INTENSITY AND POLARIZATION TRANSFORMATIONS IN COHERENT VECTOR FIELDS

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UDC 535.36

The features of the optical fields with stationary intensity and polarization, which are the coherent superposition of coherent, randomly polarized beams, have been examined. The relations, which allow the polarization state in the plane of analysis to be determined on the basis of its values in the general plane oriented normally to the Umov—Poynting vector, have been derived. The conditions for the summary uniform intensity field to be formed from the partial beams with various amplitudes and polarizations are given.

The optical fields, which are formed by coherent partial beams with arbitrary polarization states and wave vectors, are stationary at every point of a fixed plane. In this case, the field intensity and polarization across this plane can be described by some distribution functions.

To analyze such fields, it is expedient to introduce a coordinate system XYZ universal for all beams. The polarization state of a partial beam is given in its own coordinate system $X'Y'Z'$, where the OZ' axis is directed along the wave vector $\vec{k}$ of the beam and the OX' axis is parallel to the intersection line between the plane of equal phases and the XOY one [1]. The orientation of the XYZ coordinate system with respect to the own coordinate system of the beam is described by the angle θ between the OZ and OZ' axes and the angle φ between the OX and OX' axes.

The field of the beam in its own coordinate system $X'Y'Z'$ is described by the Jones vector

$$\vec{E}_i = \begin{bmatrix} a_{ix'}e^{-i\delta_i} \\ a_{iy'} \end{bmatrix} e^{i(\omega t-\alpha_{0i}-\vec{k}_i\vec{r})} \qquad (1)$$

where $a_{ix'}$ and $a_{iy'}$ are the amplitudes of the i-th beam; $\delta_i = \delta_{ix'} - \delta_{iy'}$ is the phases difference, which determines the type of polarization, and α_{0i} is the initial phase of oscillations.

The intensity and the polarization state at every point in the $X'Y'$ plane are determined by the Stokes parameters

$$S'_{1i} = |E_{ix'}|^2 + |E_{iy'}|^2$$

$$S'_{2i} = |E_{ix'}|^2 - |E_{iy'}|^2$$

$$S'_{3i} = E_{ix'}E^*_{iy'} + E_{iy'}E^*_{ix'}$$

$$S'_{4i} = E_{ix'}E^*_{iy'} - E_{iy'}E^*_{ix'} \qquad (2)$$

which are related to either the ellipsometric parameters ψ_i, the aspect ratio of a rectangle circumscribed around the polarization ellipse, and δ_i, the phase difference between the x- and y-components, or the ellipticity parameter γ_i and the polarization azimuth χ_i.

Let the given partial beam create a field in some plane which, in the general case, is not orthogonal to the radiation propagation direction, and let this field be uniform in intensity (the projection of the first Stokes parameter of the beam onto the plane) and polarization. The oscillations of the electric vector $\vec{E}_i$ of the partial beam in the coordinate system XYZ are defined by means of the rotation matrix

$$T = \begin{bmatrix} cos\varphi & -\sin\varphi\cos\theta & \sin\varphi\sin\theta \\ \sin\varphi & \cos\varphi\cos\theta & -\cos\varphi\sin\theta \\ 0 & \sin\theta & \cos\theta \end{bmatrix}. \qquad (3)$$

This allows the three-dimensional Jones vector

$$\vec{E}_i(x,y,z) = T\vec{E}_i(x',y',z') \qquad (4)$$

to be introduced in the given coordinate system in the form

$$\vec{E}_i(x,y,z) = \begin{bmatrix} a_{ix'}\cos\varphi_i e^{i\delta_i} - a_{iy'}\sin\varphi_i\cos\theta_i \\ a_{ix'}\sin\varphi_i e^{i\delta_i} + a_{iy'}\cos\varphi_i\cos\theta_i \\ a_{iy'_0}\sin\theta_i \end{bmatrix} \times$$

$$\times e^{\left(\omega t-\alpha_{0i}-\frac{2\pi}{\lambda}\vec{\mu_i}\vec{r}\right)} \qquad (5)$$

where $\vec{\mu_i}$ is the unit vector, and $\vec{r}(x,y,z)$ is the radius-vector of the point (x,y,z).

The quantities $\tilde{\delta}_x(a_i,\theta_i) = \arg A_x(a_i,\theta_i)$ and $\tilde{\delta}_y(a_i,\theta_i) = \arg A_y(a_i,\theta_i)$, where

$$A_x(a_i,\theta_i) = a_{ix'}\cos\varphi_i e^{i\delta_i} - a_{iy'}\sin\varphi_i\cos\theta_i,$$

$$A_y(a_i,\theta_i) = a_{ix'}\sin\varphi_i e^{i\delta_i} + a_{iy'}\cos\varphi_i\cos\theta_i, \qquad (6)$$

should be associated with polarization phases, and the quantities $A_x(a_i, \theta_i)$ and $A_y(a_i, \theta_i)$ with complex amplitudes. They determine the projection of the electric vector oscillations in space onto the XOY plane (in the form of an ellipse with characteristic azimuth and ellipticity degree) [2].

The Stokes parameters of the i-th partial electric vector of the beam are formally determined in terms of the components in the XOY plane by the relations [1]

$$S_{1i} = I_i - I_{1y}\sin^2\theta_i$$

$$S_{2i} = I_{ix}\cos 2\theta_i - I_{iy}\cos 2\varphi_i\cos^2\theta_i -$$

$$-2\sqrt{I_{ix}I_{iy}}\sin 2\varphi_i\cos\delta_i$$

$$S_{3i} = I_{ix}\sin 2\theta_i - I_{iy}\sin 2\varphi_i\cos^2\theta_i +$$

$$+2\sqrt{I_{ix}I_{iy}}\cos 2\varphi_i\cos\delta_i\cos\theta_i$$

$$S_{4i} = 2\sqrt{I_{ix}I_{iy}}\sin\delta_i\cos\theta_i \qquad (7)$$

where I_i is the beam intensity in the XOY plane, and $I_{iy}\sin 2\theta_i$ is the intensity of the z-component.

In accordance with Eqs. (6) and (7), the projection of three-dimensional oscillations of the plane-wave electric vector at an arbitrary point of the XOY plane onto this plane is an ellipse with the parameters

$$\tilde{\delta}_i = \tilde{\delta}_{xi} - \tilde{\delta}_{yi},\ \tilde{\psi}_i = \arctan(A_x/A_y) \qquad (8)$$

which is inscribed into a rectangle with the sides $2\left|A_x(a_i, \theta_i)\right|$ and $2\left|A_y(a_i, \theta_i)\right|$ [3].

However, at every point of the XOY plane, the orientation of the electric vector projection in the polarization ellipse will be different at any moment. This orientation is determined by the vector's amplitude, as well as by the values of the polarization phases $\tilde{\delta}_x$ and $\tilde{\delta}_y$, together with the wave phase $\left(\omega t - a_{0i} - \frac{2\pi}{\lambda}\vec{\mu}_i\vec{r}\right)$. This circumstance is especially important when the field superposition takes place. Therefore, according to Eq. (6), all the three components of the electric vector of every partial beam possess their own polarization phases which do not dependent (a uniform field) on the coordinates of the point in the plane of analysis. The phase should be taken into account if several beams are superposed. We note that the Z-component of the electric vector preserves the wave phase of the partial beam.

The introduction of the three-dimensional Jones vector enables one to describe the spatial interference of vector fields with arbitrary polarization states and wave vector directions. Let there be two arbitrary beams presented in the form of two three-dimensional vectors as

$$\vec{E}_m = \begin{bmatrix} A_{mx}e^{i\delta_{mx}} \\ A_{mx}e^{i\delta_{mx}} \\ A_{mz} \end{bmatrix} e^{i(\omega t - \alpha_{0m} - \frac{2\pi}{\lambda}\vec{\mu}_m\vec{r})},$$

$$\vec{E}_l = \begin{bmatrix} A_{lx}e^{i\delta_{lx}} \\ A_{lx}e^{i\delta_{lx}} \\ A_{lz} \end{bmatrix} e^{i(\omega t - \alpha_{0l} - \frac{2\pi}{\lambda}\vec{\mu}_l\vec{r})}. \qquad (9)$$

The superposition intensity $I = \left|E_m^2 + E_l^2\right|$ of these fields at the point characterized by the radius-vector $\vec{r}$ is determined by the expression

$$I - I_m + I_l + 2A_{mx}A_{lx}\cos[(\delta_{mx} - \delta_{lx}) +$$

$$+(a_{0m} - a_{0l}) + \frac{2\pi\vec{r}}{\lambda}(\mu_m - \mu_l) +$$

$$+2A_{my}A_{ly}\cos[(\delta_{my} - \delta_{ly}) + (a_{0m} - a_{0l}) +$$

$$+\frac{2\pi\vec{r}}{\lambda}(\mu_m - \mu_l) + 2A_{mx}A_{lx} +$$

$$+\cos[(a_{0m} - a_{0l}) + \frac{2\pi\vec{r}}{\lambda}(\mu_m - \mu_l)]. \qquad (10)$$

From Eq. (9), it follows that the X- and Y-components of the intensity depend on the polarization and wave phases, while the Z-component on the wave phase difference only. Whence, it follows that the conditions for the field to be uniform in the plane of analysis are realized in such cases : (1) the wave vectors are coplanar ($\mu_m = \mu_l$), (2) the counter-propagating beams are coplanar ($\theta_m = -\theta_l$ and $\varphi_m = \pi + \varphi_l$), (3) the wave vectors are orthogonal to each other ($\mu_m\mu_l = 0$), and (4) if the following equality is valid:

$$2A_{mx}A_{lx}\cos[(\delta_{mx} - \delta_{lx}) + (a_{0m} - a_{0l}) +$$

$$+\frac{2\pi\vec{r}}{\lambda}(\mu_m - \mu_l)]2A^+_{my}A_{ly}\cos[(\delta_{my} - \delta_{ly}) +$$

$$+(a_{0m} - a_{0l}) + \frac{2\pi\vec{r}}{\lambda}(\mu_m - \mu_l)]2A^+_{mz}A_{lz}\times$$

$$\times\cos[(\delta_{mz} - \delta_{lz}) + (a_{0m} - a_{0l}) + \frac{2\pi\vec{r}}{\lambda}(\mu_m - \mu_l)] = 0. \qquad (11)$$

Condition (11) is satisfied if

$$(\delta_{mx} - \delta_{lx}) - (\delta_{my} - \delta_{ly}) = \delta_m - \delta_l = \pm\pi \qquad (12)$$

or in the case where

$$A_{mx}A_{lx}/A_{my}A_{ly} = 1,\ \mathrm{tg}\tilde{\psi}_m = \mathrm{ctg}\tilde{\psi}_l, \qquad (13)$$

and one of the beams is normal to the plane of analysis.

Equations (11) and (12), together with Eq. (3), describe the modes, the polarization of which is orthogonal to the XOY plane. It means that, irrespective of the partial beam intensities, the intensity of the summary field in the plane of analysis is constant if the beams possess alternative polarizations $\tilde{\chi}_m - \tilde{\chi}_l = \pm\pi/2$ and $\tilde{\gamma}_m = -\tilde{\gamma}_l$ at every point of the plane.

Under conditions (12) and (13), the interference field of two partial beams is constant by intensity, and its polarization state varies continuously from one point to another. Along the line where the difference of wave phases is the same, the polarization states of the summary field are the same.

The analysis of such a field with the help of an analyzer has to reveal interference fringes. The 90°-rotation of the analyzer would result in the shift of the interference pattern by a half of the fringe.

In case where several coherent beams interfere, the polarization state of the summary field is determined in the base plane, which, in its turn, is determined by the general direction of the Umov–Poynting vector [4].

Let us introduce the Stokes parameters for the superposition of partial coherent beams in three orthogonal planes – the $S_{0i}^{(1)}$ parameters for the XOY plane, the $S_{0i}^{(2)}$ parameters for the ZOX plane, and the $S_{0i}^{(3)}$ parameters for the ZOY plane – making use of the corresponding projections of the summary field. In an arbitrary plane of analysis, whose normal is given by the angles φ and θ, the Stokes parameters in the vicinity of a given point of the field can be calculated by the formulas

$$S_1 = S_{01}^{(1)} - S_{02}^{(3)} \sin\theta - 0,5 S_{03}^{(3)} \sin 2\theta,$$

$$S_2 = \cos 2\varphi (S_{02}^{(1)} + S_{02}^{(3)} \sin^2\theta - 0,5 S_{03}^{(3)} \sin 2\theta) +$$

$$+ \sin 2\varphi (S_{03}^{(2)} \sin\theta - S_{02}^{(1)} \cos\theta),$$

$$S_3 = \sin 2\varphi (S_{02}^{(1)} + S_{02}^{(3)} \sin^2\theta + 0,5 S_{03}^{(3)} \sin 2\theta) +$$

$$+ \cos 2\varphi (S_{03}^{(2)} \cos\theta - S_{02}^{(1)} \sin\theta),$$

$$S_4 = S_{04}^{(1)} \cos\theta + S_{04}^{(2)} \sin\theta + 0,25 S_{04}^{(3)} \sin 2\varphi \sin 2\theta. \qquad (14)$$

The absence of intensity interference fringes in the plane of analysis, which is illuminated with two coherent alternatively polarized beams, can be used for the encoding and decoding of polarization fields taking advantage of a holographic equipment. For example, let there be an isotropic photosensitive layer in a certain plane. This layer is used for the registration of the hologram of an object wave by means of two reference beams, which do not interfere with each other by intensity. The object wave is formed by transmitting a coherent laser beam with circular polarization through an amplitude transparency. The transparency is located on a polaroid film and consists of separate fragments with different polarization azimuths.

Let us introduce the concept of a polarization contrast vector in the following manner. Let two points, A and B, in the object plane be characterized by a corresponding set of Stokes parameters. We define the contrast between these points as the vector $\vec{K} = (K_a, K_p, K_q)$, where

$$K_a = \frac{|I^{(A)} - I^{(B)}|}{I^{(A)} + I^{(B)}}, \qquad (15)$$

$$K_p = \frac{\sqrt{(S_2^{(A)} - S_2^{(B)})^2 + (S_3^{(A)} - S_3^{(B)})^2}}{I^{(A)} + I^{(B)}}, \qquad (16)$$

$$K_q = \frac{|S_4^A - S_4^B|}{I^{(A)} + I^{(B)}}. \qquad (17)$$

In accordance with Eq. (13), the component K_a characterizes the contrast of the field amplitude, K_p the contrast by the linear polarization, and K_q the contrast by the ellipticity. The objects (two points), for which all three components of the polarization contrast vector are equal to zero, become optically indistinguishable. In all other cases, this method makes it possible to restore the encoded information.

The object for investigations (Fig. 1) was created making use of a diffusing screen 1a (milk glass) and the fragments of a polaroid film arranged on it (fragments *2a*, *3a*, and *4a* specify their orientations). The restoration of the image by two orthogonally polarized reference waves (in accordance with its record) allows each fragment to be restored in turn, by changing the analyzer azimuth (fragments *2b*, *3b*, and *4b*). The restoration of the encoded image making use of one reference wave does not allow the fragments, which are inhomogeneous by polarization, to be discerned (fragments *2c*, *3c*, and *4c*).

The absence of the interference by intensity between the reference beams results in that every point of the amplitude transparency is responsible for the formation of two gratings on the hologram, which are phase-shifted by π with respect to each other. Provided that such a hologram is illuminated with the reference beams in the

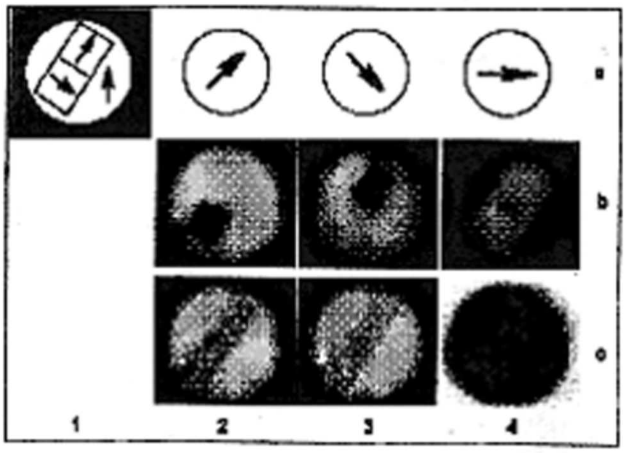

Fig. 1. Results of the polarization structure restoration (decoding)

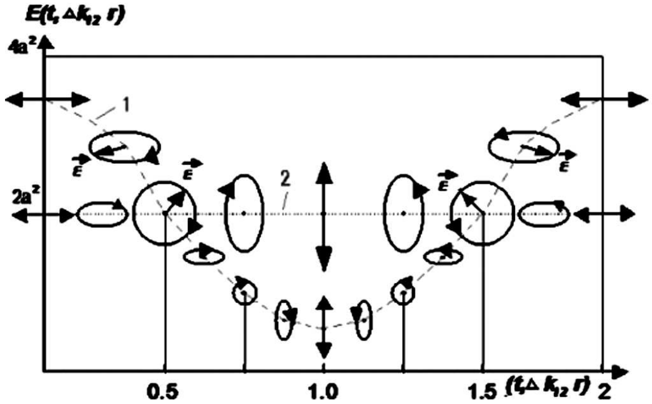

Fig. 2. Intensity and polarization of a stationary field in the YOZ plane as a function of the angle $\wedge(\Delta\vec{k}_{1,2},\vec{r})$

same geometry, as was used while recording it, a polarization image of the object arises in the object wave direction. The image is graded by intensity (amplitude), which corresponds to the gradation by polarization. Such an object wave consists of two beams with a polarization that corresponds to the polarization of the reference beams. These beams, being added, form an object wave with a characteristic polarization contrast. The considered hologram, together with the optical system of reference beams, is a polarization decoder, while the recording system is a polarization coder, respectively.

The speculations stated above were confirmed by the experiment described in work [1].

The tensor character of the stationary field polarization evidently manifests itself while considering the interference between two linearly polarized beams, provided that the electric vector oscillates in the plane of their wave vectors. Let us determine the field which is formed in this case. The oscillations of the electric vectors of the partial beams are defined by the expression

$$\vec{E_1}(t,\vec{k}_1,\vec{r}) = \vec{n}a\ \cos(\omega t - \vec{k}_1\vec{r}),$$

$$\vec{E_2}(t,\vec{k}_2,\vec{r}) = \vec{m}b\ \cos(\omega t - \vec{k}_2\vec{r}), \tag{18}$$

where $\vec{n}$ and $\vec{m}$ are unit vectors, a and b are the beam amplitudes, and $\theta = \angle\left(\vec{k}_1,\vec{k}_2\right)$ is the angle between the wave vectors $\vec{k}_1$ and $\vec{k}_2$ lying in the YOZ plane. It is expedient to present the strength of the summary field $\vec{E}\left(t,\Delta\vec{k}_{1,2},\vec{r}\right) = \vec{E}_1 + \vec{E}_2$ at an arbitrary point as a sum of oscillations in two orthogonal directions, $\vec{n}_1$ (the Y-component) and $\vec{n}_2$ (the Z-component). In this case in accordance with Eq. (8), the amplitude of the summary field, provided that the amplitudes of both oscillations are equal ($a = b$), looks like

$$\vec{E}(t,\Delta\vec{k}_{1,2},\vec{r}\,) = \vec{n}_1 2a\ \cos(\theta/2)\cos\left(\frac{\Delta\vec{k}_{1,2},\vec{r}}{2}\right)\times$$

$$\times\cos\left(\omega t - \frac{\Delta\vec{k}_{1,2},\vec{r}}{2}\right) + \vec{n}_2 2a\sin(\theta/2)\times$$

$$\times\sin\left(\frac{\Delta\vec{k}_{1,2},\vec{r}}{2}\right)\sin\left(\omega t - \frac{\Delta\vec{k}_{1,2},\vec{r}}{2}\right). \tag{19}$$

According to Eq. (15), the trajectory of the electric vector oscillations is an ellipse inscribed into a rectangle with the sides $4a\sin\left(\frac{\theta}{2}\right)\sin\left(\frac{1}{2}\angle\left(\Delta\vec{k}_{1,2},\vec{r}\right)\right)$ and $4a\cos\left(\frac{\theta}{2}\right)\cos\left(\frac{1}{2}\angle\left(\Delta\vec{k}_{1,2},\vec{r}\right)\right)$. At the spatial points, where the condition

$$\angle\left(\Delta\vec{k}_{1,2},\vec{r}\right) = (2n+1)\pi \pm \theta,\ n = 0,\ 1,.. \tag{20}$$

is satisfied, the ellipse transforms into a circle. The intensity $I(\Delta\vec{k}_{1,2},\vec{r}) = \left|\vec{E}(t,\Delta\vec{k}_{1,2},\vec{r})\right|^2$ of the summary field is determined by the equality

$$I(\Delta\vec{k}_{1,2},\vec{r}) = 2a^2\left[1 + \cos\theta\cos(\widehat{\Delta\vec{k}_{1,2},\vec{r}})\right]. \tag{21}$$

The character of variations in the intensity and polarization of the summary field in the YOZ plane is exhibited in Fig. 2. The characteristic feature of this distribution is that the electric vector oscillations are parallel to the YOZ plane at the intensity maxima (at $\theta < 90°$) and orthogonal to it at the intensity minima. If $\theta = 90°$ (the mutually orthogonal beams), the intensity does not change, and the total electric vector changes only its polarization. In case $\theta > 90°$, the maxima and minima swap places.

The stationary field in the YOX plane is shown in Fig. 3. The introduction of particles, which are embedded into such a field and whose dimensions are much smaller than the field wavelength, gives rise to the appearance of a scattered wave which is a result of characteristic oscillations of the field-induced dipole moment. While observing with the use of a magnifying system, the interference pattern, its contrast will depend on the angles of observation δ and α.

In our experiment, thin layers of MgO particles were sputtered onto a transparent substrate. The average radius of the particles was about 400 Å and the optical thickness of the deposited layer was about 1 μm. Light scattering might be considered single. The specimen was placed into the field of two coherent linearly polarized beams emitted by a He-Ne laser ($\lambda = 0.6328$ Å), with the angular convergence $\theta = 10°$. The interference fringes were observed with a microscope, the angular aperture of which was of the order of the angular beam convergence. At small observation angles δs, the brightness of the fringe maxima along the fringe ($\alpha = 90°$) turned out higher than that in the transverse direction. At the observation angles in the vicinity of $\delta = 90°$, the maxima became linearly polarized, and the intensity of the minima became lower in comparison with the case of small δs. The qualitative results obtained correspond to our understanding of the character of the dipole radiation scattering by magnesium oxide particles. Therefore, the emergence of a scattered wave, which accompanies the embedding of a particle into a stationary field, can be interpreted as a result of the action of the variable component of the field's electric vector on the particle. Such an interpretation can be useful for studying stationary electromagnetic fields in the radio-frequency region. We would like to attract attention to the peculiarity of stationary vector fields with respect to the total amplitudes of the electric and magnetic vector components. The stationary fields, which are presented in Figs. 1 and 2, characterize the trajectory of the electric vector $\vec{E}$ oscillations. The strength of the magnetic component $\vec{H}$ of the field of each partial beam turns out orthogonal to the plane defined by the vectors $\vec{k}_1$ and $\vec{k}_2$. Therefore, the stationary field of the vector $\vec{H}$ is linearly polarized at any spatial point. Provided that the amplitudes of both beams are identical, the vector $\vec{H}$ equals zero at those points where the intensity of the vector $\vec{E}$ is minimal. If $\vec{k}_1\vec{k}_2 = 0$, zero values for the vector $\vec{H}$ are also obtained

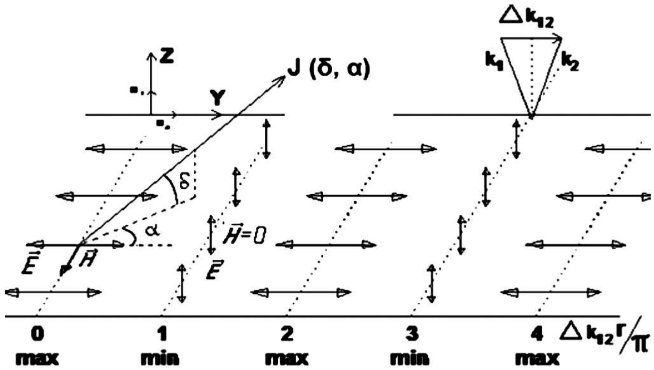

Fig. 3. Stationary field experimentally observed at scattering by fine MgO particles. $\vec{E}$ and $\vec{H}$ are the orientations of the electric and magnetic fields at the points of extremal intensity; δ and α are the angles which describe the observation directions of the scattering

at the points where $\angle\left(\Delta\vec{k}_{1,2}, \vec{r}\right) = (2n + 1)\pi$. If the electric vectors of the partial beams are oriented perpendicularly to the plane $\left(\vec{k}_1, \vec{k}_2\right)$, the behaviors of the vectors $\vec{E}$ and $\vec{H}$ swap places.

The spatial superposition of the coherent vector beams allows one to carry out the spatial separation of the electromagnetic field by both intensity and polarization. In the vicinity of a given point, the calculation of the bulk energy density in terms of either $\vec{E}$- or $\vec{H}$-components, taken separately, of the electromagnetic field becomes invalid. Nevertheless, the averaging of the bulk energy density of the summary field over the volume, the linear dimensions of which are larger than $\lambda/\left(2\sin\frac{\theta}{2}\right)$, restores the eligibility to apply the known formulas.

1. Conclusions

The superposition of the coherent beams with arbitrary states of polarization brings about the summary field, whose intensity and polarization vary continuously in space. The intensity and polarization distributions depend on the orientation of the plane of analysis. In the vicinity of the intensity extremal points, the fields with the symmetric arrangement of the opposite polarization forms emerge.

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Received 15.11.05.
Translated from Russian by O.I. Voitenko

ПЕРЕТВОРЕННЯ ІНТЕНСИВНОСТІ ТА ПОЛЯРИЗАЦІЇ В КОГЕРЕНТНИХ ВЕКТОРНИХ ПОЛЯХ

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Р е з ю м е

Розглянуто особливості аналізу стаціонарних полів інтенсивності та поляризації у тривимірному просторі, створених суперпозицією когерентних довільно поляризованих пучків. Отримано співвідношення, які дозволять визначити поляризаційний стан поля в заданій точці простору при довільній орієнтації площини аналізу на основі даних про поляризаційний стан в площині, перпендикулярній до вектора Умова—Пойтінга. Наведено умови формування однорідного сумарного поля інтенсивності із парціальних пучків різної амплітуди та поляризації.