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Polarization characteristics of backscattering of turbid media based on Mueller matrix

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ABSTRACT

Mueller matrix is one approach to characterizing optical polarization of the turbid media. We have simulated the two-dimensional images of Mueller matrix based on single-scattering approximation model and implemented experiments to verify the simulations. By comparing the experimental results to the theoretical simulations, we have obtained some conclusions. When the particle size is smaller than the wavelength, the linearly polarized light propagating through the turbid media of Rayleigh scatterers has better polarization-maintaining ability. Whereas when the particle size is larger than the wavelength, the circularly polarized light propagating through the turbid media of Mie scatterers has better polarization-maintaining ability. Moreover, the radial dependence of the element patterns becomes weak as the transport mean free path decreases. This study can help us understand to the fundamental principle of optical polarization.

1. Introduction

Optical polarization is a fundamental concept and an intrinsic property of electromagnetic wave and has wide applications in various fields [1–4]. In recent years there has been an increased interest in the propagation of polarized light in turbid media [5–9]. One approach to characterizing material properties of optical polarization is through the determination of its Mueller matrix. This 4×4 matrix represents all interactions between an electromagnetic wave and a turbid medium in terms of energy and polarization. As the optical fingerprint, Mueller matrix provides complete information about the polarization properties of a turbid medium. Determination of the elements of the Mueller matrix is typically done by analyzing the polarization of the light reflected from a turbid medium as a function of the polarization of the incident light [10]. This involves two processes: polarization state generation, whereby the polarization of the incident light is varied systematically, and polarization state detection, in which the polarization of the diffusely reflected light is determined.

In this paper, we choose the polystyrene (PST) sphere suspensions as a turbid medium. Mueller matrices of PST sphere suspensions with different particle sizes and suspension concentrations at backscattering surface are measured. To validate the experimental results, backscattering Mueller matrices of PST sphere suspensions are simulated by single-scattering approximation method [11]. This work is organized as follows. In Section 2, we present the single-scattering approximation method. In Section 3, we then show how our setup is used for measuring backscattering Mueller matrix of PST sphere suspensions. In Section 4 will be devoted to the results and conclusions. Finally, we draw our conclusions in Section 5.

2. Theory

Our theoretical analysis is based on the assumption that the scattering of light is incoherent and single-scattering approximation. We also assume that all photons which exit the medium reach the detector, no matter their propagation angle and position as it exit the medium. Fig. 1 shows the geometry of a backward single-scattering event. A narrow laser beam propagates downward along the z axis into a plane-parallel medium with thickness h.

Scattering events occur at the lower half-space of the medium, $-h \leq z \leq 0$. Let V_0 be the Stokes vector that corresponds to the power of the incident laser beam with respect to the x-z reference plane. We assume that the light crosses a small surface element ds_0 at upper surface of turbid medium, so the vector that describes the incident total light power is [11]

$$\mathbf{P}_0 = \mathbf{V}_0 \mathrm{d}s_0. \quad (1)$$

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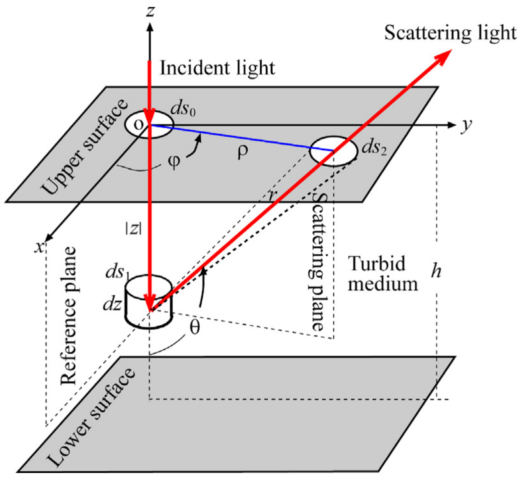

Fig. 1. Geometric scheme for single-scattering event.

Then according to Beer–Lambert law the power $\mathbf{P}_1$ that reaches the depth $|z|$ is

$$\mathbf{P}_1 = \mathbf{P}_0 \exp(-\mu_t |z|), \tag{2}$$

where μ_t is the extinction coefficient. The differential power $\mathrm{d}\mathbf{P}_2$, scattered from the differential volume $\mathrm{d}s_1\mathrm{d}z$ into the solid angle $\mathrm{d}\omega_1$ in the direction (θ,ϕ), is given by

$$\mathrm{d}\mathbf{P}_2 = \mu_s \mathrm{d}z\mathbf{M}(\theta)R(\phi)\mathbf{P}_1 d\omega_1, \tag{3}$$

where μ_s is the scattering coefficient, $\mathbf{M}(\theta)$ is the Mueller matrix of homogeneous spheres

$$\mathbf{M}\left(\theta\right) = \begin{pmatrix} m_{11}(\theta) & m_{12}(\theta) & 0 & 0 \\ m_{12}(\theta) & m_{11}(\theta) & 0 & 0 \\ 0 & 0 & m_{33}(\theta) & -m_{34}(\theta) \\ 0 & 0 & m_{34}(\theta) & m_{33}(\theta) \end{pmatrix}, \tag{4}$$

and

$$\begin{cases} m_{11}(\theta) = \dfrac{S_1^2(\theta) + S_2^2(\theta)}{2} \\ m_{12}(\theta) = \dfrac{S_2^2(\theta) - S_1^2(\theta)}{2} \\ m_{33}(\theta) = \dfrac{S_1(\theta)S_2^*(\theta) + S_1^*(\theta)S_2(\theta)}{2} \\ m_{34}(\theta) = \dfrac{S_1(\theta)S_2^*(\theta) - S_1^*(\theta)S_2(\theta)}{2} \end{cases} \tag{5}$$

where $S_1(\theta)$, $S_2(\theta)$ are the perpendicular and parallel polarization component of the scattered electric filed vector based on Mie theory [12]. $R(\phi)$ is a 4×4 rotation matrix that rotates the reference plane to the scattering plane.

$$R(\phi) = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos 2\phi & -\sin 2\phi & 0 \\ 0 & \sin 2\phi & \cos 2\phi & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}. \tag{6}$$

It should be noted that the rotation angle looking into the direction of the initial beam is $-\phi$ because the direction of rotation is counterclockwise by the usual definition of $R(\phi)$. The differential power $\mathrm{d}\mathbf{P}_2$ into the detector at $\mathrm{d}s_2$ is given by

$$\mathrm{d}\mathbf{P}_3 = \mathrm{d}\mathbf{P}_2 \exp(\mu_t r). \tag{7}$$

Then we get the Stokes vector $\mathrm{d}\mathbf{I}_{bs}$ that describes the radiance at the detector

$$\mathrm{d}\mathbf{I}_{bs} = \frac{R(\phi)\cdot \mathrm{d}\mathbf{P}_3}{\mathrm{d}s_2} = \frac{\mu_s \mathrm{d}z}{r^2}\exp\left[-\mu_t(|z|+r)\right]\cdot R(\phi)\mathbf{M}\left(\theta\right)R(\phi)\mathbf{P}_0. \tag{8}$$

Now the Stokes vector $\mathbf{I}_{bs}(\rho,\phi)$ that describes the total radiance at the detector on the surface of the scattering medium is obtained by integration of the last expression over z

$$\mathbf{I}_{bs} = \mu_s \int_{-\infty}^{0} \mathrm{d}z \frac{\exp\left[-\mu_t(|z|+r)\right]}{r^2}\cdot R(\phi)\mathbf{M}\left(\theta\right)R(\phi)\mathbf{P}_0, \tag{9}$$

where $r = \sqrt{\rho^2 + z^2}$, $\tan\theta = \rho/z$. Set $\mathbf{M}_{ij}(\rho,\phi)$ as Mueller matrix of backscattering, then $\mathbf{I}_{bs} = \mathbf{M}_{ij}(\rho,\phi)\mathbf{P}_0$. Therefore $\mathbf{M}_{ij}(\rho,\phi)$ is given by

$$\mathbf{M}_{ij}(\rho,\phi) = \mu_s \int_{-\infty}^{0} dz \frac{\exp\left[-\mu_t(|z|+r)\right]}{r^2}\cdot R(\phi)\mathbf{M}\left(\theta\right)R(\phi). \tag{10}$$

After some simple transformations we obtain

$$\mathbf{M}_{ij}(\rho,\phi) = \frac{\mu_s}{\rho}\int_0^{\pi/2} \exp\left[-\rho\mu_t \cot\ (\theta/2)\right] \mathrm{d}\theta \mathbf{F}_{ij}, \tag{11}$$

where expressions for the functions $\mathbf{F}_{ij}$ are listed as

$$\begin{aligned} &F_{11} = m_{11}(\theta),\\ &F_{12} = F_{21} = m_{12}(\theta)\cos 2\phi,\\ &F_{13} = -m_{12}(\theta)\sin 2\phi,\\ &F_{14} = F_{41} = 0,\\ &F_{22} = m_{11}(\theta)\ \cos^2 2\phi - m_{33}(\theta)\sin^2 2\phi,\\ &F_{23} = -\cos 2\phi \sin 2\phi\left[m_{11}(\theta) + m_{33}(\theta)\right],\\ &F_{24} = -F_{42} = -m_{34}(\theta)\sin 2\phi,\\ &F_{31} = -F_{13},\\ &F_{32} = -F_{23},\\ &F_{33} = -F_{22},\\ &F_{34} = -F_{43} = -m_{34}(\theta)\cos 2\phi,\\ &F_{44} = m_{33}(\theta). \end{aligned} \tag{12}$$

Based on the model of single-scattering approximation mentioned above, we can calculate the 16 elements of Mueller matrix.

3. Methods

3.1. Materials and setup

Polystyrene (PST) spheres suspensions were used as the turbid medium. The original PST_2.5% suspension (Wuxi Nanozymics Biotech Co., Ltd) was diluted with deionized water to concentrations of 0.01%, 0.02%, 0.03%, 0.04% and 0.05% by weight. The average diameters of the two PST spheres were 198, and 2420 nm, respectively. The sphere morphology and size distribution showed in our previous work [6]. Because PST spheres were monodispersed, narrowly distributed, and highly purified, they were used to test Mie theory in the experiments.

Fig. 2 shows a schematic diagram of the experimental setup for studying the diffuse backreflectance of polarized light. A semiconductor laser (Beijing LASER OptoMechatronic) with a wavelength of 650 nm was used as the light source. The incident light power on the sample was fixed at 1.2 mw. A polarizer $\mathbf{P}_1$ was placed in front of