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Calculating model of depolarization coefficient for microstructured media

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A R T I C L E   I N F O

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A B S T R A C T

As a new analytical method to study the propagation of polarized light, the system to classify the microstructure of a surface had been established. In this paper, the Jones Matrix and Mueller Matrix had been used to set up the physical model. By using the propagation path theory of polarized light, the mechanism of the scattering of electromagnetic wave had been observed, the relationship between the characteristics of depolarization and mechanism of scattering had been analyzed, and the relation formula of Mueller matrix, Mueller–Jones matrix and Isotropic-Depolarizer matrix had been deduced. Then combined with Fresnel formula, the depolarization coefficients of samples had been obtain, which was described the ability of material to weaken the polarization attribute of incident light. Finally, the theoretical model had been verified by experiments. The results showed that, the depolarization coefficients of the samples were related to the surface microstructure and scattering characteristics, and this model was more effectively to analyze the microstructure of the surface. Therefore, the model had a great application value, and the paper had very important significance on the development of polarization measurement technique.

1. Introduction

Micro-structure of materials affects the measurement results seriously in the precision optical experiment [1,2]. Therefore, how to detect the texture characteristics of material surface quickly and to take corresponding measures is urgently. As a measuring technology, the ultrasonic tomography was aimed at the detection of flawed zones in unilaterally accessible concrete structures, the determination of their thickness and coordinates was presented [3]. Available X-ray beams create visible images from the internal structure of object in two dimensions. Primary radiological images are taken by radiography from hand-made carpets. They has been converted to structural recognizable images by employing different image processing techniques by Karamad and Latifi [4]. Recent advances in application of microwave measuring techniques to nondestructive determination of moisture content were reviewed, with a special emphasis being put on a newly developed concept of a density-independent calibration. It was concluded that those techniques provide accurate, fast and nondestructive means for moisture content testing [5].

Interference, diffraction and polarization are the three characteristics of light. Polarized light interacts with the target, and the scattered light contains polarized information which is determined by the medium's characteristics. The polarized information is different from the message of spectrum, light intensity and phase. By the polarized information, we can get the polarization characteristics of the measured target accurately. Both the Mueller matrix and Jones matrix can be used as the polarized state transformation matrix when modeling light-matter interactions [6,7]. The polarization technology is a new type of identification technology. The advantages of polarization technology led to the rapid development of science and technology. The study of Polari metric technology has been carried out for many years, and has made great achievements in the aspects of target detection and recognition. Now the polarization technology is widely used in military [8], astronomy [9,10] and other fields [11,12]. Those measurement methods could effectively describe the polarization characteristics of material which are based on the feedback signal. But the propagation path of incident polarized light in the microstructure has been neglected in those measurement models.

For that reason, this paper has used the polarization detection technology to analyze the propagation paths of incident polarized light in the surface microstructure of material. Combined with Fresnel formula, the relation formula of Mueller matrix [13], Mueller–Jones matrix [14] and Isotropic-Depolarizer matrix had been deduced. And the results showed that the method was fast and accurate, and the experiment process was simple and could be used for rapid detection effectively.

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2. Experimental procedures

2.1. Decomposition of Mueller matrix

Jones matrix or Mueller matrix can be used as the polarized state transformation matrix [15,16]. Optical equations are usually described by Jones matrix, such as Fresnel equations [17,18]. Therefore, Jones matrix and Mueller matrix are the good choices in material identification. However, Jones matrix can only detect the pure material and have no way to model rough surfaces samples whose polarized state transformations are mixed. Relatively, Mueller matrix can do it, but it is difficult to establish the physical model. In a real world application, the study on the mixed state is more valuable. From this idea, the Mueller matrix (M) of this letter can then be decomposed as

$$M = M_J + M_D, \tag{1}$$

where M_J is a Mueller–Jones matrix and M_D is the matrix of an isotropic depolarizer. And

$$M_J = A\left(J \otimes J^*\right) A^{-1}, \tag{2}$$

$$M_D = d\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}, \tag{3}$$

d is the coefficient of depolarization, J is the Jones matrix. And where

$$A = \begin{bmatrix} 1 & 0 & 0 & 1 \\ 1 & 0 & 0 & -1 \\ 0 & 1 & 1 & 0 \\ 0 & i & -i & 0 \end{bmatrix}, \tag{4}$$

according to the Eq. (3), define

$$M_{dp} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}, \tag{5}$$

then Mueller matrix (M) can then be decomposed as

$$M = A\left(J \otimes J^*\right) A^{-1} + dM_{dp}. \tag{6}$$

2.2. Models optimization

When modeling surface reflection, Jones matrix can be modeled as

$$J = \begin{bmatrix} r_h & 0 \\ 0 & r_v e^{i\theta} \end{bmatrix}, \tag{7}$$

where r_h is the horizontal reflection amplitude coefficient, r_v is the vertical reflection amplitude coefficient, and θ is the phase retardation angle which describing phase difference between horizontal and vertical caused by reflection. Here r_h, r_v and θ are real numbers. Then

$$J \otimes J^* = \begin{bmatrix} r_h^2 & 0 & 0 & 0 \\ 0 & r_h r_v e^{i\theta} & 0 & 0 \\ 0 & 0 & r_h r_v e^{-i\theta} & 0 \\ 0 & 0 & 0 & r_v^2 \end{bmatrix}, \tag{8}$$

and the Eq. (6) can be converted into

$$M = \begin{bmatrix} r_h^2 + r_v^2 & r_h^2 - r_v^2 & 0 & 0 \\ r_h^2 - r_v^2 & r_h^2 + r_v^2 & 0 & 0 \\ 0 & 0 & 2r_h r_v \cos\theta & 2r_h r_v \sin\theta \\ 0 & 0 & -2r_h r_v \sin\theta & 2r_h r_v \cos\theta \end{bmatrix} + dM_{dp}, \tag{9}$$

extract r_v^2 in the first matrix, and

$$M = r_v^2 \begin{bmatrix} \left(\frac{r_h}{r_v}\right)^2 + 1 & \left(\frac{r_h}{r_v}\right)^2 - 1 & 0 & 0 \\ \left(\frac{r_h}{r_v}\right)^2 - 1 & \left(\frac{r_h}{r_v}\right)^2 + 1 & 0 & 0 \\ 0 & 0 & 2\left(\frac{r_h}{r_v}\right)\cos\theta & 2\left(\frac{r_h}{r_v}\right)\sin\theta \\ 0 & 0 & -2\left(\frac{r_h}{r_v}\right)\sin\theta & 2\left(\frac{r_h}{r_v}\right)\cos\theta \end{bmatrix}, \tag{10}$$
$$+ dM_{dp}$$

define amplitude ratio $P = r_h/r_v$, and weight coefficient of Mueller–Jones matrix $\omega_j = r_v^2$, and weight coefficient of depolarization $\omega_d = d$, then

$$M = \omega_j \begin{bmatrix} P^2 + 1 & P^2 - 1 & 0 & 0 \\ P^2 - 1 & P^2 + 1 & 0 & 0 \\ 0 & 0 & 2P\cos\theta & 2P\sin\theta \\ 0 & 0 & -2P\sin\theta & 2P\cos\theta \end{bmatrix}, \tag{11}$$
$$+ \omega_d M_{dp}$$

where ω_j and ω_d represent the weight coefficient. Considering the model error, Eq. (11) is changed to

$$M = \omega_j \begin{bmatrix} P^2 + 1 & P^2 - 1 & 0 & 0 \\ P^2 - 1 & P^2 + 1 & 0 & 0 \\ 0 & 0 & 2P\cos\theta & 2P\sin\theta \\ 0 & 0 & -2P\sin\theta & 2P\cos\theta \end{bmatrix}, \tag{12}$$
$$+ \omega_d M_{dp} + M_n$$

where M_n is the model error matrix. And defined

$$M_J' = \begin{bmatrix} P^2 + 1 & P^2 - 1 & 0 & 0 \\ P^2 - 1 & P^2 + 1 & 0 & 0 \\ 0 & 0 & 2P\cos\theta & 2P\sin\theta \\ 0 & 0 & -2P\sin\theta & 2P\cos\theta \end{bmatrix}, \tag{13}$$

then

$$\left\|M_n\right\| = \left\|M - \omega_j M_J' - \omega_d M_{dp}\right\|. \tag{14}$$

Using optimal methods to minimize $\|M_n\|$ can obtain P, θ, ω_j and ω_d.

2.3. The experiment platform

In this experiment, we used seven different incident angles (40°, 45°, 50°, 55°, 60°, 65°, 70°) to measure the samples, and calculated the Mueller matrix and depolarization coefficient respectively. Experiments were carried out in a darkroom. The light source was a Helium–neon gas laser, and the wavelength was 632.8 nm. The detector was a CCD camera (image size: 800 × 600 pixels for 4096 gray levels, and the physical size of detector is 5.27 mm × 3.96 mm). A CCD camera was used as photometer [19]. It was a kind of CCD aperture photometry, and algorithms for CCD photometry were shown in Ref. [20]. The experimental apparatus was shown in Fig. 1.

The experiment device was composed of light source, optical lens, diaphragm, deviation device, polarizer, quarter-wave plate and CCD camera. The laser light was focused for parallel beam by lens, and through a diaphragm with 1.88 mm circular aperture to be the controllable linear polarized light. Then the polarizer and quarter-wave plate were controlled to simulate different polarized lights with unique polarization states. According to the scattering principle, the signal of scattering light could be acquired by CCD camera which was through the quarter-wave plate and polarizer of receiving terminal. Finally, the Matlab software had been used to analyze the measurement data, the polarization parameters and Mueller matrixes of the samples.