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Spatial Polarimetry of Inhomogeneous Surfaces under Laser Illumination

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Abstract—A study aimed at improving the methods of remote laser polarimetry of inhomogeneous surfaces using complex probe signals with a combined amplitude-phase and polarization modulation has been performed. It is shown that the informative properties of probe signals can be improved that potentially allows for carrying out some operations of forming and processing polarization images of objects in the probe stage. The efficiency of application of the proposed probe signals for recognizing various types of materials is experimentally confirmed.

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1. INTRODUCTION

Polarimetric methods are widely used in nondestructive control of the properties of scattering surfaces. They are promising, e.g., for preparing nanostructures from various materials (including crystals), as well as in vacuum and corrosive media with a high chemical activity. An advantage of polarimetric methods is their universality. Indeed, the optical constants (refractive, absorption, and scattering indices), which determine the results of measurements based on these methods, are fundamental parameters of a specific material and its aggregate state. Polarimetric measurements have a high sensitivity (on the order of 10^{-3} to 10^{-4} with respect to the refraction index measurements). Violation of the initial polarization (depolarization) of a field incident on the surface of a material under study is caused by the secondary backscattered radiation from this surface due to the conduction currents (for conductors) or bias currents (for insulators) induced in it.

The accuracy of polarimetric measurements depends on the observation conditions (including the relative position of the object under study, the probe signal (PS) source, and the scattered-radiation detector) and the recorded-signal distortions caused by the signal reflection from the sample and the radiation propagation generally through a randomly inhomogeneous medium located between the measuring system and the object of study. These conditions affect significantly the correctness of the data processing results.

The formation of reflected signal is a rather complex technical process (even for planar homogeneous objects with a relatively simple configuration), which depends on a number of interrelated factors. At the same time, the method of active interferometry proposed by us, which is based on the use of femtosecond laser signals, allows one to carry out polarimetric measurements of transparent optically inhomogeneous bulk objects. In this paper, we consider one of the approaches to polarimetric observations of objects with optically inhomogeneous surfaces, which is based on the use of probe signals with a complex spatial polarization structure.

2. POLARIMETRIC METHOD FOR OPTICALLY INHOMOGENEOUS SCATTERING SURFACES USING LASER SIGNALS WITH A COMPLEX SPATIAL POLARIZATION STRUCTURE

Information redundancy can be provided using methods of active interferometry by irradiating an object with a double-beam probe signal characterized by mutually orthogonal planes of polarization of the waves in different interferometer arms, which

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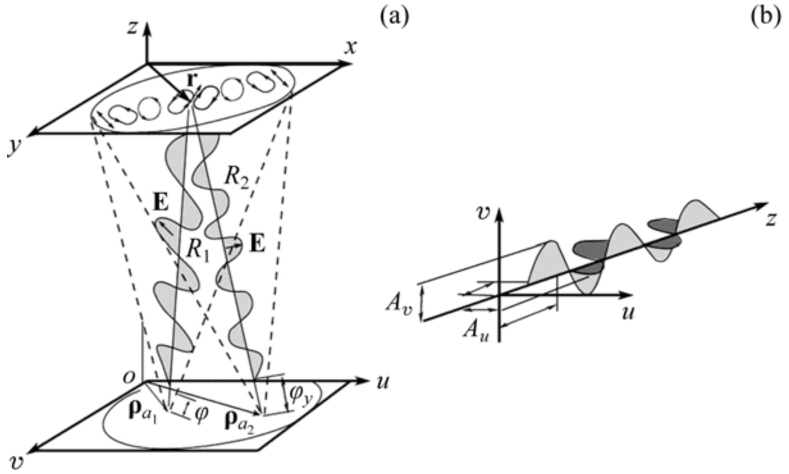

Fig. 1. (a) Spatial modulation of polarization type in a probe signal, caused by a change in the phase shift between orthogonally polarized optical components and (b) the structure of electromagnetic oscillations in the interfering beams.

can form a field in the image plane with a combined amplitude-phase and polarization modulation. The resulting field of the probe signal in the image plane (Fig. 1) is determined by the interaction of two waves:

$$\mathbf{E}_{\parallel}(\mathbf{r},t)=\frac{\exp\Big[j(K/R+\omega_0 t)\Big]}{j\lambda R}S_A A_u\exp\left\{j\frac{K}{2R}|\boldsymbol{\rho}_{a_1}|^2\frac{K\mathbf{r}\boldsymbol{\rho}_{a_1}}{R}+\varphi_u\right\}, \quad (1)$$

$$\mathbf{E}_{\perp}(\mathbf{r},t)=\frac{\exp\Big[j(K/R+\omega_0 t)\Big]}{j\lambda R}S_A A_v\exp\left\{j\frac{K}{2R}|\boldsymbol{\rho}_{a_2}|^2\frac{K\mathbf{r}\boldsymbol{\rho}_{a_2}}{R}+\varphi_v\right\}. \quad (2)$$

Here, ω_0 is the carrier oscillation frequency of interfering beams; R is the distance to the object; $A_u = \mathrm{Re}\{A_u \exp j[\omega_0(t - z/c)] + \varphi_u\}$ is the amplitude of the uth component of the electric vector of light; $A_v = \mathrm{Re}\{A_v \exp j[\omega_0(t - z/c)] + \varphi_v\}$ is the amplitude of the vth component of the electric vector of light; c is the speed of light; $\mathbf{r}$ is the radius vector describing the object coordinates in the image plane (x, y, z); $\boldsymbol{\rho}$ is the radius vector describing the coordinates in the transmitter–receiver plane; $\boldsymbol{\rho}_{a_1}$ and $\boldsymbol{\rho}_{a_2}$ are the radius vectors describing the coordinates of the centers of radiating apertures of the active interferometer in the transmitter–receiver plane (uov) $(\boldsymbol{\rho} = \boldsymbol{\rho}_{a_1} + \boldsymbol{\rho}_{a_2})$; S_A is the area of radiating apertures; $K = 2\pi/\lambda$ is the wavenumber; λ is the wavelength of the laser forming interfering beams; and t is time.

For a planar object with sizes exceeding the overlap area of laser beams in the image plane, the intensity distribution of received signal in the transmitter–receiver plane, with allowance for the random-phase delay $\gamma(\boldsymbol{\rho})$ caused by the effect of the medium in which laser radiation propagates, can be written as [2, 3]

$$I(\theta,\boldsymbol{\rho}) = I_u\cos^2\theta + I_v\sin^2\theta + 2\sqrt{I_u}\sqrt{I_v} \times \sin\theta\cos\theta|\mu_{uv}|\cos\big[\beta_{uv}-\varepsilon(\boldsymbol{\rho})-\gamma(\boldsymbol{\rho})\big], \quad (3)$$

where μ_{uv} is the complex coefficient of correlation of orthogonal components, θ is the angle of the analyzer orientation with respect to the polarization plane of probe beams, β_{uv} is the degree of the effective phase difference between the u and v components of laser beams (a parameter providing the desired contrast of the interference pattern at the each point in the overlap area of interfering beams in the image plane (x, y, z)), and $\varepsilon(\boldsymbol{\rho})$ is the phase delay of the compensator of the optical path difference of the interfering beams, which provides the desired β_{uv} value.

An analysis of relation (3) shows that the intensity distribution over the object image under illumination by a double-beam probe signal with mutually orthogonal planes of polarization of the waves is modulated (as in the case when an active interferometer is used to form a probe signal). The spatial period of the interference pattern, M, is determined by the active-interferometer base $|\boldsymbol{\rho}|$ and the distance R to the object; it can be found from the relation

$$M \cong (\lambda/|\boldsymbol{\rho}|)R. \quad (4)$$

When the relative time delay of the orthogonal components of the probe signal does not exceed $t_{\mathrm{coh}} = 1/\Delta f$, the following relation [3, 4] is valid for quasi-monochromatic light:

$$\mu_{uv} = |\mu_{uv}| \exp(j\beta_{uv}) = \frac{j_{uv}}{\sqrt{j_{uu}} + \sqrt{j_{vv}}}, \tag{5}$$

where Δf is the width of the laser spectrum; μ_{uv} is the degree of coherence between the u and v components of the probe signal, with allowance for the depolarization upon reflection from the object surface and defocusing of the interfering beams [5]; and j_{vv}, j_{uu}, j_{uv}, and j_{vu} are the elements of the light-wave coherence matrix

$$\overset{\frown}{j} = \begin{bmatrix} \langle E_u E_u^* \rangle \langle E_u E_v^* \rangle \\ \langle E_v E_u^* \rangle \langle E_v E_v^* \rangle \end{bmatrix} = \begin{bmatrix} \langle A_u^2 \rangle \big\langle A_u A_v \exp[j(\varphi_1 - \varphi_2)] \big\rangle \\ \langle A_v^2 \rangle \big\langle A_u A_v \exp[-j(\varphi_1 - \varphi_2)] \big\rangle \end{bmatrix}, \tag{6}$$

the diagonal (real) elements of which are the intensities of the u and v components.

The contrast of the interference pattern at each point of the object image is determined by not only the mutual coherence of the interacting components of the probe signal but also the polarization properties of the materials used to prepare object surface elements. When the degree of polarization of a signal reflected from an object is unity, the unpolarized component is absent in the reflected signal, $|\mu_{xy}| = 1$, and the contrast of the resulting interference pattern becomes maximum.

Generally, the relationship between the orthogonally polarized components of the incident and reflected fields depends strongly on the phase shift of the orthogonal light components $\delta_{\|}$ and $\delta_{\perp}$, which arise when a wave reflects from the object surface. When reflection occurs from optically homogeneous smooth conducting surfaces, characterized by surface type of scattering, the condition $\delta_{\|} - \delta_{\perp} \neq 0$ is valid, and the difference between the phase shifts depends mainly on the angle of wave incidence on the scattering surface. Under illumination of objects made of these materials by a double-beam probe signal composed of components (1) and (2), the object image formed after the analyzer, oriented at the angle $\theta = 45°$, exhibits a regular spatial modulation of intensity with a contrast close to unity.

In the case of reflection from smooth surfaces of low-conducting optically homogeneous materials and insulators, characterized by bulk type of scattering, the difference between the phase shifts is close to zero. Under exposure of these surfaces to linearly polarized light, the reflected signal is also linearly polarized and the intensity distribution in the images of objects made of the aforementioned materials is uniform.

The situation is different when light reflects from optically inhomogeneous surfaces characterized by combined type of scattering. A signal reflected from optically inhomogeneous surface includes two components: external and internal [6]. The external component is formed due to the light reflection from the interface between inhomogeneities. The internal component is formed upon scattering of the refracted part of incident radiation from bulk inhomogeneities of the material and is determined by the light penetration depth into this material. The internal-component intensity depends on the structure and the optical and electrical properties of medium inhomogeneities; this component is totally depolarized light; its intensity significantly exceeds that of the external component for inhomogeneous insulators with low specific absorption. This leads to the fact that the light reflected from these materials is almost depolarized and $|\mu_{xy}| \to 0$ that yields a zero interference term in expression (3). For materials with a high conductivity, the internal component of reflected light is small: $0 < |\mu_{xy}| < 1$.

Thus, it can be shown (see, for example, [5]) that there is always a pair of mutually orthogonal directions in which the $|\mu_{xy}|$ value is maximum for each type of the surface material. In this case, the contrast of the interference pattern described by the third term in expression (3) depends on the parameters of specific material. This circumstance allows one to provide the maximum contrast of interference fringes in the recorded image when the angle of rotation of the analyzer changes in the image plane and thus determine possible types of materials for the optically inhomogeneous surface.

3. EXPERIMENTAL RESULTS

The experiments aimed at establishing the possibility of recognizing various types of materials were carried on an experimental setup (Fig. 2), which made it possible to form probe signals with a combined amplitude-phase and polarization modulation. The amplitude-phase modulation was performed by an active interferometer, the base of which was set by the parameters of beam splitter *5*. The orthogonality of the polarization planes in the probe beams was provided using polarizers *9* and *10*. The detector unit included analyzer *15*, objective *16*, and photodetector *17*. Optical elements *2*, *6–8*, *11–13* were used to collimate laser beams and control their intensity.

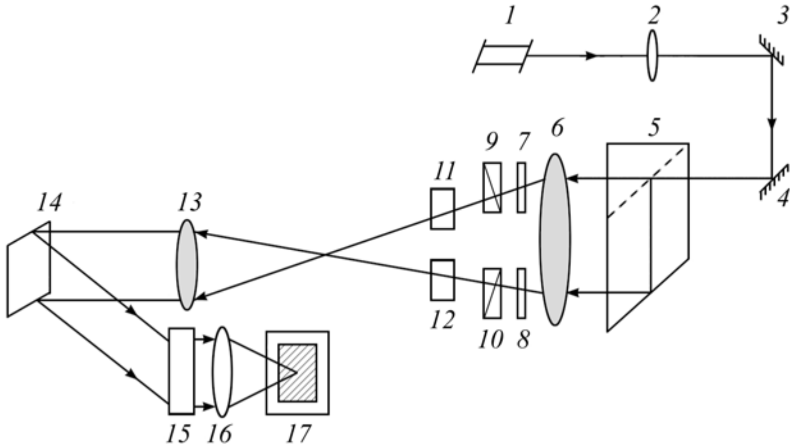

Fig. 2. Schematic of the experimental setup: (*1*) laser, (*2*) condenser, (*3*, *4*) mirrors, (*5*) beam splitter, (*6*, *13*) combined collimator lenses, (*7*, *8*) light filters, (*9*, *10*) polarizers, (*11*, *12*) plane-parallel plates (compensator of optical path difference of interfering beams), (*14*) object, (*15*) analyzer, (*16*) objective, and (*17*) photodetector.

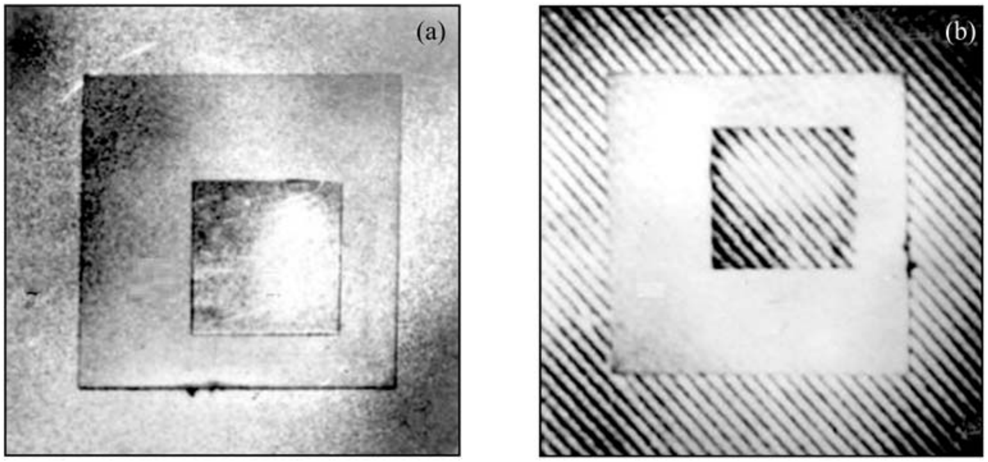

Fig. 3. (a) Classical and (b) polarization images of optically inhomogeneous surface composed of different materials.

The experimental results are shown in Figs. 3(a) and 3(b). One can see two realizations of intensity distribution over an image of the same flat surface, composed of different materials, under exposure to, respectively, conventional and double-beam signals with mutually orthogonal polarization planes. The central and external elements of the object are made of titanium alloy and polished aluminum, respectively. Both materials are characterized by surface-type scattering. The intermediate element is a colored metal substrate. Such treatment of the reflecting surface results in the bulk type of scattering of optical signals by this surface. An analysis of the signal structure (see Fig. 3(b)) shows that the difference in the types of scattering of the probe signal by different object elements is transformed into the modulation of interference-pattern contrast for the corresponding elements of the object image. Based on the results obtained, we can conclude that an additional modulation of the spatial and temporal field coherence in the image plane arises upon scattering of a signal with a combined amplitude-phase and polarization modulation by the object surface. The information obtained can be used to recognize types of materials forming optically inhomogeneous scattering surfaces.

4. CONCLUSIONS

The results of our study, which was aimed at improving the methods of spatial laser polarimetry of optically inhomogeneous surfaces, showed that it is expedient to use probe signals with a combined amplitude-phase and polarization modulation to this end. An advantage of this approach is that the informative properties of probe signals can be improved that potentially makes it possible to carry out some operations of forming and processing polarization images of objects in the probing stage. The results obtained showed that various types of materials of optically inhomogeneous scattering surfaces can be recognized.

On the whole, the results of this study can be used to solve many scientific and practical problems that imply remote polarimetric observations in vacuum and corrosive media.

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