AUTOMATED SYSTEM FOR INVESTIGATION OF THE POLARIZATION STRUCTURE OF OPTICAL FIELDS SCATTERED BY NATURAL OBJECTS

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In this paper we analyze the requirements that are imposed upon optical measuring devices in studying the polarization structure of optical radiation scattered by different objects with fluctuating parameters. We also discuss the ways to overcome certain difficulties that emerge in the studies through the use in the sounding channel of a polarimeter of an electrically controlled phase plate fabricated from a $\mathrm{LiNbO_3}$ *crystal. This provides for fully automated measurement and calibration procedures and improves the accuracy of measuring Müller's matrices.*

The polarization state of scattered light in the interaction of a light beam of arbitrary polarization with an object is related to the polarization state of an incident beam through a 4×4 matrix.[1] This matrix, called Müller's or polarization matrix, is the characteristic of the object and represents its full optical description. Thus the problem of determination of the polarization structure of optical field scattered by different objects is solved by measuring the elements of their polarization matrices.

The most promising techniques for measuring the polarization matrices are so–called modulation techniques. This is connected with the fact that the modulation techniques are capable of measuring in real time.[2] Obviously the last is the necessary condition for investigation of different objects with fluctuating parameters, such as atmospheric formations, rough water surface, etc. These techniques are based on the continuous change in a predetermined manner of the polarization of sounding radiation and radiation reflected from the object under investigation. In this case 16 frequency components, whose the intensities are proportional solely to one element of the polarization matrix of the object, can be selected from the spectrum of a received signal. The simplest way to modulate the polarization is to use a mechanically rotating phase plate. However, in this case some difficulties arise in synchronization of mechanical rotation with a computer that controls the measurement process. In addition, it becomes impossible to tune the measuring system over the optical frequency range without replacing the plate. A particular problem is the error in measuring the elements of the polarization matrices. Due to the facts that scattering is the statistical process and propagation of optical radiation through the atmosphere is accompanied by various distortions, the necessity of repeated measurements arises. This also imposes more stringent requirements upon the rate of response of the system, which cannot be meet if one uses mechanically rotating phase plates.

In these cases so–called active converters of polarization[2] such as magneto–optical, acousto–optical, electro–optical, etc. are used. They all have definite merits and demerits. For example, most of magneto–optical converters are characterized by large value of absorption, small angle of rotation of the polarization plane, large time constant, and large overall dimensions. The acousto–optical converters are the narrow–band devices operating at fixed frequencies.

In this connection, in our opinion the rotating phase plates fabricated from electro–optical crystals are most promising to overcome these difficulties and to meet the requirements for the development of systems measuring the polarization matrices of the objects with fluctuating parameters..

The experimental automated system was developed using a rotating phase plate fabricated from a $\mathrm{LiNbO_3}$ electro–optical crystal. A block diagram of this system is shown in Fig. 1. The electro–optical phase plate was used in a sounding channel of the system, while the crystal phase plate was used in a receiving channel. The orientation of the fast axis of the last plate was changed by a stepping motor. The system parameters and measurement process were computer–controlled through a standard fast CAMAC interface.

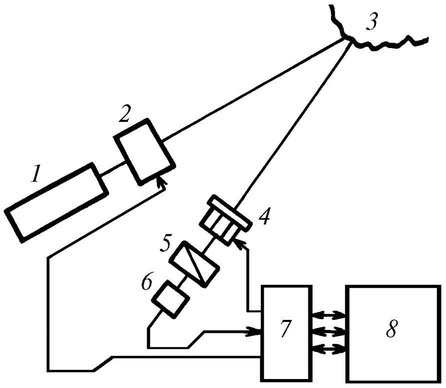

FIG. 1 Block diagram of the experimental automated system: 1) laser, 2) rotating phase plate fabricated from a $\mathrm{LiNbO_3}$ *electro–optical crystal, 3) object under investigation, 4)* $\lambda/4$ *phase plate controlled by the stepping motor, 5) analyzer, 6) photomultiplier, 7) CAMAC, and 8) computer.*

Optical field on a photodetector can be found with the use of Müller's matrix formalism from the equation

$$S_{\mathrm{pd}} = [M4]\,[M3]\,[M2]\,[M1]\,S\,, \tag{1}$$

where $M1$ is Müller's matrix of the rotating phase plate, $M2$ is Müller's matrix of the object under investigation, $M3$ is Müller's matrix of the phase plate with fixed number of the orientation azimuths of the fast axis, $M4$ is Müller's matrix of an analyzer with the horizontal transmission axis, and S_{pd} and S are the Stokes vectors of the optical field on the photodetector and of the field incident on the rotating phase plate, respectively.

In this case a signal selected on the photodetector and representing the first element of the Stokes vector has the form

$$2I_0 = S_0 N_1 + S_1 (1 + \beta) N_2/2 + S_2 (1 + \beta) N_3/2 + S_3 \beta N_4 +$$
$$+ \mu (S_3 N_3 - S_2 N_4) \cos (2\Omega t) + \mu (S_1 N_4 - S_3 N_2) \sin (2\Omega t) +$$
$$+ [(1 - \beta) (S_1 N_2 - S_2 N_3) / 2] \cos (4\Omega t) +$$
$$+ [(1 - \beta) (S_1 N_3 - S_2 N_2) / 2] \sin (4\Omega t) , \qquad (2)$$

where S_0, S_1, S_2, and S_3 are the elements of the Stokes vector of optical field incident on the rotating phase plate; $N_i^k = M_{1i} + a_1^k M_{2i} + a_2^k M_{3i} - a_3^k M_{4i}$, M_{ij} are the elements of Müller's matrix of the object under investigation, $a_1^k = \cos^2(2\alpha_k) + \beta \sin^2(2\alpha_k)$, $a_2^k = (1 - \beta) \cos(2\alpha_k) \sin(2\alpha_k)$, $a_3^k = \mu \sin(2\alpha_k)$, $i, j, k = \overline{1, 4}$, α_κ is the orientation angle of the fast axis of the phase plate $M3$; $\beta = \cos(D)$; $\mu = \sin(D)$, D is the phase shift due to the rotating phase plate; and Ω is the rotation frequency of the phase plate.

Thus there are four frequency components in signal spectrum (2). Their intensities are proportional to the corresponding elements of Müller's matrix of the object under investigation. By measuring the intensities of the signal selected on the photodetector for four predetermined orientations of the fast axis of the phase plate $M3$, taking the discrete Fourier transform of this signal, and assuming for definiteness that the Stokes vector of the optical field incident on the rotating phase plate has the form $S = \{1, -1, 0, 0\}$, we obtain four systems of linear equations (in the elements of Müller's matrix of the object under investigation) of the form

$$\left[\begin{array}{l} M_{12} + a_1^1 M_{22} + a_2^1 M_{32} - a_3^1 M_{42} = -I_{C4}^1 / C , \\ M_{12} + a_1^2 M_{22} + a_2^2 M_{32} - a_3^2 M_{42} = -I_{C4}^2 / C , \\ M_{12} + a_1^3 M_{22} + a_2^3 M_{32} - a_3^3 M_{42} = -I_{C4}^3 / C , \\ M_{12} + a_1^4 M_{22} + a_2^4 M_{32} - a_3^4 M_{42} = -I_{C4}^4 / C ; \end{array}\right. \qquad (3a)$$

$$\left[\begin{array}{l} M_{13} + a_1^1 M_{23} + a_2^1 M_{33} - a_3^1 M_{43} = -I_{S4}^1 / C , \\ M_{13} + a_1^2 M_{23} + a_2^2 M_{33} - a_3^2 M_{43} = -I_{S4}^2 / C , \\ M_{13} + a_1^3 M_{23} + a_2^3 M_{33} - a_3^3 M_{43} = -I_{S4}^3 / C , \\ M_{13} + a_1^4 M_{23} + a_2^4 M_{33} - a_3^4 M_{43} = -I_{S4}^4 / C ; \end{array}\right. \qquad (3b)$$

$$\left[\begin{array}{l} M_{14} + a_1^1 M_{24} + a_2^1 M_{34} - a_3^1 M_{44} = -I_{S2}^1 / F , \\ M_{14} + a_1^2 M_{24} + a_2^2 M_{34} - a_3^2 M_{44} = -I_{S2}^2 / F , \\ M_{14} + a_1^3 M_{24} + a_2^3 M_{34} - a_3^3 M_{44} = -I_{S2}^3 / F , \\ M_{14} + a_1^4 M_{24} + a_2^4 M_{34} - a_3^4 M_{44} = -I_{S2}^4 / F ; \end{array}\right. \qquad (3c)$$

$$\left[\begin{array}{l} M_{11} + a_1^1 M_{21} + a_2^1 M_{31} - a_3^1 M_{41} = 2 (I_0^1 + d N_2^1) , \\ M_{11} + a_1^2 M_{21} + a_2^2 M_{31} - a_3^2 M_{41} = 2 (I_0^2 + d N_2^2) , \\ M_{11} + a_1^3 M_{21} + a_2^3 M_{31} - a_3^3 M_{41} = 2 (I_0^3 + d N_2^3) , \\ M_{11} + a_1^4 M_{21} + a_2^4 M_{31} - a_3^4 M_{41} = 2 (I_0^4 + d N_2^4) , \end{array}\right. \qquad (3d)$$

where I_0^k, I_{s2}^k, I_{s4}^k, and I_{c4}^k are the intensities of the corresponding frequency components at kth orientation of the phase plate $M3$, $C = (1 - \beta)/4$, $F = \mu/2$, and $d = (1 + \beta)/4$.

To calibrate the system, we measured Müller's matrix of the empty space. The error in measuring the matrix elements did not exceed 0.1% for individual measurement. Measurement period, determined by the time of positioning the phase plate $M3$ by the stepping motor, was 2 s. Measurements were carried out at two optical wavelengths of 0.63 and 1.06 μm. The electrically controlled phase plate was tuned from one wavelength to another by way of increase of controlling voltage. As to the phase plate in the receiving channel, only the change in the phase shift controlled by a program must be taken into account. The rotating phase plate was fabricated from a 2×2×40 mm $LiNbO_3$ crystal cuted in the direction of the optical axis with electrodes located on crystal sides. The rotation frequency of the fast axis of the phase plate was equal to 1 kHz. Since the measured value of the parallel resistance of the crystal was 500 MΩ and corresponding quarter–wavelength voltage on the crystal of the above–indicated geometry at a wavelength of 0.63 μm was 95 V, the controlling power applied at the crystal must be only a few milliwatts.

Thus the above–described optical system is capable of measuring the polarization characteristics of the object with fluctuating parameters in real time with high accuracy. The analysis shows that significant decrease of time (10^{-3} s and less) and increase of the measurement accuracy are provided by the use of the electro–optical phase plate in the receiving channel instead of the crystal phase plate with a fixed number of orientations of its fast axis. However, the use of the electro–optically controlled phase plates fabricated from single–axis crystals in the receiving channel is hampered by their significant natural anisotropy. Here either a phase plate fabricated from a suitable (transparency region, values of the electro–optical coefficients, etc.) cubic crystal cuted out in accordance with the requirements given in Ref. 3 or a phase plate fabricated from a single axis crystal with coaxial point diaphragms limiting the input and output beams may be used. The last results in the significant losses of energy of the received signal, however, it is quite acceptable under laboratory conditions for small distances to the object under investigation.

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