



Entanglement performance of light through the composite free space channel

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Abstract

Entanglement transmission is utilized widely in quantum communication. In this paper we establish a model, which characterizes the performance of entanglement state passing through the composite free space channel. This free space channel is compounded with atmosphere, sea surface and underwater channel. Based on the model, the entanglement photon pairs transmitted through composite channel are simulated. Simulation results show that the beam wandering, the incident angle of the beam on the sea surface, the concentration of chlorophyll in the seawater and other factors will lead to the degradation of the entanglement and these factors have a nonlinear relationship with transmittance. Moreover, the increase of the chlorophyll concentration is found to be a relatively heavy impact on the entanglement. In addition, expanding the aperture size of the receiving telescope will improve entanglement. The research of this paper has momentous meaning to the transmission of quantum entanglement in free space. What's more, the results have an extremely vital reference value for quantum communications in diverse natural environments.

Keywords Entanglement · Composite free space channel · Bell parameter

1 Introduction

Quantum entanglement (Horodecki and Horodecki 2009) has been studied intensively due to its characteristics of nonlocality. It has been widely applied with the rapid development of quantum information technology (Ma et al. 2012; Ren et al. 2017; Guo et al. 2016), especially in the atmosphere, underwater and other single free space channel. Since the turbulence effects attenuation and scattering commonly exists in free space channel, the free space channel is more complex than fiber optical transmission. The research of propagation of entanglement is highly essential in free space channel.

The effects of complex transmission channels on the propagation of optical signals are mainly absorption and scattering, as well as turbulence disturbance caused by the

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instability of transmission medium (Wang et al. 2015; Vasylyev et al. 2016; Glauber 1963). The absorption and scattering mainly cause the loss of beam energy, which is called attenuation; the phenomenon of beam scintillation, beam wandering, expanding and jitter are generated by turbulence disturbance, which is named of turbulence effect. Up to now, the properties of light beams propagating in the atmosphere have been studied successively. Among them, Vasylyev et al. (2012) found that the entanglement property of light was maintained after it was transmitted through the fluctuating atmospheric channel. The group of Wang et al. (2018) deduced a new secret key rate of continuous variable quantum key distribution (CVQKD) based on atmospheric channels, and analyzed the parameters that affect the secret key rate. Vasylyev et al. (2017) made an investigation on quantum state through atmospheric channel under the diverse weather conditions. Besides, there have been advances in the underwater transmission of light beams as well. The group of Guo et al. (2018) made a research on parameters of channels for satellite-submarine. Mullen (2009) studied the influence of temperature and salinity on the transmission of light in the underwater environment. Zhang et al. (2009) studied the scattering effect of salinity on light in pure seawater. John (1994) took advantage of underwater irradiance measurements to evaluate absorption and scattering factors of natural water. However, the research on the entanglement performance for the beams experiences composite free space channel is almost blank. Nevertheless, with the advancement of quantum satellite (Zhao et al. 2019; Liao 2017) and the demand of marine strategy, it is extremely indispensable to thrive the communication of air-sea surface-underwater link, so it has profound significance to study the transmission of quantum state in composite channel.

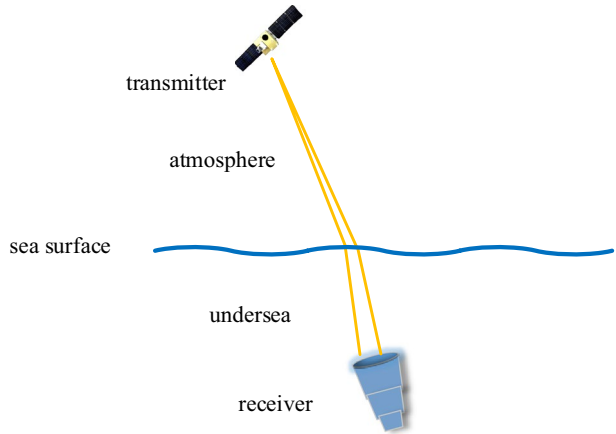
In our paper, a composite free space channel model of air-sea surface-underwater free space channel is established. The synthetical effects of atmosphere, sea surface and underwater on Bell parameter are anatomized with numerical simulations. The results of our research indicates that degradation of entanglement will be affected by the beam wandering and broadening, the incident angle of beam on the sea surface and the concentration of chlorophyll in seawater. The larger the beam deflection variance is, the worse the entanglement performance is. When the incidence angle is greater than, the transmittance drops sharply. In addition, the increase of chlorophyll concentration will make the outstanding contribution to the entanglement degradation. Moreover, in seawater, as the propagation depth increases, the transmittance of the light beam in seawater tends to decrease, to a certain degree, which also adds resistance to the transmission of beam for long distances in seawater. In addition, the increase of entanglement is attributed to the enlargement of the aperture of the receiving telescope. In conclusion, we provides a basis for the realization of quantum communication with long distance and wide scale by using the entanglement in the future.

The paper is organized as follows. In Sect. 2, firstly, the composite free space channel model is introduced, and then the characteristics of different transmission medium in the composite link are described respectively. In Sect. 3, we analyze the calculation of Bell parameter under practical conditions. The conclusion is given in Sect. 4.

2 Composite free space channel model

Composite free space channel consists of both atmosphere and seawater. In this section, we will introduce the model of composite free space channel. Figure 1 illustrates the Composite Free space channel model. In the side of transmitter, an entanglement state is prepared

Fig. 1 Composite free space channel model



and transmitted to the receiver through atmosphere and sea water medium. The entanglement state will be affected by two transmission mediums. Meanwhile, rough sea surface also triggers losses to the transmission of beam. In the aspect of the atmospheric channel, the phenomena of beam wandering and beam broadening caused by atmospheric turbulence are mainly considered. The contribution of fluctuation for seawater and the incident angle of beam are mainly considered on sea surface. As for the transmission under the water, we mainly consider the extinction effect of seawater on beam attenuation and the concentration of chlorophyll. Next, we will introduce the above affecting factors, respectively.

2.1 Atmospheric turbulence effect

Atmospheric turbulence is a motion with irregular and random of the atmosphere. The physical properties such as temperature, velocity, pressure and refractive index of turbulence fluctuate randomly with time (Tatarskii 1978; Okwudili 2013). Atmospheric turbulence is the dominating factor that restricts the performance of free space optical communication, which will lead to beam wandering and broadening. Finally, the reliability and stability of the overall communication system reduce conspicuously (Fig. 2).

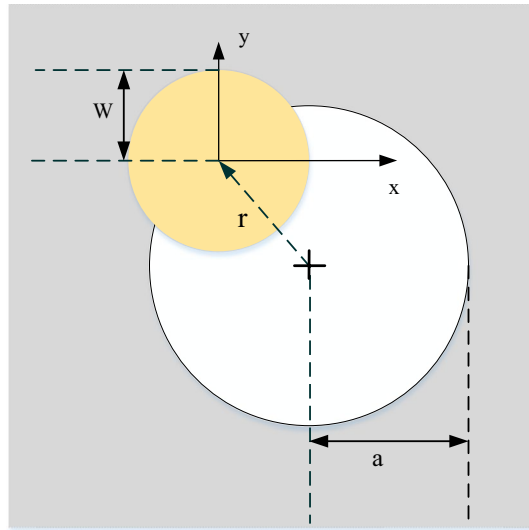
When the beam propagates in the turbulent atmosphere, the diameter or area of the spot received by the aperture will increase and the center of the spot will deflect at the receiving plane, which are the phenomenon of beam wandering and broadening. The geometry for this model is shown in Fig. 1. Where, a is the radius of receiver, W is the radius of beam, in this paper $W = 0.2a$, and r is the distance of wandering (Wang et al. 2018).

Assuming that the beam fluctuates in the central plane of the receiver aperture. The probability density distribution can be expressed by Weibull distribution (Vasylyev et al. 2012):

$$P(T_{air}) = \frac{2R^2}{\sigma^2 Q T_{air}} \left(2 \ln \frac{T_0}{T_{air}} \right)^{\frac{2}{Q}-1} \exp \left(-\frac{1}{2\sigma^2} R^2 \left(2 \ln \frac{T_0}{T_{air}} \right)^{\frac{2}{Q}} \right), \tag{1}$$

σ^2 is variance of wandering, R is scale parameter, Q is shape parameter.

Fig. 2 Beam wandering and broadening



$$R = a \left[\ln \left(\frac{2T_0^2}{1 - \exp \left(-4 \frac{a^2}{W^2} \right) I_0 \left(4 \frac{a^2}{W^2} \right)} \right) \right]^{\frac{1}{Q}}, \tag{2}$$

$$Q = 8 \frac{a^2}{W^2} \frac{\exp \left(-4 \frac{a^2}{W^2} \right) I_1 \left(4 \frac{a^2}{W^2} \right)}{1 - \exp \left(-4 \frac{a^2}{W^2} \right) I_0 \left(4 \frac{a^2}{W^2} \right)} \times \left[\ln \left(\frac{2T_0^2}{1 - \exp \left(-4 \frac{a^2}{W^2} \right) I_0 \left(4 \frac{a^2}{W^2} \right)} \right) \right]^{-1}, \tag{3}$$

I_i is modified Bessel function, T_0 is the maximum transmission efficiency for a given beam radius W , which can be expressed as:

$$T_0^2 = 1 - \exp \left(-2 \frac{a^2}{W^2} \right), \tag{4}$$

the transmission efficiency of the beam with a beam radius W on the receiving plane can be expressed as follows:

$$T_{air}^2 = T_0^2 \exp \left[- \left(\frac{r}{R} \right)^Q \right]. \tag{5}$$

2.2 The effect of sea surface

The sea surface that can be considered as a mirror is calm, while usually fluctuat. When the incidents of beam from the atmosphere through the sea surface to the water, refraction and reflection phenomenon will stay on the sea surface, due to the change of the medium for beam transmission and the fluctuation of the sea surface. The

phenomenon of this will engender the beam to lose energy. The geometry for refraction of seawater surface is depicted in Fig. 3. Here α is the incident angel, β is the refraction angel.

In order to describe the influence of seawater surface on incident light in more detail, the transmittance of seawater surface light beam can be obtained by taking advantage of Fresnel equation (Hieronymi 2016):

$$\begin{aligned} T_V &= 1 - \frac{\sin^2(\alpha - \beta)}{\sin^2(\alpha + \beta)} \\ T_H &= 1 - \frac{\tan^2(\alpha - \beta)}{\tan^2(\alpha + \beta)}, \end{aligned} \quad (6)$$

hence, the whole transmittance of the Fresnel is given as:

$$T_r = \frac{1}{2}(T_V + T_H), \quad (7)$$

the roughness of sea surface caused by waves and sea foam also affects the whole communication link. The effect of this impact expressed by η_r . Therefore, transmittance of sea surface is written as:

$$T_{surface} = \eta_r T_r. \quad (8)$$

The curve in Fig. 4 shows the relationship between sea surface and incident angle. We can obtain from the figure that when the incident angle is about within 0° – 50° approximately, the sea surface transmittance is almost constant with the change of the incident angle. When the incident angle is beyond 50° , the transmittance decreases sharply with the incident. When the incident angle is 90° , the transmittance is almost 0. It offers a kind of solution for the improvement of this communication model. We could select the incident angle appropriately to enhance the transmittance of the overall channel by using this model, when the beam enters the water through the sea surface.

Fig. 3 The refraction of the beam, where α is the incident angel, β is refraction angel

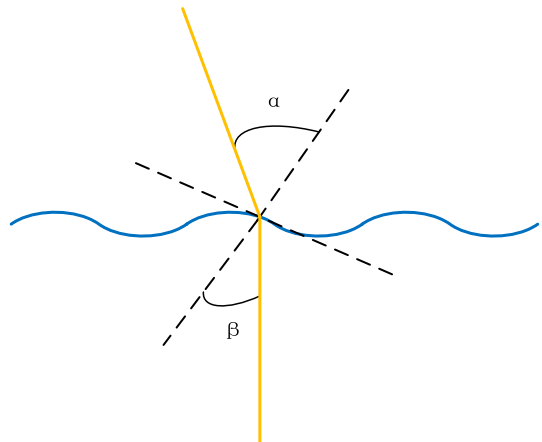
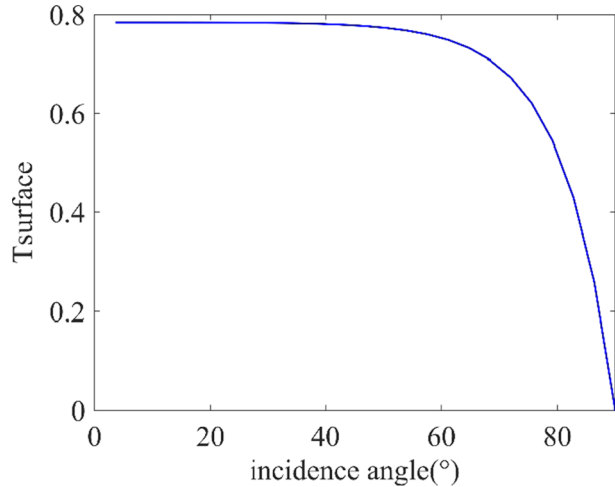


Fig. 4 Curve of sea surface transmittance and incident angle



2.3 The effect of seawater

Compared to the medium for atmospheric transmission, seawater is different transmission medium, but it also has an important effect on the transmission of beam. Seawater, as the living body of quite a few organisms, the composition of it is exceedingly complex. It not only contains large amounts of phytoplankton and suspended particles, but also a mass of salt and other dissolved organic substances. These components will interact with the beam that incident to the seawater, thus affecting the propagation of the beam (Mackinnon 2008).

When the beams enter the seawater via the sea surface, a part of the beams will be absorbed by the seawater and other components, while a part of the beams will be scattered due to scattering effect. Next, the effect of seawater on beam propagation will be analyzed in detail from the aspects of absorption and scattering.

The absorption of beam by seawater can be divided into pure seawater absorption, dissolved organic matter absorption and phytoplankton absorption. The absorption of pure seawater is relatively simple that consists mainly of water and dissolved inorganic salts. Smith and Baker (1981) obtained the absorption coefficient of pure seawater through measurement. The spectral absorption coefficient obtained from the experimental measurement shows that the absorption coefficient of pure seawater near the wavelength of 500 nm light band is minor, while the absorption coefficient of other bands of wave is much larger than that.

The phytoplankton and dissolved organic matter in seawater have strong ability of absorption to light as well. In general, chlorophyll absorption is the main consideration in the study for beam absorption capacity of phytoplankton. In most seawater, the concentration of phytoplankton is exceeded that of non-biological particles, and chlorophyll and other pigments of plant plays a dominant role in the absorption of light. Therefore, based on the chlorophyll concentration, spectral absorption model of natural seawater including phytoplankton and organic particles is given (Prieur and Sathyendranath 1981):

$$a(\lambda) = [a_w(\lambda) + 0.06a_c(\lambda)C^{0.65}] [1 + 0.2e^{-0.014(\lambda-440)}], \quad (9)$$

where $a_w(\lambda)$ is the absorption coefficient in pure ocean water, $a_w(\lambda) = 0.02 \text{ m}^{-1}$. $a_c(\lambda)$ is the statistically derived chlorophyll specific absorption coefficient. C is the chlorophyll concentration. λ is the wavelength, $\lambda = 550 \text{ nm}$.

The scattering of seawater is relevant to the wavelength of transmitted light and the composition, size and concentration of various particles in seawater. However, it is hard to grasp exactly what the particles are in seawater. Therefore, Gordon proposed the model of spectral scattering coefficient based on the chlorophyll concentration (Gordon 2012):

$$b(\lambda) = 0.3 \frac{550}{\lambda} C^{0.62}, \tag{10}$$

so the attenuation coefficient of natural seawater can be expressed as:

$$c(\lambda) = a(\lambda) + b(\lambda), \tag{11}$$

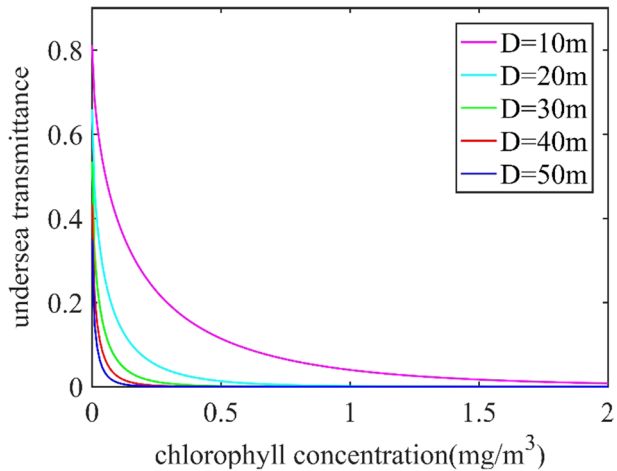
when the beam propagates in seawater, the transmittance of it can be expressed as:

$$T_{sea} = e^{-c(\lambda)D}, \tag{12}$$

where D is the depth of the propagation.

The underwater transmittance is shown in dependence of the chlorophyll concentration under different depth of the seawater in Fig. 5. Here the depth of the seawater is $D = 10 \text{ m}$, $D = 20 \text{ m}$, $D = 30 \text{ m}$, $D = 40 \text{ m}$, $D = 50 \text{ m}$, respectively. As can be seen from the figure, the transmittance decreases drastically with the increase of chlorophyll concentration. When the chlorophyll concentration remains fixed, with the increase of depth of propagation, the transmittance become small, gradually. Obviously, when the depth is set as 50 m, undersea transmittance trend to 0 quickly with the increasing of chlorophyll concentration.

Fig. 5 The values of depth and undersea transmittance are shown as a function of the chlorophyll concentration, where $D = 10 \text{ m}$, $D = 20 \text{ m}$, $D = 30 \text{ m}$, $D = 40 \text{ m}$, $D = 50 \text{ m}$



3 Entanglement transmission

In the following, we will introduce the calculation of Bell parameter briefly. The configuration of the Bell test experimental measurement is shown in Fig. 6. Parametric down-conversion source generates the entangled photon pairs, and then the entangled photon pairs are sent to receiver via composite channel. After receiving the beam through the telescope, the beam splitter is used to split the beam, and the corresponding polarization analyzer is used for processing. The polarization analyzers are composed of half-wave plates, which are utilized to change the polarization angles $\theta_A, \theta_B, D_{TA}, D_{TB}$ for the transmitted light and D_{RA}, D_{RB} for the reflected light (Fedrizzi 2009; Ekert 1991). The Bell test experimental configuration is originated from (Fedrizzi 2009; Ekert 1991) where the quantum states are transmitted through the atmospheric channel. Here the transmission channel is changed to composite free space channel that consists of atmospheric channel, sea surface channel and underwater channel. The schemes only consider the events that the photons left different output ports of the beam splitter in Fedrizzi (2009). Figure 6 (a) clicks at the reflection port in side A and the transmission port in side B, (b) clicks at the transmission port in the side A and the reflection port in the side B. and considering the additional 50% detection losses caused by the beam-splitters, the final expression of Bell parameter is same as the one in Huang and Zeng (2020).

The expression of Bell parameter is shown as:

$$B = \left| E(\theta_A^{(1)}, \theta_B^{(1)}) - E(\theta_A^{(1)}, \theta_B^{(2)}) \right| + \left| E(\theta_A^{(2)}, \theta_B^{(2)}) + E(\theta_A^{(2)}, \theta_B^{(1)}) \right|, \tag{13}$$

$E(\theta_A, \theta_B)$ is the correlation coefficient shown as

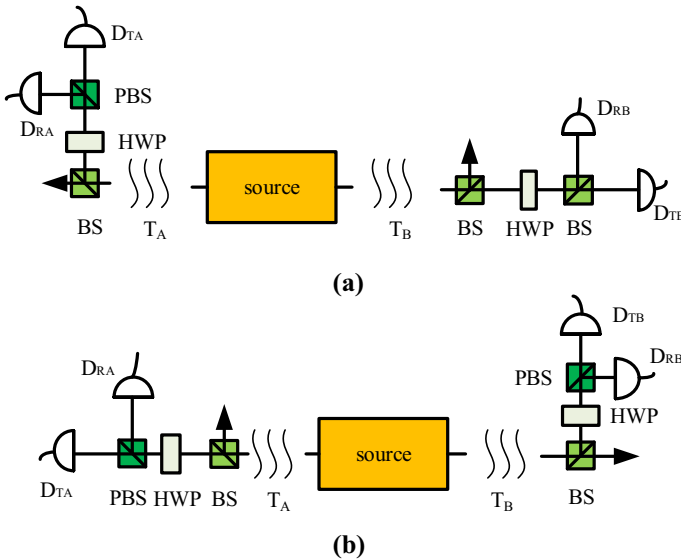


Fig. 6 **a** Clicks at the reflection port in side A and the transmission port in side B. **b** Clicks at the transmission port in the side A and the reflection port in the side B. The Bell test schemes. *BS* beam splitter, *PBS* polarizing beam splitter, *HWP* half-wave plates

$$E(\theta_A, \theta_B) = \frac{P_{same}(\theta_A, \theta_B) - P_{different}(\theta_A, \theta_B)}{P_{same}(\theta_A, \theta_B) + P_{different}(\theta_A, \theta_B)}, \tag{14}$$

where $P_{same}(\theta_A, \theta_B)$ is probability to get clicks on detectors in the same channels of polarization analyzers,

$$P_{same}(\theta_A, \theta_B) = P_{T_A, T_B}(\theta_A, \theta_B)P_{R_A, R_B}(\theta_A, \theta_B), \tag{15}$$

$P_{different}(\theta_A, \theta_B)$ is the probability to get clicks on detectors in different channels.

$$P_{different}(\theta_A, \theta_B) = P_{T_A, R_B}(\theta_A, \theta_B)P_{R_A, T_B}(\theta_A, \theta_B), \tag{16}$$

here $P_{i_A, i_B}(\theta_A, \theta_B)$ is the probability of registering clicks at the detectors, for polarization angles $\theta_A, \theta_B, i_A = \{T_A, R_A\}, i_B = \{T_B, R_B\}$.

According to the input–output relation of the quantum state and the characteristic function of it, we get the probability form of simultaneous clicks at both sides:

$$P_{i_A, i_B}(\theta_A, \theta_B) = (1 - \tanh^2 \chi)^4 \left[\left\langle \frac{\exp(-2N)}{C_0 + 2C_1 + C_{i_A, i_B}} \right\rangle - \left\langle \frac{2\exp(-3N)}{C_0 + C_1} \right\rangle + \left\langle \frac{\exp(-4N)}{C_0} \right\rangle \right], \tag{17}$$

where $\langle \cdot \rangle$ denotes averaging with respect to T .

$$\begin{aligned} C_0 &= \{ \eta^2 T^4 \tanh^2 \chi - [1 + (\eta T^2 - 1) \tanh^2 \chi]^2 \}^2, \\ C_1 &= \eta T^2 (1 - \eta T^2) (1 - \tanh^2 \chi) \tanh^2 \chi \{ \eta^2 T^4 \tanh^2 \chi - [1 + (\eta T^2 - 1) \tanh^2 \chi]^2 \}, \\ C_{T_A, T_B} &= C_{R_A, R_B} = \eta^2 T^4 \tanh^2 \chi [1 - \tanh^2 \chi] [(1 - \eta T^2)^2 \tanh^2 \chi - \sin^2(\theta_A - \theta_B)], \\ C_{T_A, R_B} &= C_{R_A, T_B} = \eta^2 T^4 \tanh^2 \chi [1 - \tanh^2 \chi] [(1 - \eta T^2)^2 \tanh^2 \chi - \cos^2(\theta_A - \theta_B)], \end{aligned} \tag{18}$$

where χ is the squeezing parameter. N is the mean number of stray-light and dark counts, $N = 5 \times 10^{-7}$. η is the detection efficiency, $\eta = 0.125$.

In this paper, we consider the transmission of beam through the composite channels. The transmission can be expressed as follow:

$$T = T_{air} T_{surface} T_{sea}. \tag{19}$$

The graph for squeezing parameters and Bell parameters is obtained by numerical simulation. Figure 7 demonstrates that the chlorophyll concentration have a great influence on Bell parameters. When the concentration of chlorophyll increases from 1 to 2 mg/m³ without changing other parameters, the Bell parameter decreases strikingly. In addition, incident angle and beam wandering variance also have effects on Bell parameters, but the levels of them on Bell parameters are less than that of chlorophyll concentration.

Figure 8 describes the relationship between squeezing parameters and Bell parameters under different receiving apertures of 0.11 m, 0.33 m and different chlorophyll concentrations of 1 mg/m³ and 2 mg/m³. We can find that when chlorophyll concentration remains unchanged, the Bell parameter can be improved by increasing the receiving aperture obviously. However, in comparison with the effect of chlorophyll concentration on Bell parameters, the change of aperture size has a small effect on Bell parameters. In practical communication, the natural characteristics including seawater including chlorophyll concentration, are difficult to be changed artificially and the communication performance can

Fig. 7 Bell parameter as a function of squeezing parameter under various chlorophyll concentration 1 mg/m^3 , 2 mg/m^3 , incident angles $\frac{\pi}{3}$, $\frac{\pi}{8}$ and beam wandering variance a , $4a$

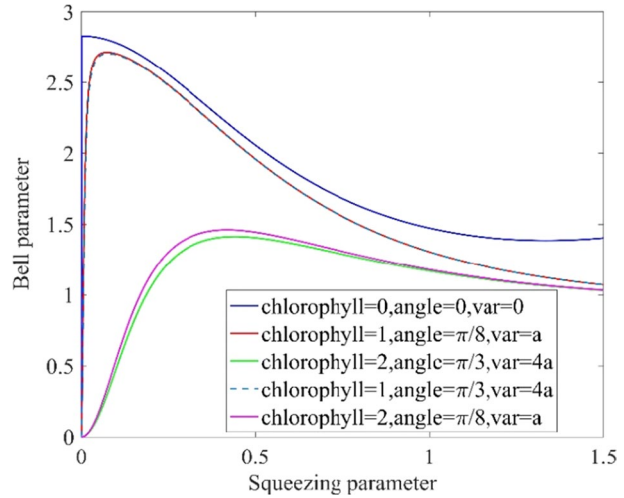
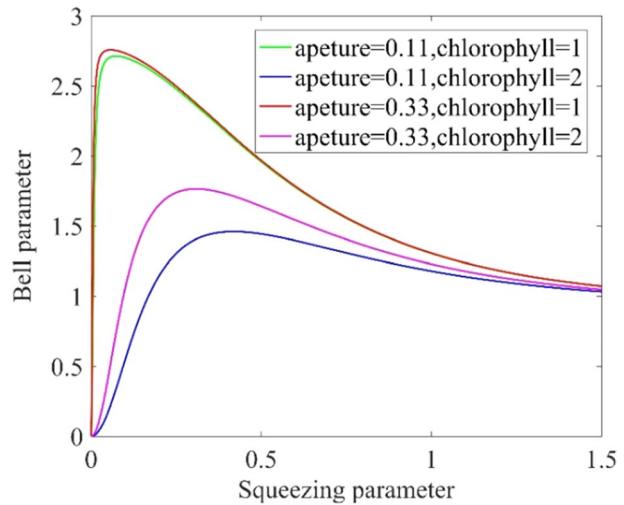


Fig. 8 The panel of Bell parameter and squeezing parameter under various chlorophyll concentration 1 mg/m^3 , 2 mg/m^3 , and different receiving apertures 0.11 m, 0.33 m



only be improved by enhancing the performance of equipment and optimizing protocols scheme. Therefore, it is more convenient and feasible to change the aperture size in practical application.

4 Conclusion and perspectives

The beam in the atmosphere is mainly affected by atmospheric turbulence, which will contribute to the beam wandering and broadening. Due to the fluctuation of sea surface and the change of transmission medium, the beam in sea surface is primarily affected by the incident angle. Seawater of overwhelmingly complex composition leads to badly severe

attenuation of the beam. In this paper, the properties of the beams in different transmission medium based on composite free space channel model are investigated. The alteration of entanglement photon pairs in the atmosphere, seawater surface and underwater channel are analyzed with numerical simulation. The results show that the entanglement is aggravated by the beam wandering and broadening, the incident angle of the beam, and the concentration of chlorophyll in the seawater. Compared with other influencing factors, the degradation of entanglement degree caused by the chlorophyll concentration is more obvious. In addition, the transmittance of light beam in seawater not only decreases with the increase of chlorophyll concentration, but also degenerates with the increase of propagation depth. It limits the propagation distance of light in seawater to some extent. Meanwhile, the results show that the aperture of the receiving telescope can regulate the entanglement of entanglement states. Amplifying the aperture of the receiving telescope, entanglement will be increased. This paper may shed light on studying the transmission of entanglement photon pairs in composite free space channel communication. In addition, this paper may play an auxiliary role in establishing multi-media composite channels and realizing the globalization of quantum communication.

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