About the Using of Polarization Methods in Investigating the Polarization Sensitive Nanosystems

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***Abstract* –The paper shows the possibilities of defining the degree of correlation of mutually orthogonal superposing circularly-polarized and linearly-polarized plane waves. The proposed results widen possibilities of metrological use the methods of spatial polarization modulation for investigating the properties of polarization sensitive systems and nanoobjects.**

***Index Terms* – spatial modulation of polarization, visibility, degree of coherence.**

I. INTRODUCTION

One of the manifestations of the coherence of superposing fields, one of the diagnostic indicators of coherence is the spatial periodical polarization modulation of the resulting spatial distribution. The depth, the level of such a modulation is connected with the degree of coherence, correlation of superposing fields. The interconnection of the degree (or level) of the polarization modulation of the resulting field and the characteristics of coherence in the approximation of plane waves is rather thoroughly studied within the framework of the stokes-polarimetric approach [1, 2].

The manifestation of the superposing wave coherence in the case when it is necessary to take into consideration the longitudinal z-component of the field, and the modulation polarization of the resulting field realized in the plane of incidence is studied in a number of papers offered by the authors [3]. The possibility of measuring the field coherence function through estimating the degree (level) of field polarization modulation is shown and justified in the framework of such an approach [4, 5]. Thus, these papers suggest a method for defining the degree of coherence of linearly-polarized fields, where the polarization distribution takes place in one of the planes – the plane of observation. The offered paper widens the proposed method and demonstrates the possibility of using it for circularly-polarized fields at the formation of two polarized distributions in two mutually orthogonal planes. Thus this paper proposes to widen the possibilities of metrological use of the method of spatial polarization modulation of the field for estimating the coherence of superposing waves by considering the case of superposition not only of linearly polarized in the incidence plane waves, but, in the general case, of circularly polarized interacting waves as well. Practical importance of this problem increases owing to the development of the techniques of confocal microscopy of isolated molecules, including long molecules oriented along the direction of beam propagation and systems of 3D imaging of such molecules, when accounting z-component of a field is absolutely necessary. Generally, such situations occur in solving of many problems:

- transmission of radiation through optically anisotropic crystals;
- multiple light scattering of coherent radiation in turbid media, as well as transmission of optical radiation through optical waveguides;
- heterodyning (nonlinear mixing) of optical waves of different states of polarization, as well as at near zone of a field scattered by random phase objects.

At the same time the information contained in the polarization distribution of interacting circular waves of a similar polarization, essentially enriches the ideas on the properties of optical fields. The paper offers for investigation the results of computer simulation, which allow to define both coherent peculiarities of vector optical fields and the ways of forming periodically modulated polarization distribution in the registration plane.

II. THE BASE OF THEORETICAL APPROACH AND COMPUTER SIMULATION

The time-averaged intensity distribution [4,5] of a random electromagnetic field formed at instant t by the sources $\vec{Q}_1, \vec{Q}_2, \vec{Q}_3$ and observed at point $\vec{r}$ at the observation plane can be put down as,

$$I(\vec{r}) = \sum_{ij} \Big\{ \varphi_{ii}^{(1)}(\vec{r}) + \varphi_{ii}^{(2)}(\vec{r}) + \varphi_{ii}^{(3)}(\vec{r}) + 2\sqrt{\mathrm{tr}[W(\vec{Q}_1,\vec{Q},0)]\mathrm{tr}[W(\vec{Q}_2,\vec{Q}_2,0)]}\,\eta_{ij}^{(1,2)}\cos[\delta_1] + 2\sqrt{\mathrm{tr}[W(\vec{Q}_1,\vec{Q}_1,0)]\mathrm{tr}[W(\vec{Q}_3,\vec{Q}_3,0)]}\,\eta_{ij}^{(1,3)}\cos[\delta_2] + 2\sqrt{\mathrm{tr}[W(\vec{Q}_2,\vec{Q}_2,0)]\mathrm{tr}[W(\vec{Q}_3,\vec{Q}_3,0)]}\,\eta_{ij}^{(2,3)}\cos[\delta_3] \Big\},\quad i,\ j = x,\ y,\ z. \tag{1}$$

Here $\varphi_{ii}^{(m)}(\vec{r}) = \langle E_i^{(m)}(\vec{r},t)E_i^{*(m)}(\vec{r},t)\rangle$ $i, j = x, y, z$, (m =1, 2, 3) describes the time-averaged intensities of corresponding sources, the angle brackets denote the time averaging and the superscript * stands for complex conjugation. The coherence properties of vector optical fields are described using the mutual coherency matrix $W(\vec{Q}_m,\vec{Q}_n,t)$ [6] characterizing correlation of the fields at two different spatio-temporal points $\vec{Q}_m$ and $\vec{Q}_n$, being determined as $W(\vec{Q}_m,\vec{Q}_n,t) = \langle E_i(\vec{Q}_m,t)E_j^*(\vec{Q}_n,t)\rangle$.

Within the framework of such approach $\eta_{ij}^{(m,n)} = \dfrac{W_{ij}(\vec{Q}_m,\vec{Q}_n,t)}{\sqrt{\mathrm{tr}[W(\vec{Q}_m,\vec{Q}_n,0)]\mathrm{tr}[W(\vec{Q}_n,\vec{Q}_n,0)]}}$, ($m$, n = 1, 2, 3, $i, j = x, y$, z) and determines the degree of correlation of the field components. $\delta_1 = k(R_1 - R_2)$, $\delta_2 = k(R_1 - R_3)$, $\delta_3 = k(R_2 - R_3)$ are the phase differences of the corresponding fields at the registration plane, $R_1 = |\vec{r} - \vec{Q}_1|$, $R_2 = |\vec{r} - \vec{Q}_2|$, $R_3 = |\vec{r} - \vec{Q}_3|$ are distances of point $\vec{r}$ from the sources centers.

Changing a phase of the reference wave within the interval $0..2\pi$ results in periodical changing of visibility of the registered interference pattern following the harmonic law [4,5].

The visibility modulation depth (VMD) is determined as

$$M = \max[V] - \min[V] = 4\sum_m \sum_{ij} \frac{\sqrt{\mathrm{tr}[W(\vec{Q}_m,\vec{Q}_m,0]\mathrm{tr}[W(\vec{Q}_3,\vec{Q}_3,0)]}}{\varphi_{ij}^{(m)}(\vec{r}) + \varphi_{ij}^{(3)}(\vec{r})} \left|\eta_{ij}^{(m,3)}\right|$$

m = 1, 2; $i, j = x, y$ z. (2)

Choosing a reference wave to be completely correlated with one of the initial waves, to say $\left|\eta^{(1,3)}\right| = 1$, one can see that the VMD of an interference pattern, M, characterizes, up to the constant depending on the intensity values, the degree of mutual coherence of the reference wave and the second of the initial waves, i.e. $M = \left|\eta^{(2,3)}\right|$. Accounting $\left|\eta^{(1,3)}\right| = 1$, one concludes that $\left|\eta^{(2,3)}\right| = \left|\eta^{(1,2)}\right|$. Thus, by proper choice of intensities of the interfering waves $\left|\eta^{(1,2)}\right|$ will be determined by the VMD of an interference pattern: $M = \left|\eta^{(1,2)}\right|$.

Superposition of plane waves of equal intensities linearly polarized at the incidence plane whose degree of mutual coherence equals zero at the same registration scheme results in homogeneous intensity distribution at the registration plane. The use of the plane reference wave coherent with one of the initial waves enables to visualize the intensity distribution with the certain visibility. In the case of two uncoherent waves, the VMD is equal to zero. It means that the VMD is in quite correspondence with the degree of mutual coherence of the initial superimposing waves. The experiments [4,5] carried out for the cases when $0 < \eta^{(1,2)} \le 1$ completely proved the conclusion that the VMD of a pattern corresponds to the magnitude $\eta^{(1,2)}$ of the superimposing waves.

It is possible to perform a correct experiment if some factors are taken into account. To avoid distortions introduced by the optical system, we must take into account the fact that the propagation of radiation through a microscope is accompanied by the change of a cone angle of the beams, so that this angle differs from the right one. This leads to the violation of the strict orthogonality of the electrical vectors of the interfering beams and manifests itself in the spatial intensity modulation. We employ a holographic recording system in an immersion liquid (Fig. 1). Such a system fulfills the strict angular requirements for the waves in the recording region. We set the reference wave intensity equal to the net intensity of the plane waves in the recording region, thus ensuring a larger percentage modulation and therefore a higher recording efficiency of the interference fringes that visualize the polarization modulation of the field. The same scheme was used for the readout of a hologram. The prism positioned in an immersion liquid was used for coupling out radiation diffracted by the holographic grating.

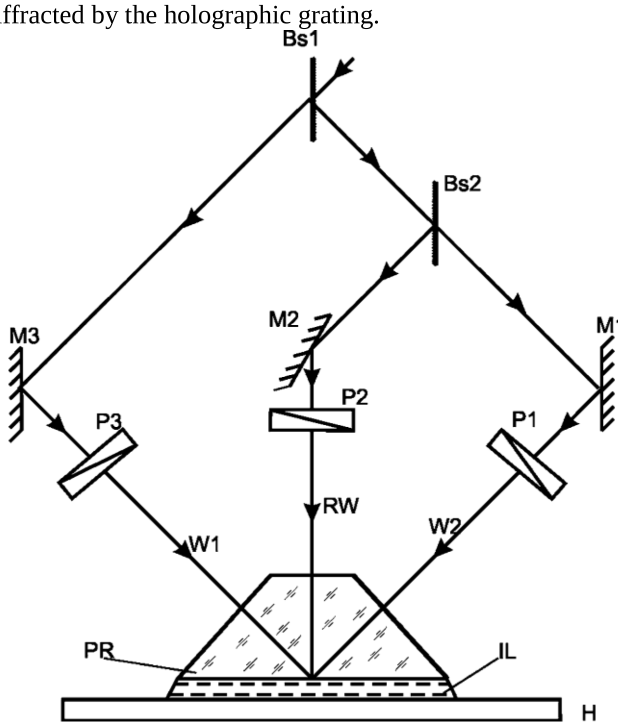

Fig.1. Optical arrangement for holographic experiment: Bs1 and Bs2, beam splitters; M1, M2, and M3, mirrors; P1, P2, and P3, polarizers; PR, prism; IL, immersion liquid; H, hologram.

It can be ascertained that the maximal intensity of the reconstructed signal corresponds to the case in which the electrical vector of the reference wave lies in the incidence plane, and the minimal intensity corresponds to the case in which the polarization of the reference wave is orthogonal to the incidence plane. Changing the polarization azimuth of the reference wave leads to a decrease in contrast of the interference pattern.

The experimental results are shown in the form of interferograms obtained in various polarization situations. It is seen from the photos shown in Fig. 2(a) that the interference of two plane object waves which are linearly polarized in the plane of the figure results in the interference pattern with the period corresponding to the angle of convergence of the two beams, and the visibility is determined by the ratio of the $x-$ and $z-$ components of the decomposition. The use of the third linearly polarized beam with the direction of oscillation of the electrical vector perpendicular to the figure plane does not result in any changes in the structure (period) of an interference pattern. Only the visibility of the pattern is changed due to changing the level of background, see Fig. 2(b). If the state of polarization of the reference beam is linear and the electrical vector lies in the figure plane, then the structure (period) of the registered interference pattern is changed, as a rule, it is doubled, Fig. 2(c). The doubling of the period of the interference pattern is the most pronounced in the situation in which the intensity of the reference beam exceeds the intensity of the object beams. Such doubling of a period is of pure polarization nature and has been quite comprehensively described in the previous experiment and illustrated in Fig. 1. If intensity of the reference beam is spatially nonuniform, one can observe the mechanism of the period doubling of the interference distribution – see the picked out fragment in Fig. 2(d). Thus, similarly to the previous experiment, the contribution of the polarization component to the correlation of optical fields has been shown.

The given experiment shows the contribution of the polarization component into the correlation of optical fields. The parameter, which was introduced by us directs the way to the quantitative estimation of this correlation.

The results of computer simulation for the same arrangement and the same states of polarization of the superposing initial and reference waves but for different magnitudes of the degree of mutual coherence of the initial waves show that the VMD of an interference pattern strictly corresponds to the degree of mutual coherence of these waves.

Similar results of defining the degree of coherence of superposing waves are observed at interacting of two circularly-polarized waves when the angle of their convergence is equal to 90^0 [7]. In this case all three components (*x*, *y*, *z*) of the interacting fields determine the formation of the resulting distribution of intensity and polarization.

Let us consider the result of circularly polarized waves interference in the general case with the angle 2θ between the initial W_1 and W_2 waves and the third reference wave *RW*, spreading perpendicular to the registration plane (Fig.3, a). Here $\vec{E}^{(1)}$, $\vec{E}^{(2)}$, $\vec{E}^{(3)}$ are the electrical vectors of the waves W_1, W_2 and *RW* correspondingly.

The formation of the resulting intensity and polarization distribution at interacting of two circularly-polarized waves (W_1, W_2) of a similar handedness is determined by the relationship among the amplitudes and phases *Ox*, *Oy*, *Oz* field components. We shall deal with the special case of the convergence angle $2\theta = 90^0$.

The circularly polarized wave can be obtained by superposition of two linearly polarized waves, which differ in phase by 90^0, and spread in two mutually orthogonal planes *xOz* and *yOz*. The axis *z* is directed perpendicular to the observation plane *xOy*. The result of the superposition of circularly polarized fields will be the intensity distribution, which is formed as a result of interference of *x*-components (curve 1), *y*-components (curve 2), *z*-components (curve 3) of the fields. Figure 1, b demonstrates the result of such interaction at point O. In this case the *x*-distribution of intensity diverges in localization by a quarter of period with respect to the *y*-distribution.

The amplitude distribution only for the *z* and *y* components can be obtained by analyzing plane *yOz*. Since the two analyzed waves of a similar handedness are incident upon a registered plane at the angle of 45^0, the value of the y-projection of these waves will be maximum. The *x* and *z* wave projections are determined by similar amplitude distributions, which when combined, cause the homogeneous distribution of intensity

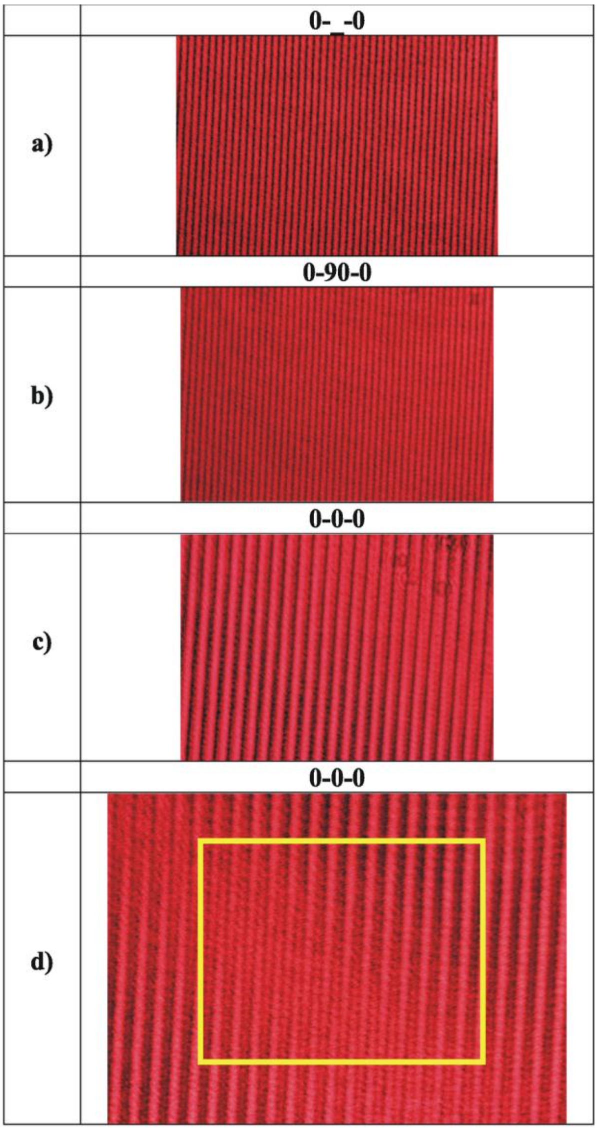

Fig. 2 a-d

Images of two resulting interferograms:

(a) for two object waves with the plane of polarization in the figure plane;
(b) for two object waves with the plane of polarization in the figure plane and the reference wave with the plane of polarization perpendicular to the figure plane;
(c) for two object waves and the reference wave with the plane of polarization in the figure plane;
(d) the result of doubling the period of an interference pattern for interference of three beams with polarization in the figure plane.

. The superposition of the *y*- field components will cause the resulting distribution of intensity.

We can state with assurance that the spatial distribution of polarization is set by the phase difference between the *x* and *z* components of the interacting optical fields at different points of the observation plane. (Fig. 1, c). The correlation of the interacting field components, i.e. the degree of agreement the diagonal and the nondiagonal components of the mutual coherence matrix are additively taken into consideration when estimating the resulting intensity distribution. To visualize the polarization modulation the reference wave *RW* is used, which spreads perpendicular to the registration plane.

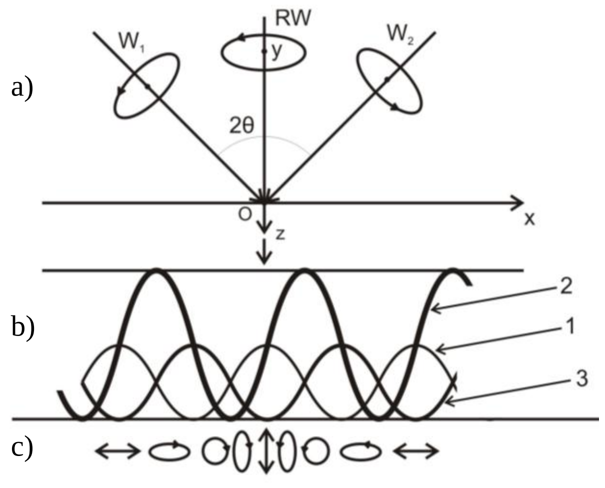

Fig.3. The scheme *a)* demonstrates the interaction of three waves, W_1, W_2, RW – are circularly polarized waves in the general case; *b)* the field distribution at the registration plane: curve 1 is formed by the superposition of *x*-components, curve 2 – by *y*-components, curve 3 – by *z*-components; *c)* the modulation polarization scheme.

When projecting the amplitude vector of the electric field onto the axis *Ox*, *Oy, Oz* the values of the projections on the plane *xOy* will be maximum and the value of the projection on the axis *Oz* will be practically equal to 0. Thus, the results of the interference of three waves change the distribution of the resulting components of the field. The contribution of the resulting *z* component to the formation of the terminal intensity distribution decreases. The influence of the *x*- and *y*- components on the formation of the interference picture changes as well. By changing the amplitude and the phase of the reference wave it is possible to note the zero value of intensity at certain points of the plane, which allows to realize the maximum visibility. It may be concluded, that by the help of the reference wave it is possible to obtain information on the distribution of polarization in the observation plane, which is set by the initial fields. The decrease of the phone takes place and the visibility of the picture increases. The reference wave is used for diagnosing the change of the polarization state at the expense of converting it into the distribution of intensity.

The change of the reference wave phase leads to the spatial modulation of visibility. The influence of one of the components (e.g., *x*-component) on the formation of the resulting intensity distribution increases. It allows to set the VMD and to estimate the degree of coherence of corresponding fields.

By the trial-and-error method of determining the value of amplitudes of the field components we obtain the maximum (minimum) values of the VMD at certain points of the observation area, which enables to estimate the degree of coherence of the initial superposing waves, according to $M = \left|\eta^{(1,2)}\right|$.

We can distinguish two distributions of polarization modulation in two mutually perpendicular planes: in the incidence plane and in the plane perpendicular to it, which are connected with the change of the phase difference between *x* and *z*, *y* and *z* field components at different points of the observation area.

The choice of the reference wave as a circularly-polarized one and at its interference with the initial waves provides both the zero-phase difference at the formation of the linearly polarized state and the zero value of intensity at certain points of the registration plane.

In this case we achieve the VMD which is equal to 1. This corresponds to the degree of coherence of the initial waves.

The polarization modulation, which is determined by the alignment of the phases of field components, becomes more complex and the depth of the polarization changes, which corresponds to the depth of the intensity modulation, exactly corresponds to the correlation properties of the initial superposing waves.

III. CONCLUSIONS

The achieved results allow to extend the notion about the theory of coherence (the metrological use) and is sure to be useful in investigating polarization sensitive systems of biological objects.

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