (1996).
3. C.Rockstuhl, M.Salt, and H.P.Herzig, "Theoretical and experimental investigation of phase singularities generated by optical micro- and nano-structures," J. Opt. A: Pure Appl.Opt. **6,** 271 - 276 (2004).
4. H.F. Schouten, T.D. Visser, G. Gbur, D. Lenstra, and H. Blok, "The diffraction of light by narrow slits in plates of different materials" J. Opt. A: Pure Appl.Opt. **6,** 277 - 280 (2004).
5. H.F. Schouten, T.D. Visser, G. Gbur, D. Lenstra, and H. Blok, "Phase singularities and Enhanced Transmission at a Subwavelength slit," Opt. Photon. News **14**, 23 (2003).
6. M. Mujat and A. Dogariu, "Polarimetric and spectral changes in random electromagnetic fields," Opt. Lett. **28**, 2153-2155 (2003).
7. G. Popescu and A. Dogariu, "Spectral anomalies at wave-front dislocations," Phys. Rev. Lett. **88**, 183902 (2002).
8. V.K. Polyanskii, O.V. Angelsky, and P.V. Polyanskii, "Scattering-induced spectral changes as a singular optical effect," Opt. Appl. **32**, 843-848 (2003).
9. J.W. Goodman, *Statistical Optics* (Wiley, New York, 1985).
10. M.V. Berry "Coloured phase singularities," New J. Phys., **4**, 66.1-66.14 (2002).
11. M.V. Berry "Exploring the colours of dark light," New J. Phys. **4**, 74.1-74.14 (2002).
12. J. Leach, M. Padgett "Observation of chromatic effects near a white-light vortex," New J. Phys. 154.1-154.7 (2003).

1. Introduction

A wide usage of nanotechnologies in various industrial applications demands development of metrology providing diagnostics for nanostructures. In this process, the ideas and principles of singular optics give promising perspectives. This is confirmed by the creation of optical traps and tweezers [1,2], by realization of super-resolution in microscopy [3], by the effect of enhanced energy transfer through nanoholes [4,5], as well as by the spectral effects observed in the vicinity of amplitude zeroes in polychromatic fields [6,7]. The use of spectral effects in polychromatic fields enables the design of new instruments with sub-wavelength resolution for control of surface processing, etching, crystal- and thin film growth in a range of nanotechnologies in microelectronics and in optics-related industries. An indispensable

#7321 - $15.00 USD Received 29 April 2005; revised 26 May 2005; accepted 26 May 2005

condition for creation of such measuring devices consists in developing the principles and techniques for detection of amplitude zeroes in polychromatic fields.

As a matter of fact, the use of the points of amplitude zeroes for the distinct spectral components of a polychromatic radiation as the diagnostic instrument provides: (*a*) increasing sensitivity and resolving power of the measuring technique, especially for the control of film growth, for spectral scanning, (*b*) reducing the inverse problem dealing with determination of the correct height distribution for rough surface inhomogeneities for processing of partial solutions for the given set of spectral components.

Computer simulations and experimental modeling for passing polychromatic radiation through a phase object, such as a frosted glass and crystals are presented. We study the structure of the field resulting from scattering of polychromatic radiation at such a surface. The amplitude and phase of the field for each spectral component are computed using the Rayleigh-Sommerfeld diffraction integral [9]:

$$U(\xi,\eta) = \frac{z}{i\lambda}\int\int \frac{A(x,y)}{R^2(x,y,z,\xi,\eta)} \exp\left\{-ik\left[R(x,y,z,\xi,\eta)+(n-1)h(x,y)\right]\right\}dxdy\ , \qquad (1)$$

where $A(x,y)$ is the aperture function that corresponds to the amplitude transmittance of a rough surface, $R(x, y; \xi, \eta, z) = [z^2 + (x - \xi)^2 + (y - \eta)^2\ ]^{1/2}$ is the distance between the surface point and the observation point, z is the distance between the plane of the object to the observation plane, x, y; ξ, η are the rectangular Cartesian coordinates at the object plane and the observation plane, respectively, $h(x,y)$ is the relief height of a rough surface, n is the bulk index of refraction, $k = 2\pi/\lambda$ is the wave number, and λ is the wavelength . Eq. (1) is applicable to the field calculations at an arbitrary distance z. In this study we replace integration by summation, dividing both the object and the field in the observation plane into elementary areas.

We use three spectral components with wavelengths 633 nm, 540 nm, and 430 nm. Subsequently, the intensity distributions for the spectral components are added. The concept of a chromascope [10,11] forms the basis of the technique for determining the points of amplitude zeroes of the field. The first experimental study using the concept of a chromascope dealt with chromatic effects near a white-light vortex generated holographically [12].

2. Simulations

Let us consider the feasibility for determining spatially separated amplitude zeroes of various monochromatic components. We illustrate this technique for an isolated fragment of a simulated speckle-field with the intensity distribution shown in Fig. 1. The spatial phase distribution for each of the three spectral components reveals the presence of the amplitude zeroes, cf. Fig. 2. Amplitude zeroes are detected as the points where the equiphase lines are broken, which is followed by spatial blurring. We define "blurring" as the smooth changing of color intensity around the amplitude zero (even for circles of varying radius). We are interested in how the points of amplitude zeroes 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 zeroes consists in three stages. In the first stage, the polychromatic field is processed by a chromascope [11]. Specifically, we normalize the colors in each point of the field (ξ,η) based on the maximum intensity of any color in the RGB scale,

$$\begin{pmatrix} R \\ G \\ B \end{pmatrix}_{CR} = \begin{pmatrix} R \\ G \\ B \end{pmatrix} \Big/ \max(R,G,B) \quad . \qquad (2)$$

This increases the brightness for points of low intensity, namely, in the vicinity of amplitude zeroes. Therefore, if all three spectral components are of low intensity, then these areas processed by a chromascope appear 'white', see Fig. 3, fragment 1.

Received 29 April 2005; revised 26 May 2005; accepted 26 May 2005

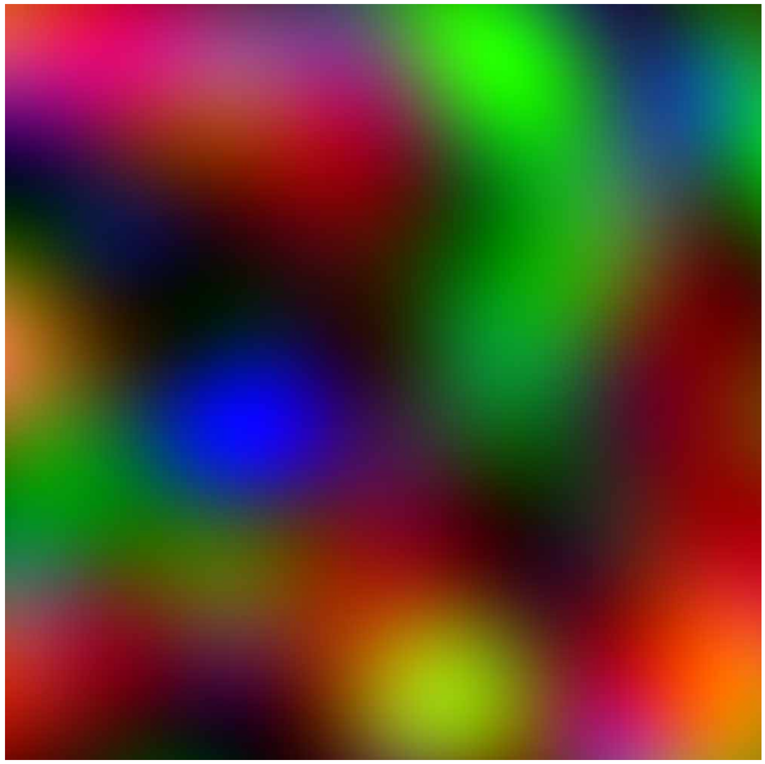

Fig. 1. Spatial intensity distribution over an isolated fragment of a speckle-field produced by three spectral components.

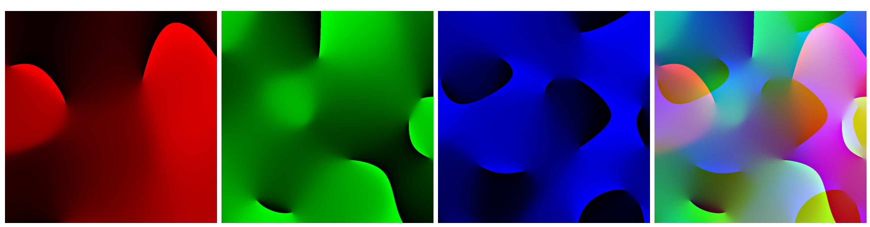

Fig. 2. Spatial phase distribution of an isolated fragment of a speckle-field produced by red (a); green (b); blue (c) and for all three spectral components (d).

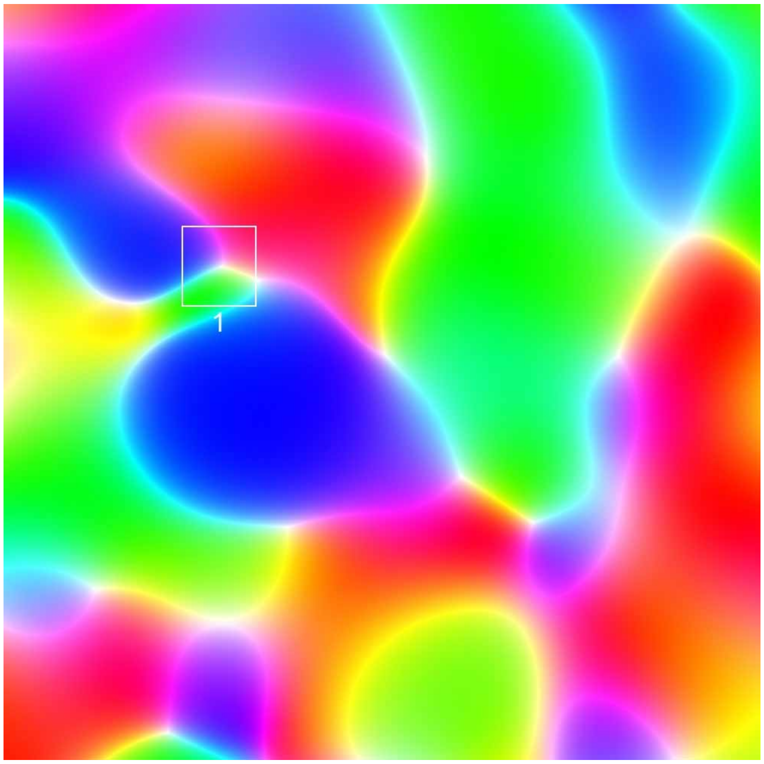

Fig. 3. Color distribution resulting from processing of the isolated fragment of a speckle-field by a chromascope. Fragment (1) depicts a zone of low intensity of the distribution shown in Fig. 1.

The following stage is the use of the "inverted" chromascope, which consists in subtraction of the spectral component in a chromascope from unity (Fig. 4).

$$\begin{pmatrix} R \\ G \\ B \end{pmatrix}_{INV} = 1 - \begin{pmatrix} R \\ G \\ B \end{pmatrix}_{CR} \tag{3}$$

The principle of this operation is as follows: Each point of the field processed by a chromascope contains three weighted monochromatic components. In other words, all three components are presented at each position of the field being weighed from unity to zero. Of course, the probability of reaching zero amplitude (or maximum amplitude) is extremely low. Obtaining the inverted pattern is reduced to subtracting the maximal weight of each of the monochromatic component from unity at every field position. As a result, the found color distribution is characterized by higher sensitivity for changing intensity, cf. Fig. 4. Hence, one can see from Fig. 4 that the areas of the expected positions of amplitude zeroes correspond to the areas of low intensity. This effect is achieved due to the nonlinear normalization using a chromascope. Further, excluding successively both the monochromatic components and the inverted (complementary) colors from the color distribution provided by the inverted chromascope, one obtains the pattern strictly reproducing the points of amplitude zeroes for the used monochromatic component Y (one of RGB) of the field, see Fig. 5(a), (c), (e),

$$\begin{pmatrix} R \\ G \\ B \end{pmatrix}_{Y} = \begin{cases} 1, & for Y_{INV} + \delta_Y \geq 1 \\ 0, & for Y_{INV} + \delta_Y < 1 \end{cases} \quad \text{and } Y = 0\,, \tag{4}$$

#7321 - $15.00 USD
Received 29 April 2005; revised 26 May 2005; accepted 26 May 2005

where δ_y is the noise of the CCD-camera for the given spectral component in the experimental study, or in the accuracy for computing the field in the computer simulation; Y_{inv} is the monochromatic component of the inverted pattern. Increasing δ_y results in spreading of the spot representing the coordinates of the amplitude zero.

This is confirmed by comparing the obtained distribution with the spatial phase distributions for each of the monochromatic components of the field, see Fig. 5(b), (d), (f).

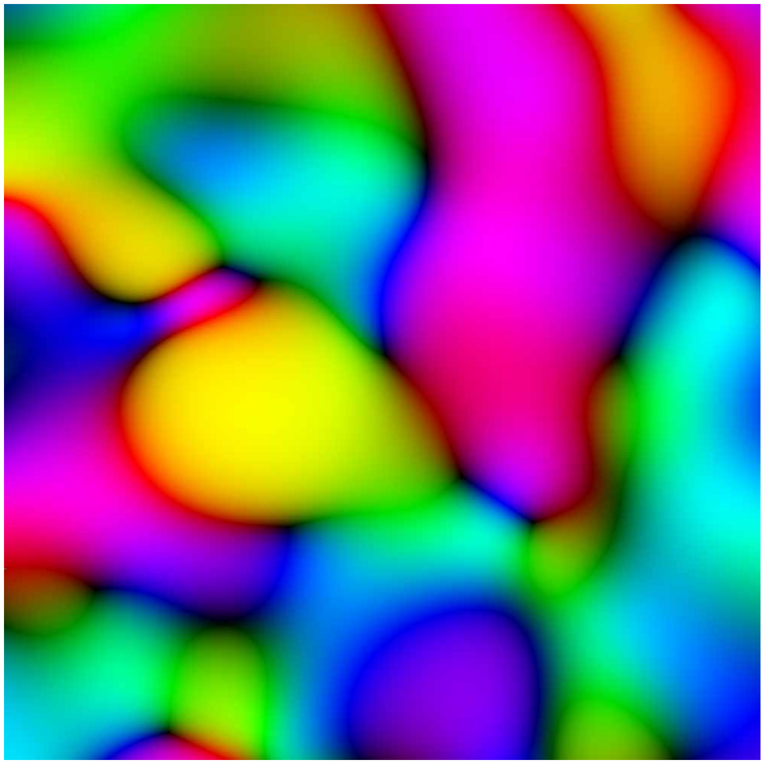

Fig. 4. Color distribution resulting from processing of an isolated fragment of a speckle-field by the inverted chromascope.

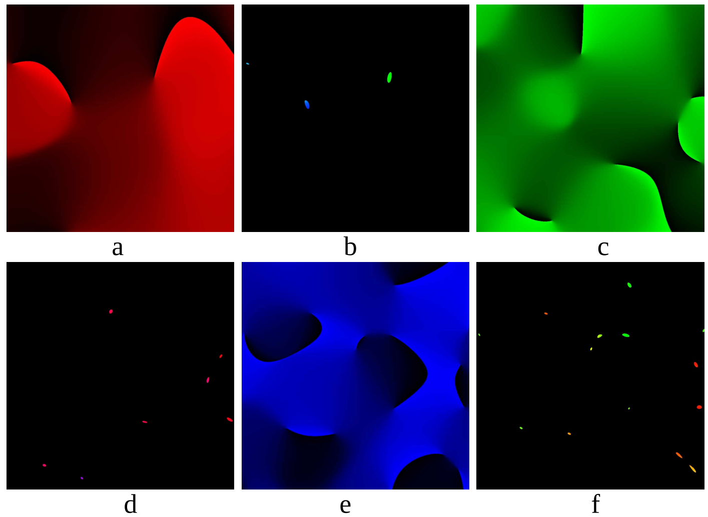

Fig. 5. Spatial phase distribution of an isolated fragment of a speckle-field produced by red (a); green (c); blue (e), and spatial distribution of amplitude zeroes of the isolated fragment of a speckle-field for red (b); green (d); blue (f) spectral component.

3. Experiments

The efficiency of the proposed approach has been experimentally estimated in the arrangement shown in Fig. 6. In the first stage – in order to prove the feasibility of this technique - we used a film made from polyethylenterephthallinum (PETP), possessing the properties of a double-axial crystal (thickness 74 μm, difference in refractive indices of 0.085). An objective, 2, images a white-light source, 1, into a 50 μm-diameter diaphragm 3, which together with the objective, (focal length 200 mm) forms a beam with a high degree of spatial coherence (~95%). One of the optical axes of the crystal coincides with the optical axis of the beam. An objective, 4, images the diaphragm, 3, onto the film, 6. A polarizer, 5, and an analyzer, 7, are rotated with respect to the optical axis and provide observation both with matched and with crossed axes of transmission. An objective, 8, images the film, 6, onto the sensitive area of the CCD-camera, 9, which roughly has a similar sensitivity to the RGB colors as the human eye.

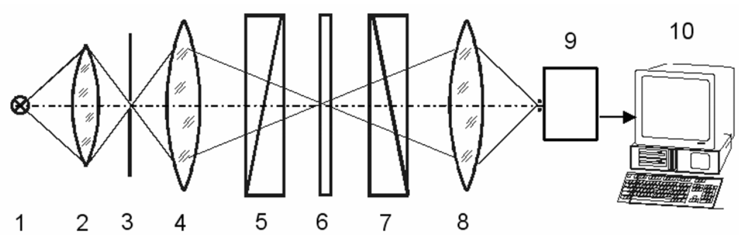

Fig. 6. The experimental optical arrangement: 1 – source of light; 2,4,8 – objectives; 3 – diaphragm; 5 – polarizer; 6 – film; 7 – analyzer; 9 – CCD-camera; 10 – computer.

In Fig. 7(a) and (b) one can see the distributions obtained with a matched and with a crossed analyzer, 5, and with the polarizer, 7, respectively. Processing of these distributions with a chromascope results in the patterns shown in Fig. 8(a) and (b), where the amplitude zeroes for all three spectral components of the field with the same azimuth of polarization are present, see Fig. 8(a). As a matter of fact, the pattern shown in Fig. 8(a), obtained using a

#7321 - $15.00 USD Received 29 April 2005; revised 26 May 2005; accepted 26 May 2005

chromascope strictly corresponds to the typical color distribution in the vicinity of an amplitude zero [11]. The pattern shown in Fig. 8(a) seems to be more suited for further processing, while within this distribution the areas where amplitude zeroes are expected are reduced to points.

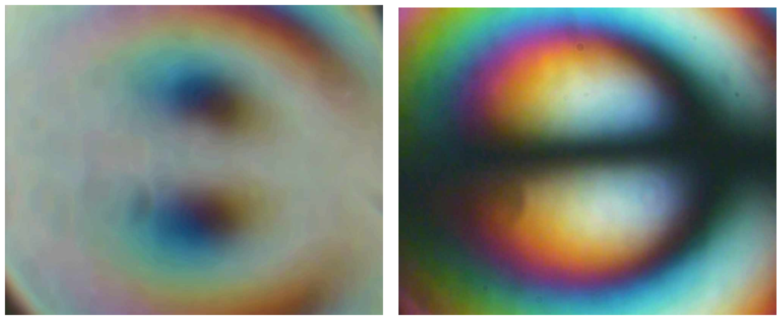

Fig. 7. Conoscopic patterns obtained for matched polarizer and analyzer (a), and for crossed polarizer and analyzer (b).

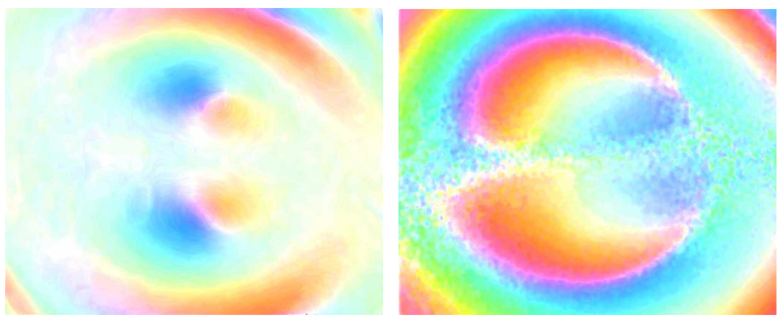

Fig. 8. Patterns shown in Fig. 7 processed by a chromascope for matched polarizer and analyzer (a), and for crossed polarizer and analyzer (b).

Processing of the obtained distributions using the technique involving the inverted chromascope, Fig. 9, facilitates the determination of the loci of amplitude zeroes for all three spectral components of the field, cf. Fig. 10(a), (b), (c). Theory predicts that amplitude zeroes must appear in-pairs. However, due to some mismatching of the crystal axes in the polarization optics we were in a position to observe only one white-light vortex shown at the bottom of Fig. 10.

In an experimental arrangement similar to the one shown in Fig. 6 we obtained the polychromatic speckle-pattern represented in Fig. 11. The color distribution resulting from processing this speckle-pattern by a chromascope is shown in Fig. 12(a), (b).

#7321 - $15.00 USD Received 29 April 2005; revised 26 May 2005; accepted 26 May 2005

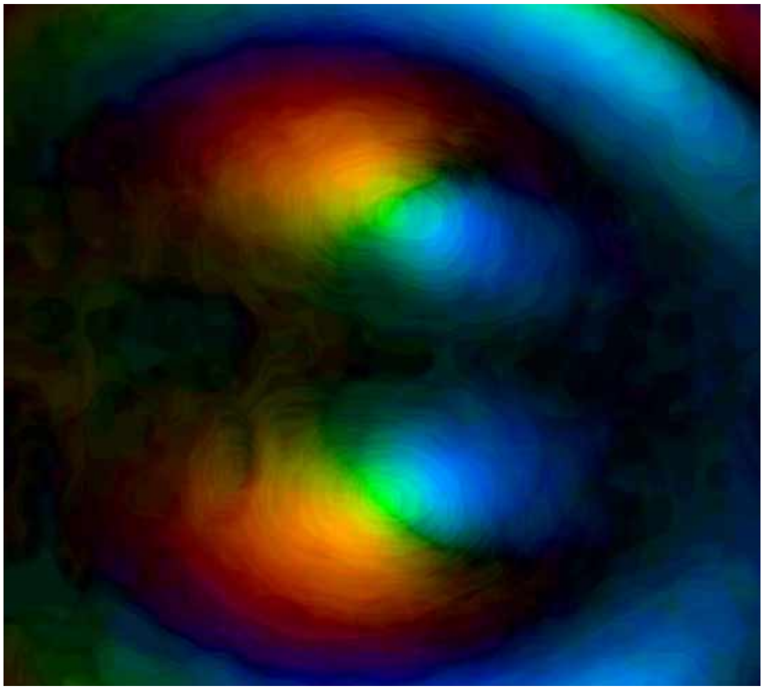

Fig. 9. Pattern shown in Fig. 7(a) processed by the inverted chromascope.

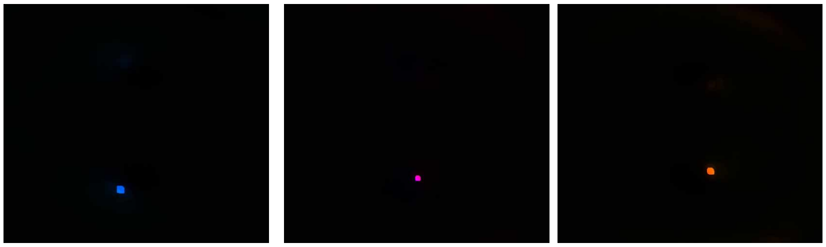

Fig. 10. Patterns illustrating the positions of amplitude zeroes of the field for red (a), green (b) and blue (c) spectral components.

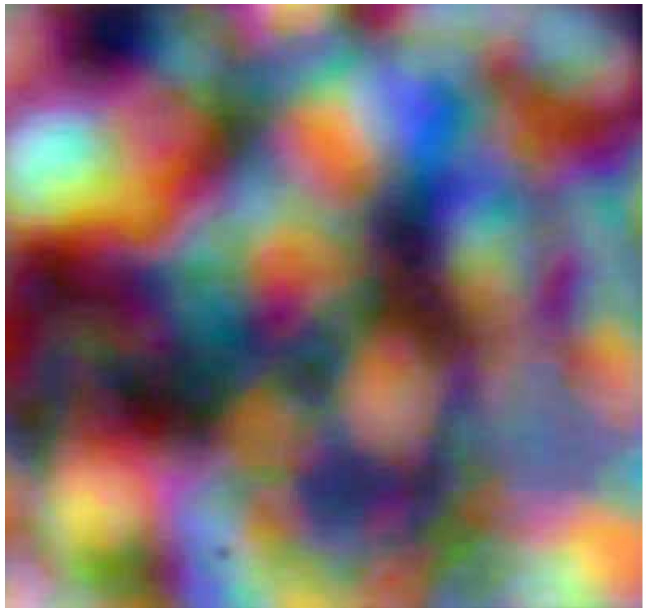

Fig. 11. Fragment of polychromatic speckle-field resulting from scattering by a rough surface.

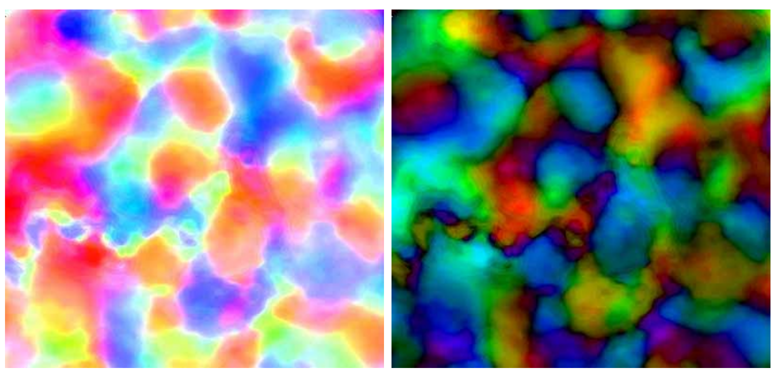

Fig. 12. The pattern obtained by applying a chromascope (a) and inverse chromascope (b) to the experimentally found intensity distribution shown in Fig. 11.

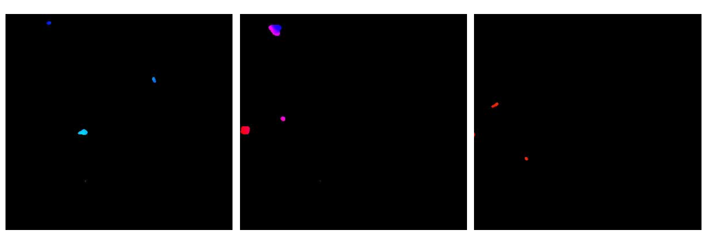

Fig. 13. The patterns illustrating the positions of amplitude zeroes of the speckle-field for red (a), green (b) and blue(c) spectral components.

Further, the use of the technique introduced here makes the determination of the points of amplitude zeroes in a speckle pattern for several spectral components possible, see Fig. 13(a), (b), (c). It is seen that using the corresponding interferometric arrangement one can determine experimentally the location of an amplitude zero at a given position of the field by obtaining the polychromatic forklet.

As a result, the technique for determining the positions of amplitude zeroes in polychromatic fields has been introduced. The technique is based on the effect of coloring the field in the vicinity of the optical singularities. It is anticipated that this principle and the mechanism of spectral changes will aid in developing nanoscale-measuring devices.

4. Summary

In conclusion, let us note that precise determination of the points of amplitude zeroes is of importance both for practical purposes and for theoretical investigations. Points of zero amplitude and minima of intensity are present simultaneously. The presented method facilitates an unambiguous discrimination between these two occurrences. This fact is the diagnostic indication of the degree of development of a speckle field, similar to the speckle field observed for monochromatic radiation. Besides, the lattice of amplitude zeroes is a skeleton of the spatial distribution of the field, which to a large extent determines the spatial correlation characteristics of the field, when the size of the elementary cell formed by adjusting the amplitude zeroes is comparable with the correlation length of the field. One of the examples for a potential practical application of the technique for diagnostics of amplitude zeroes is a technique for thickness control of growing films. Accordingly, by studying the result of interference interaction of polychromatic fields reflected by an underlying surface and by the surface itself during its growth, one can detect the thickness of the film by the birth of amplitude zero in the resulting field (as is the rule, in a speckle field). This process will provide sub-wavelength resolution due to the possibility to determine the spectral component for which zero amplitude occurs at given stage in the film growing process.