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Multi-spectral characteristics of polarization retrieve in various atmospheric conditions

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ABSTRACT

We have investigated the multi-spectral characteristics of polarization reconstruction after the incident polarized light traveled a long distance in various atmospheric conditions. In order to retrieve the original polarization information of incident light from the scattered optical field, a novel polarization retrieve (PR) method is established by using the effective Mueller matrix based on Monte Carlo (MC) algorithm, and an existing polarization maintaining (PM) method which is the usual way in quantum communication is also exploited for comparison. It is demonstrated that the original polarization states of the initial field can be reconstructed accurately by PR method, and the influence factors of PR method are related to wavelength, particle size and particle number density. Furthermore, the simulated results show that the infrared light source can reduce the loss of polarization information effectively, and our PR method not only is more applicable to disordered media, such as low altitude atmosphere with larger size of aerosols and other particles, but also has a higher robustness.

1. Introduction

Laser light with arbitrary incident polarization state that diffuses through different scattering media emerges different levels of depolarization [1], and the information of polarization properties (degree of polarization (DoP), and angle of polarization (AoP)) of incident light will be lost owing to the scattering effects. However, the change of the incident polarization information is a lethal damage to light communication in which the information is encoded by polarization states [2–4]. So how to obtain the original polarization information, or to accurately retrieve the original information from the scattered optical field, is the critical factor to decode a message accurately.

Some previous researches including recovering the incident optical field by correlating the transmitted speckle pattern with other reference fields [5] and by the spectral polarimetric measurements [6] demonstrated that the initial state of the laser beam could be reconstructed from the diffused transmitted light. But these methods failed to solve the problems existing in the real communication system in free space that contains various atmospheric conditions.

Generally speaking, PM method is the usual way to free space communication [7], but it is restricted by the multiple scattering in complex transmission medium. For ground-to-space quantum communication, the polarization encoded photons will be scattered greatly by the atmospheric molecules and other nano/micro particles in terrestrial space, and the multiple-scattering effect is the most importantly influencing factor to an accurate communication of the polarization configuration [8]. There are three scattering types [9]: single scattering, for $\tau < 1$; multiple scattering, for $\tau \le 10$; and diffusion, for $\tau > 10$, where the τ is the optical thickness. However, the PM method can only be used in the region of $\tau < 1$ to ensure negligible scattering effects.

In this letter, we propose a novel robust PR method that using effective Mueller matrix to reconstruct the original incident Stokes vector in various turbid media (urban, rural, cloudy, and sunny [10]). We use the Monte Carlo model to obtain the forward scattering matrix in the various types' scattering events. The results show that the polarization state of incident light could be retrieved accurately according to the scattered polarization state and the Mueller matrix. The influence factors of PR method in various atmospheric conditions are related to the wavelength, the particle size distribution and particle number density of the transmission medium. According to the comparison with PM method, our PR method is more appropriate to the medium system containing larger particles. A choosing standard between PM and PR has been proposed, which can serve as a guideline for choosing a proper method (PM or PR) and proper working parameters for the quantum communication system in different circumstance, such as the appropriate wavelength of incident laser source.

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2. Theoretical background

If S_o and S_i represent the scattering and incident Stokes vectors, the process of scattering can be depicted by the Stokes–Mueller formalism [11],

$$S_o = MS_i = \begin{bmatrix} m_{11} & m_{12} & m_{13} & m_{14} \\ m_{21} & m_{22} & m_{23} & m_{24} \\ m_{31} & m_{32} & m_{33} & m_{34} \\ m_{41} & m_{42} & m_{43} & m_{44} \end{bmatrix} \begin{bmatrix} I \\ Q \\ U \\ V \end{bmatrix}_i, \quad (1)$$

where M is the Mueller matrix of scattered medium and it contains four-by-four components, which can represent all scattering properties, such as linear retardance, optical rotation, linear birefringence and optical activity [12]. I, Q, U and V are four components of the Stokes vector.

Based on the Stokes vector, the degree of polarization (DoP) and the angle of polarization (AoP) can be defined as follows:

$$DoP = \frac{\sqrt{Q^2 + U^2 + V^2}}{I}, \quad (2)$$

$$AoP = \frac{1}{2}\tan^{-1}\left(\frac{U}{Q}\right). \quad (3)$$

While for a highly scattering medium, the information about particle size, particle number density and so on, can be extracted from the four-by-four elements of the Mueller matrix, because the Mueller matrix can describe the optical properties of medium system completely. Relatively speaking, the Mueller matrix is stable even if the state of incident light is variable. Theoretically, the Mueller matrix can be obtained by solving Maxwell's equations with the corresponding boundary conditions. However it seems a computationally unrealistic task because of the complicated numerical calculation. Here, the Mueller matrix is obtained by simulating four different polarization states of launching photons as Ref. [13] (complete unpolarization, horizontal polarization, 45° polarization, and right-hand circular polarization) with MC model. If the medium is decided, we can obtain the M uniquely which is stored in the corresponding pixel of the detector to make the preparation for reconstruction of the original polarization information. Obviously, once we accurately detect the Mueller matrix in advance, the Stokes vector of incident photons can be retrieved by the inverse of Mueller matrix and scattered Stokes vector:

$$S_i' = M^{-1}S_o. \quad (4)$$

Eq. (4) is the principle of our polarization retrieve (PR) method, and the retrieval error is $S_i - S_i'$. To ensure that the Mueller matrix is nonsingular, we should choose the appropriate number of incident photons. In Rayleigh condition [14], M can be simplified to a unit matrix in forward direction and $S_i' = S_o$, which is polarization maintaining (PM) method.

3. Results and discussion

3.1. Numerical scheme

The schematic of monochromatic point source with wavelength of λ and horizontal polarization state (DoP=1, AoP=0) diffusing through a homogeneous disordered medium with a long distance of 100 m is shown in Fig. 1. The model consists of four parts: (I) incident light with the wavelength λ and horizontal polarization state, x-coordinate and y-coordinate represent the direction of electric field, z is the direction of propagation; (II) scattering medium, different particle sizes and particle number density (D, ρ_n) represent corresponding atmospheric conditions; (III) the collection of scattered photons (S_o) by 1 m^2 optical detector that may contain various polarization states due to scattering, and the effective Mueller matrix is obtained in this part; (IV) the polarization retrieve by Eq. (4).

According to Refs. [10,15], the diameter in our model is set to be 0.1 μm (rural) to 0.3 μm (urban, due to pollution), and the particle number density ρ_n is $0.05 \times 10^{-6}/\mu m^3$ (sunny) and $0.5 \times 10^{-6}/\mu m^3$ (cloudy) respectively. Here, the particles' refractive index is set to be 1.37–0.00075i (i.e. water soluble). Due to the spectral limitation of optical detector, we limit the range of wavelength from 0.3 μm to 1.3 μm. For obtaining the whole impression on the retrieving errors of PR method dependent on the system parameters (λ, D and ρ_n), the whole simulation is divided into many successive sub-

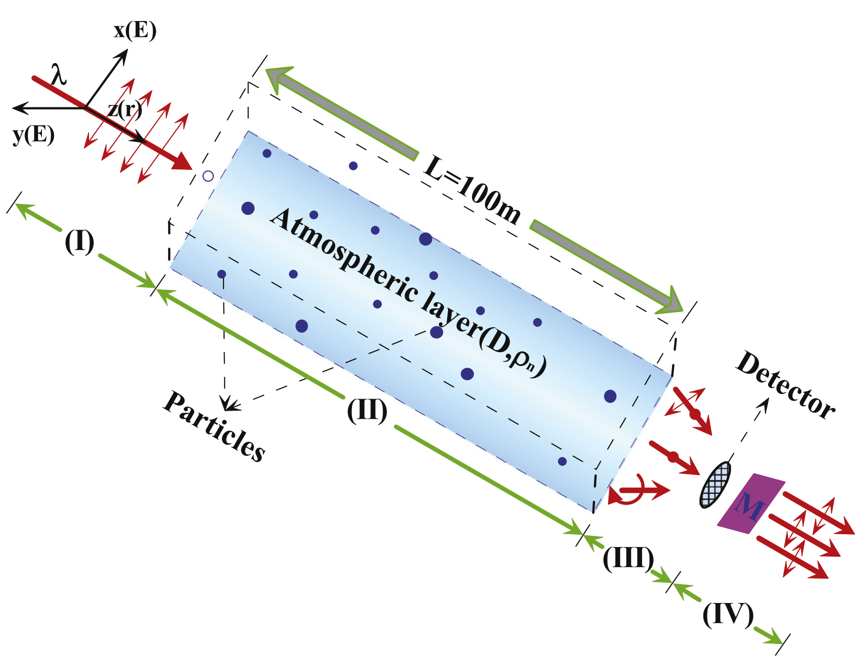

Fig. 1. The diagrammatic view of light transferring through the semi-infinite atmospheric layer.