Retrieving the polarization information for light communication

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Abstract: The transmission performances of polarization information in various scattering systems were introduced based on Stokes vectors and Monte Carlo (MC) simulation algorithm. According to the Stokes vectors′ scattering characteristics of polarized light, the polarization retrieve (PR) method was proposed theoretically, which is aiming at reducing the scattering impact on incident polarized light and increasing the transmission efficiency of light signals. In order to prove the availability and practicability of PR method, simulations on the polarization transmission and reconstruction in atmosphere and underwater, were complemented in different actual environmental circumstances. The results demonstrate that the PR method is more applicable to disordered media with relatively larger particles and the longer wavelengths can reduce the loss of polarization information effectively. Furthermore, the simulated results reveal that the downlink and uplink are not exchangeable in an inhomogeneous atmospheric medium. In underwater, the PR method is also used to reduce the scattering impacts on the degree of polarization (DoP) of the light, and the maximal enhancement of the degree of linear polarization(DoLP) can reach to about 16% by PR method. These results are significant to the quantum secure communication in atmosphere and underwater in future.

Key words: polarization; scattering; Monte Carlo; polarization retrieve
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基于偏振信息恢复的光通信

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摘 要:基于斯托克斯矢量和 MC 算法,在各种散射系统中研究了偏振信息的传输性能。根据偏振光斯托克斯矢量的散射特性,提出了一种能够减少散射对入射偏振光影响的 PR 方法。为了验证 PR 方法的有效性和实用性,仿真了在不同实际大气和水下环境,偏振传输和偏振信息恢复的结果。仿真结果表明,PR 方法更适用于粒子半径相对大的杂乱媒介,并且长波可以有效地减少偏振信息的损失。此外,仿真结果也表明,在非均匀的大气媒介中下行和上行链路是不可逆的。在水下,PR 方法同样用来减小散射对于光的偏振度的影响。通过 PR 方法,线偏振度的最大增强可达到 16%。这些结果对于未来大气,水下量子保密通信具有重要的意义。

关键词:偏振; 散射; 蒙特卡罗; 偏振恢复

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0 Introduction

Recently, there has been increasing interest in polarized light communication, motivated by the dramatic development of laser technologies and polarization analyzers[1-2]. Polarization characteristics have great potentials for light communications, and can help to overcome the weaknesses of the common encoded signal system based on the light intensity. Because of the absolute security of quantum systems, polarization information encoding strategy for light communications can achieve a real sense of secure communications and an important research field of national security as well as the bright future for the development of information technology[3-4].

Although it is more promising for realizing a global communication network in free space, the scattering effect cannot be neglected[5-6]. It might appear that the incident light's polarization information (DoP and angles of polarization (AoP)) would be lost owing to the scattering effects in the transmission medium. However, a change in incident polarization information can do a lethal damage to light communication systems in which the information is encoded by polarization states[2].

In general, the polarization maintaining (PM) method, which neglects multiple scattering, is the usual way for the free space communication[7-8], but it can only be used in non-aerosol regions ignoring the scattering effects. Some other methods have also been investigated, including recovering the incident optical field by correlating the transmitted speckle pattern with other reference fields [9] and by using spectral polarimetric measurements[10]. However, these methods have not yet solved the problems existing in real free space communication systems, such as the satellite-to-Earth light communications system.

In this paper, the main motivation is to retrieve the incident polarization state in various turbid media. For retrieving the polarization state accurately, we propose a novel robust PR method based on the MC solution. To understand how the Stokes-vectors change in the various-type scattering events, we use the PR method to examine the homogeneous and inhomogeneous atmospheric media, and different conditions of water, which demonstrate that our proposed PR method is effective for reducing the scattering influences in different systems.

1 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],

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

where M is the Mueller matrix of scattered medium and it contains four-by-four components, which can describe all scattering properties. I, Q, U and V are four components of the Stokes vector. Based on the Stokes vector, the DoP, the DoLP, the degree of circular polarization (DoCP) and the AoP can be defined as follows:

$$\mathrm{DoP}=\frac{\sqrt{Q^2+U^2+V^2}}{I} \tag{2}$$

$$\mathrm{DoLP}=\frac{\sqrt{Q^2+U^2}}{I} \tag{3}$$

$$\mathrm{DoCP}=\frac{|V|}{I} \tag{4}$$

$$\mathrm{AoP}=\frac{1}{2}\tan^{-1}\left(\frac{U}{Q}\right) \tag{5}$$

While for a highly scattering medium, the information about particle size, particle number density and so on, can be extracted from 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[12] ((1) complete non-polarization, (2) horizontal polarization, (3) 45° polarization and (4) right circular polarization). With these four polarization states as the irradiating sources, the effective Mueller matrix is given by:

$$M=\begin{bmatrix} I_1 & I_2-I_1 & I_3-I_1 & I_4-I_1 \\ Q_1 & Q_2-Q_1 & Q_3-Q_1 & Q_4-Q_1 \\ U_1 & U_2-U_1 & U_3-U_1 & U_4-U_1 \\ V_1 & V_2-V_1 & V_3-V_1 & V_4-V_1 \end{bmatrix} \quad (6)$$

where the subscripts indicate the scattered radiation associated with the aforementioned polarization states of the incident beam.

If we can accurately find a nonsingular Mueller matrix, the Stokes-vector of incident light can be retrieved by the following relation:

$$S_i=M^{-1}S_o \quad (7)$$

Equation (7) is the principle of our proposed PR method.

2 Simulation and verification

2.1 Homogeneous medium

The schematic of a monochromatic light transferring through the atmosphere is shown in Fig.1.

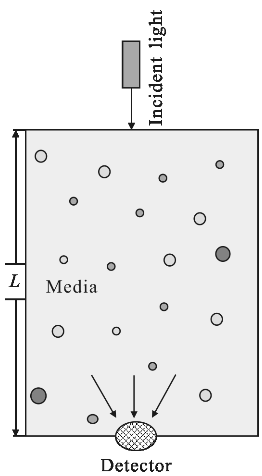


Fig.1 Schematic of light transferring though the media

The direction of incident light is vertical to the layer, and the wavelength of λ is 632.8 nm. The path length of the light equals the thickness of the atmosphere layer (i.e. L=10 m), and the area of the circle detector is $0.01\pi m^2$. The radii (r) of the spherical scattering particles in our model are set to be r_1=0.1 μm, r_2=0.2 μm(i.e. water soluble), and the particle number density ρ_n is 1.152×10^{-6} particle/μm³[13]. We suppose that the refraction index(IR) of n are n_1=1.33 and n_2=1.50−0.002 5i.

2.1.1 Single homogeneous medium

To verify our PR method, we modeled single homogeneous medium system: r_1 with n_1, r_2 with n_1 and r_2 with n_2 respectively. Additionally, the results were compared with the PM method. The simulation results of retrieved DoP and AoP by the PM and PR method are shown in Fig.2 in which the errors of the retrieved polarizations compared to the original incident polarization are expressed into three dimensional diagrams.

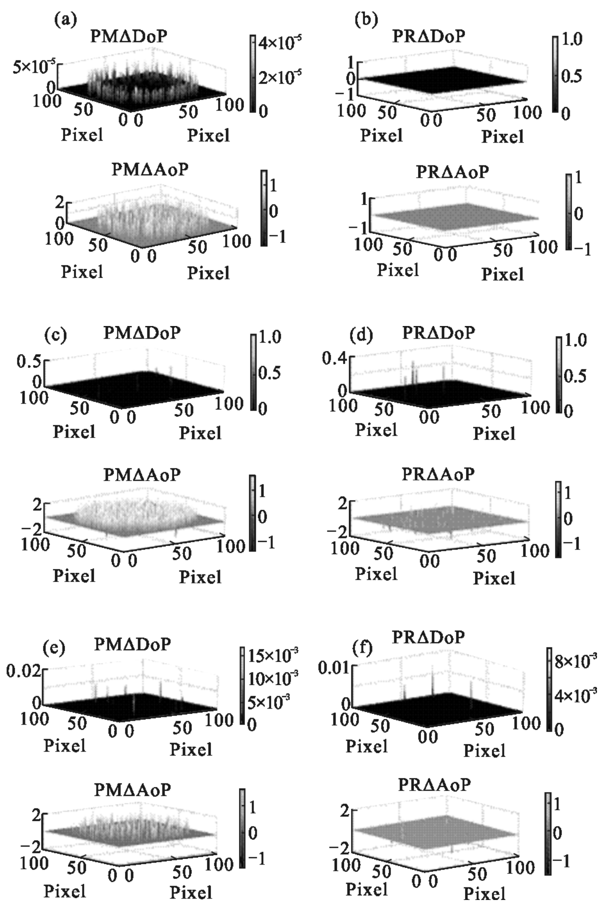


Fig.2 Mean errors of DoP and AoP by PM and PR methods with r_1 and n_1 ((a), (b)); r_2 and n_1 ((c), (d)); and r_2 and n_2 ((e), (f))

Figure 2(a), (c) and (e) are the simulation by the PM method, and we can see that the errors of DoP are very small and the values of AoP are far from the theoretical values. Both of the values of retrieved DoP and AoP are close to the theoretical value by PR method, as shown in (b), (d) and (f) of Fig.2. These results show that the polarization state of incident light could be retrieved accurately according to the PR method, and the retrieved AoP by the PR method is often more accurate than that by the method of PM.

2.1.2 Homogeneous mixed medium

Because the atmosphere is very complex, for approaching actual situations, we have also simulated the light propagation through a homogeneous mixed medium of two materials. In this medium, one of the materials is seen as "noise" and mixed into the single homogeneous medium at a certain volume ratio. We should note that the retrieval matrix is invariable in the same medium, and it is derived from the single homogeneous medium. We simulated one model: the IRs of both types of particles are set into $n=n_1$, and the particles radius of $r=r_2$ are mixed with particles of $r=r_1$ at a certain volume ratio of x (0.0−1.0), where "0.0" and "1.0" represent there are no and all particles with $r=r_1$ in the medium. However, the retrieval matrix of Equation (7) is derived in the case of "0.0". The incident light is horizontal polarization and the simulation results are shown in Fig.3.

From Fig.3 (a), we can see that the DoP by the PM method increases with the decrease of the mixed ratio and gradually deviates from the theoretical value. Because of the multiple scattering (due to large particles), there is a greater deviation around "0.0". The AoP by the PM method shows systematic deviations around the theoretical value, as depicted in Fig. 3 (b). However, the simulation results show that the retrieved value by the PR method is more stable, and the maximal errors of retrieved DoP and AoP by PR are 0.11% and 0.54%, respectively, which prove that the proposed PR method is more effective than the conventional PM method according to MC simulations.

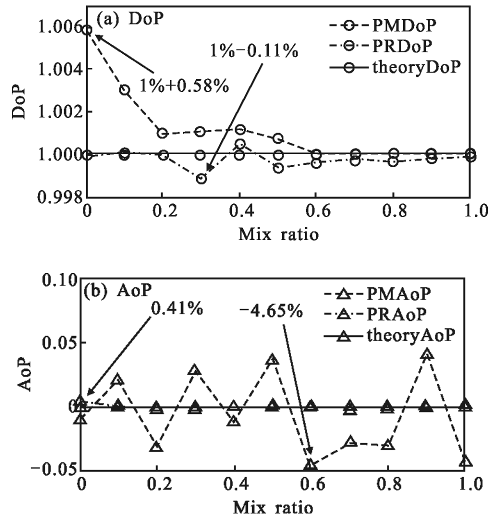
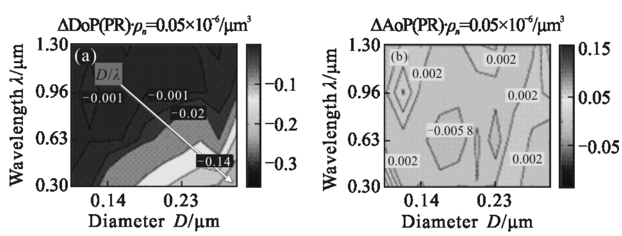


Fig.3 Retrieved DoP (a) and AoP (b) by the methods of PR and PM, versus the volume ratio with a homogeneous mixed medium(n_1, r_1 and n_1, r_2)

2.2 Multi-spectral

We use the horizontal polarization state (DoP=1, AoP=0) light incident and the L is 100 m. According to reference [14], the diameter is set to be 0.1 μm (rural) to 0.3 μm (urban), and the particle number density ρ is set into $\rho=\begin{cases}\rho_1=0.05\times10^{-6}\ \text{particle}/\mu\text{m}^3(\text{sunny})\\ \rho_2=0.5\times10^{-6}\ \text{particle}/\mu\text{m}^3(\text{cloudy})\end{cases}$. And the particles′ IR is set to be $1.37-0.000\ 75i$ (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. The simulated retrieval errors of DoP and AoP between PR method and theoretical value in various atmospheric conditions can be obtained as shown in Fig.4.

From Fig.4, we can observe an obvious trend that the retrieved errors of DoP by PR method increase with the growth of D/λ as depicted by the arrows in Fig.4 (a) and (c). However there are no evident trends for the retrieved errors of AoP as shown in Fig.4(b) and (d).



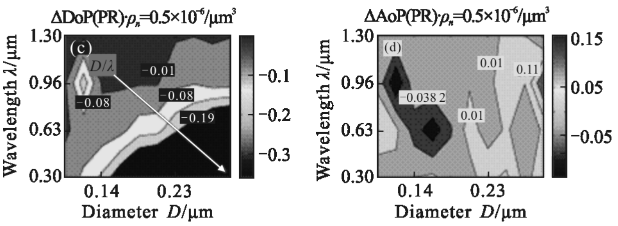


Fig.4 Retrieval errors of DoP and AoP by PR method as the function of the diameter of the scattering particles (D=0.1–0.3 μm), incident wavelength (λ=0.3–1.3 μm) under the particle number density of ρ_1(a), (b) and ρ_2(c), (d) respectively

In order to obtain more accurate information and guide the engineers to make a better choice in reality, we define a parameter of "amplification factor (AF)"[15] to analyze the retrieved deviation of DoP between PM method and PR method. The AF is defined as:

$$\mathrm{AF(DoP)}=\frac{1-|\Delta\mathrm{DoP(PR)}|}{1-|\Delta\mathrm{DoP(PM)}|} \tag{8}$$

where ΔDoP(PR) is presented in Fig.4 and ΔDoP(PM) is the errors of DoP between the retrieved value by PM method and theoretical value. The contour maps of AF(DoP) with the different particle number density of ρ_1 and ρ_2 as the function of the wavelengths and the particle sizes are shown in Fig.5 (a) and (b) respectively.

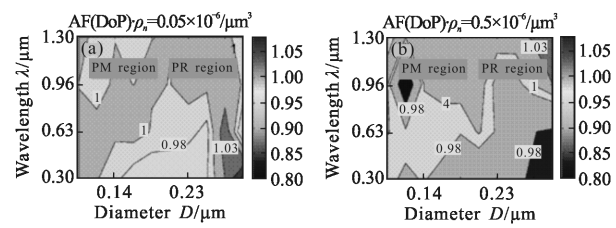


Fig.5 Ratio of retrieved DoP by PR and PM method

From Fig.5 (a) and (b) we can observe that in longer wavelengths region, PM method is applicable to small particles (rural), but PR method is more suitable for large particles, such as low altitude atmosphere and urban atmosphere (due to pollution). Small particles scattering system has a low scattering coefficient, in which the single scattering is dominant. In this case, the Mueller matrix in Eq.(7) is needless, and we cannot obtain the effective Mueller matrix by scattering. However, for large particles the PM is inappropriate in these conditions because of the multiple scattering. But the PR can overcome this problem because it is mainly applied in Mie range (larger particles) and all optical properties of medium can be effectively recorded in Mueller matrix. As depicted in Fig.5, we have also obtained two regions which are called "PM region"(AF<1) and "PR region" (AF >1) respectively, which can supply a guide to choose a proper method (PM or PR) to the engineers for the real working system. About the AoP, the AF is homogeneous with the relationship of optical wavelength and particle size, and we will not illustrate more about it in this paper.

3 Applied research

3.1 Satellite-to-ground light communication

In this model, only atmospheric scattering in the region of troposphere (about 10 km) is considered because the multiple scattering is almost concentrated in this region. There are two channels in the direction of light propagation, namely downlink and uplink. Actually, the atmosphere is inhomogeneous along vertical direction. For simplicity, the atmosphere is subdivided into 10 layers with the depth of 1 km for each layer and every sublayer is regarded as a homogeneous medium. The parameters of our model are reference [16].

Firstly, we consider the case of downlink in a cloudy day. Based on the aforementioned PM method and PR method, the simulated results of reconstructed DoP and AoP of incident light which passed through the 10 km atmospheric medium are shown in Fig. 6. Here, the incident beam is horizontal polarized light with DoP=1 and AoP=0. Fig.6 (a) and (c) are the reconstructed DoP and AoP of incident light by PM method. And Fig.6 (b) and (d), are the reconstructed by PR method. Obviously, in Fig.6(b) the distribution of reconstructed DoP is uniform and all of them are equal to 1, which is the theoretical DoP. Compared with the retrieved DoP in Fig.6 (a), there is no valley in Fig.6(b). For the retrieved AoP in Fig.6(d), there are only several extremums around the center, and both values are close to zero (less than 0.5×10^{-15}). These results show that the polarization characteristics of incident light are retrieved accurately from scattered field by PR method, and both DoP and AoP are more close to theoretical value than those by PM method.

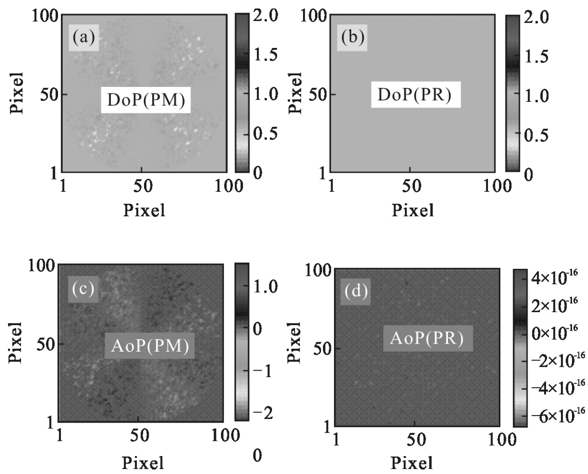


Fig.6 Reconstructed polarization characteristics of incident horizontal polarized light by PM and PR method in the detector

As the same case as Fig.6, the simulated results of reconstructed DoP and AoP by uplink Mueller matrix (Eq.(15)) is shown in Fig.7. We observe that the minimum DoP is about 0.75 and maximum AoP is about 0.15. Although the retrieved results is better than those by PM method, the retrieved DoP and AoP of incident light are still worse than those by PR method with the downlink Mueller matrix. From the above analysis, we can conclude that the two links are not exchangeable in real free space model because the atmosphere is inhomogeneous actually.

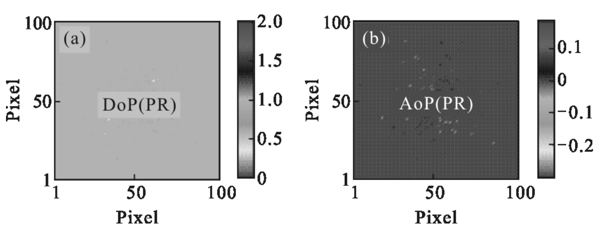


Fig.7 Reconstructed polarization characteristics of incident light with $(S\downarrow)_i=[1,1,0,0]^T$ by uplink Mueller matrix

3.2 Underwater light communication

As discussed in reference [16], the λ is set as 530 nm, and L can be set from 0 to 200 m. And, we have considered three kinds of ocean water (clear ocean, coastal ocean and harbor water).

In order to better understand the change of DoP in different types of ocean water, we emit two kinds of polarization states light: LP and RCP. The results are shown in Fig.8.

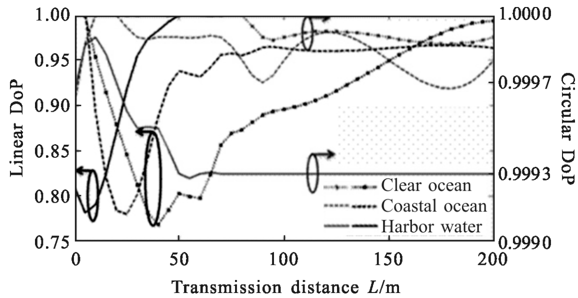


Fig.8 Received DoP of linear and circular polarization light in three kinds of ocean water

In Fig.8, we can easily find that both DoPs of LP and RCP remain above 0.75 (−1.25 dB). From the simulated results, we can observe an obvious trend that the linear DoP decreases to a minimum value and then increases with the increase of transmission distance in all kinds of seawater, and the valley point shifts with the variation of extinction coefficients. When the transmission distance of photons is short, more scattered photons can reach to the receiver and the DoP will be seriously influenced by the multiple scattering. As the transmission distance increase, an overwhelming majority of scattered photons disappear due to long-distance attenuation and small field of view(FOV). So only the photons that travel in straight lines can reach the receiver.

Although underwater channel have a little impact on both DoPs of LP and RCP by comparison to intensity, and the DoP of LP is far less than that of RCP [17]. In order to further reduce decline of DoLP due to scattering and expand the communication degrees of freedom, we utilize PR method to reconstruct the incident Stokes vector in various-types seawater and the results of reconstruction are shown in Fig.9.

Figure 9(a) depicts the retrieved DoLP in different types of seawater and transmission distance. Compared with Fig.8, all DoLPs increase in Fig.9 (a) especially L<50 m. Particularly, when L<20 m, the DoLP of harbor water is greater than that of clear ocean and coastal ocean. Obviously, this phenomenon once again demonstrate that PR method is more applicable to disordered media. Here, in order to analyze the increment of DoLP in Fig.9(a), we define a parameter of enhancement:

$$\text{Enh}=\text{DoLP}_{\text{Fig.9(a)}}-\text{DoLP}_{\text{Fig.8}} \quad (9)$$

which is shown in Fig.9(b). There is no doubt that "Enh" is greater than zero except some fitting errors where L<10 m, and the maximal increment is 16%.

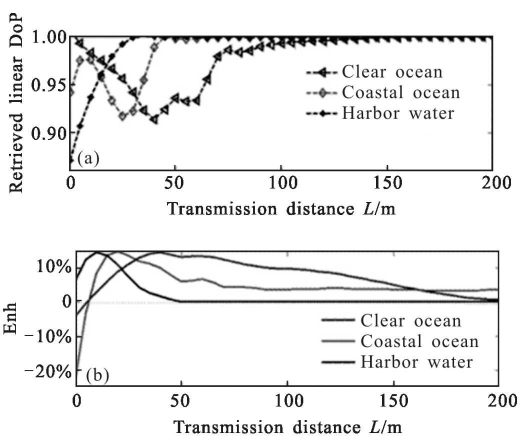


Fig.9 PR for DoLP (a) and enhancement factor (b) in three types of seawater

4 Conclusion

This paper is focused on light transmission in different kinds of medium. We have developed a MC simulation to test the variations of single photon polarization states induced by scattering and have obtained the normalized Mueller matrix of forward scattering. A new PR method is proposed to recover the incident polarization state, which is the key point in light communication. The results show that the polarization state of incident light could be retrieved accurately according to the scattered polarization state and the inverse Mueller matrix. In all simulated cases, the retrieved polarization states by PR method are much closer to the theoretical expectations compared with PM method. By investigating homogeneous medium and the multi-spectral characteristics of the polarization retrieve in various atmospheric conditions, we know that the PR method is more appropriate to the medium contains larger-sized particles and the longer wavelengths can reduce the loss of polarization information effectively. Furthermore, we have simulated the 10 km inhomogeneous atmospheric medium and the underwater medium in different types of seawater. The simulation results reveal that the downlink and uplink are not exchangeable in inhomogeneous atmospheric medium and the DoLP has maximum improvement of about 16 percent by PR method in underwater. These results could provide a valuable reference to the quantum secure communication in a scattering medium, especially for complex conditions and should be very significant for underwater wireless optical transmission system in the future.

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