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Article

Effect of Marine Planktonic Algal Particles on the Communication Performance of Underwater Quantum Link

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Abstract: As one of the main application directions of quantum technology, underwater quantum communication is of great research significance. In order to study the influence of marine planktonic algal particles on the communication performance of underwater quantum links, based on the extinction characteristics of marine planktonic algal particles, the influence of changes in the chlorophyll concentration and particle number density of planktonic algal particles on the attenuation of underwater links is explored respectively, the influence of marine planktonic algal particles on the fidelity of underwater quantum links, the generation rate of the security key, and the utilization rate of the channel is analyzed, and simulation experiments are carried out. The results show that with the increase in chlorophyll concentration and particle density of aquatic planktonic algal particles, quantum communication channel link attenuation shows a gradually increasing trend. In addition, the security key generation rate, channel fidelity and utilization rate are gradually decreasing. Therefore, the performance of underwater quantum communication channel will be interfered by marine planktonic algal particles, and it is necessary to adjust the relevant parameter values in the quantum communication system according to different marine planktonic algal particle number density and chlorophyll concentration to improve the performance of quantum communication.

Keywords: quantum communication; marine planktonic algal particles; channel fidelity; security key generation rate; channel utilization

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0 Introduction

Quantum mechanics and quantum information science have led to quantum communication. Quantum communication technology consists of two major technologies, quantum key distribution (QKD) and quantum invisible state transmission. When the information transmitter transmits a quantum state through a quantum link, quantum key distribution establishes a secure communication channel between the two sides of the communication by sharing a piece of cipher string between the transmitter and the receiver; and quantum invisible state transfer provides a complete and secure information transmission by consuming the resources of the quantum link and at the same time combining with the measurement of the Bell state of the entangled state[1]. Compared with traditional optical communication, quantum communication utilizes quantum superposition states and entanglement effects for high-performance information transfer, resulting in a significant increase in security, communication efficiency and anti-interference. Quantum communication has become one of the cutting-edge technologies of strategic significance, and has significant potential for application in marine science and the military.

In recent years, researchers have made breakthroughs in ground-to-star quantum communication. In 2002, Hughes' team completed the first free-space quantum key distribution experiment with a transmission distance of 10 km during the daytime[2]. In 2012, Nauerth et al. Experimentally proved that quantum key distribution technology can establish a reliable information exchange mechanism between fast-moving platforms such as aircraft and satellites[3]. In 2016, China successfully launched the quantum satellite "Mozi", which became the world's first space quantum science experiment satellite[4]. In September 2017, the "Beijing-Shanghai trunk line" of quantum confidential communication was officially opened and operated, and the experimental distance exceeded 1,200 km. The experimental distance exceeded 1,200 km, and the satellite-to-ground link with the "Mozi" quantum satellite was achieved[5]. In 2023, Yuan Zhiliang et al. achieved the first open architecture dual-field quantum key distribution system using the optical frequency comb technology, and completed the 615-km fibre-optic quantum key distribution experiment[6].

Underwater quantum communication is also booming along with marine science development, the continuous development of quantum communication technology, and the increasing improvement of sensor and optoelectronic technology. Therefore, conducting research on underwater quantum communication plays a significant role in promoting quantum communication development. In 2015, the University of Missouri[7] conducted research on digital key distribution in the marine environment. It verified that it is feasible to perform up to 60-metre-long BB84 protocol quantum key distribution in clear seawater. In 2017, Prof. Minxian Jin and his team at the Quantum Information Technology Research Centre of Shanghai Jiao tong University successfully observed experimentally that photon polarized quantum states and quantum entangled states can demonstrate quantum communication in seawater, which verified the feasibility of underwater quantum communication[8]. In 2020, Minxian Jin provided the basis for the underwater quantum key distribution in a clear seawater environment can be transmitted wirelessly. It lays the foundation for the next step in underwater high-dimensional quantum communication and quantum sensing[9]. Zongliang Liang et al[10] studied and analysed the performance of an underwater wireless optical communication system under the combined effect of ocean link loss, ocean optical turbulence and aiming error. Ruixi Liu et al[11] studied photon orbital angular momentum-based quantum communication in an underwater quantum channel subject to ocean turbulent motion. This provides a reference for underwater quantum communication performance and environmental parameter adjustment.

Different suspended particles in the ocean have a significant impact on the optical properties of seawater. Marine phytoplankton, as the main component of suspended particles in the ocean, has dual optical properties of absorption and scattering, which can affect underwater quantum communication to some extent. Anni Lehmuskero presented the discovery of light behavior in microalgae and demonstrated the special role of these microalgal populations in light interactions[12]. Yingluo Zhang investigated the effects of suspended particle (including algal particles) size and complex refractive index on received normalized energy, received light intensity, channel transmission length and channel delay during underwater laser transmission[13].This paper establishes the extinction coefficient model of marine planktonic algae particles based on the optical properties of marine planktonic algae particles. And explore the relationship between the chlorophyll concentration and particle number density of planktonic algal particles and the attenuation of underwater quantum communication links. Then we analyse the influence of oceanic planktonic algal particles on the fidelity, security key generation rate and channel Utilisation of underwater quantum communication links. We conduct simulation experiments.

1 Optical Properties of Marine Planktonic Algal Particles

In the study of underwater quantum communication, many complex marine phytoplankton scatter and absorb light quanta. This results in dramatic attenuation of light quantum signals in underwater transmission, which seriously affects communication quality. Phytoplankton in the ocean is composed of planktonic algae. As the chlorophyll contained in algae particles absorbs light, and the scattering characteristics of marine phytoplankton are mainly related to their particle size, density, and other factors. Therefore, the chlorophyll concentration and particle size distribution were chosen to establish the extinction coefficient model of planktonic algal particles. This was done to study marine planktonic algal particles' optical properties.

1.1 Extinction Characteristics of Chlorophyll Concentration in Planktonic Algal Particles

When light quanta are transmitted in seawater, the absorption and scattering of light quanta by chlorophyll in marine planktonic algal particles can seriously interfere with the quantum system. According to the model proposed by Bricaud and Loisel[14-16], the wavelength of incident light is λ, and there is a power function relationship between the chlorophyll concentration of the algal particles C_{chl} in the water and the absorption coefficient $a_{\mathrm{ph}}(\lambda)$ and scattering coefficient $b_{\mathrm{ph}}(\lambda)$, which is expressed as

$$a_{\mathrm{ph}}(\lambda) = 0.06A(\lambda)C_{\mathrm{chl}}^{0.65}, \tag{1}$$

$$b_{\mathrm{ph}}(\lambda) = b_{\mathrm{ph}}(550) \times (\frac{\lambda_0}{\lambda})^p, \tag{2}$$

where $A(\lambda)=A_{\mathrm{chl}}(\lambda)/A_{\mathrm{chl}}(440)$ is absorption rate, $A_{\mathrm{chl}}(\lambda)$ is the unit absorption coefficient, $A_{\mathrm{chl}}(440)$ is the absorption coefficient of chlorophyll per unit concentration at 440 nm; $b_{ph}(550)$ is the scattering coefficient of phytoplankton at a reference wavelength of 550 nm, so λ_0= 550 nm. Retrieve a value p=1, therefore $b_{ph}(550) = 0B_C C_{chl}^{0.62}$, B_C is a constant between 0.12 and 0.45, it takes the average value of 0.3, existing that

$$b_{ph}(\lambda) = 0.3 \times C_{chl}^{0.62} \times \frac{550}{\lambda}. \quad (3)$$

Then the extinction coefficient of the propagation of the photonic quantum signal in the environment of marine planktonic algal particles is expressed as

$$c_{ext1}(\lambda)=a_{ph}(\lambda)+b_{ph}(\lambda). \quad (4)$$

1.2 Extinction Characteristics of Particle Size Distributions of Marine Planktonic Algal Particles

Particles of different sizes in the water column absorb and scatter light to different degrees, so particle size distribution models are used to describe the number distribution of particles of different sizes. For suspended particulate matter in natural waters, the Junge-type particle size distribution model[17] is most commonly used, which describes the number concentration of particles as a function of particle diameter, expressed as

$$N(D) = N_{ph} D^{-\varsigma}, \quad (5)$$

where D is diameter of the particles; N_{ph} is the number of particles per unit volume. The value determines the order of magnitude of the particulate matter and is related to the concentration of the particles, with larger values indicating a higher number of particles and a higher mass concentration. ζ is the slope of the particle size distribution. The typical values of ζ for marine particle populations range from 3 to 5, with a general value of 4[18].

When the light quantum signal is transmitted underwater, the influence of marine planktonic algae particles will inevitably produce extinction effects. According to the Mie scattering theory, the planktonic algae particles are equivalent to a spherical shape, and when the wavelength of incident light is, the relationship between the extinction cross section of unpolarised natural light σ_{ext} and a_n, b_n is as follows

$$\sigma_{ext} = \frac{\lambda^2}{2\pi}\sum_{n=1}^{\infty}(2n+1)\mathrm{Re}\{a_n + b_n\}, \quad (6)$$

where a_n, b_n is the Mie scattering coefficient; Re(·)is for taking the real part of the operation. The extinction efficiency factor reflects the ability of particles to scatter light and is an important factor influencing the magnitude of the extinction coefficient of planktonic algal particles. By comparing the actual scattering cross-section of the particle σ_{ext} to the geometric cross-section of the particle πr^2, the extinction efficiency factor of the particle K_{ext} is obtained[19], and hence the extinction efficiency factor is expressed as

$$K_{ext} = \frac{4\sigma_{ext}}{\pi D^2} = \frac{2\lambda^2}{\pi^2 D^2}\sum_{n=1}^{\infty}(2n+1)\mathrm{Re}\{a_n + b_n\}. \quad (7)$$

From Eq. (7), the extinction efficiency factor is a function of incident wavelength, particle scale, and complex refractive index. The extinction coefficient of planktonic algal particles is expressed as

$$c_{ext2} = \frac{\pi}{4}\int_{D_{min}}^{D_{max}} N(D)K_{ext}D^2 \mathrm{d}D = \frac{\pi}{4}\int_{D_{min}}^{D_{max}} N_{ph}K_{ext}D^{-2}\mathrm{d}D, \quad (8)$$

where D_{min}=0.2 um, D_{max}=100 um are the minimum and maximum algal particle diameters, respectively. From Eq. (8), it can be seen that, using the Mie scattering theory, according to the radius size and scale distribution of planktonic algal particles in seawater to find the scattering efficiency factor K_{ext}, combined with the extinction cross-section of the relational equation can be calculated for the extinction coefficient of planktonic algal particles in seawater.

Similar to the atmospheric window region[20], the attenuation coefficient of light waves between 440 and 660 nm is smaller when transmitted in seawater channels, so the blue-green laser band is the "light transmission window" for laser transmission in seawater channels. When the incident wavelength is 440 nm and 660 nm, the absorption efficiency of planktonic algal particles is faster and the scattering efficiency is lower; when the incident wavelength is 580 nm, the scattering efficiency of planktonic algal particles is faster and the absorption efficiency is lower[21]. Therefore, the incident wavelengths of 440 nm, 580 nm and 660 nm were selected, and the extinction coefficients of the planktonic algal particles at different wavelengths were simulated according to Eq. (4) and Eq. (8), and the results were shown in Figs.1–2.

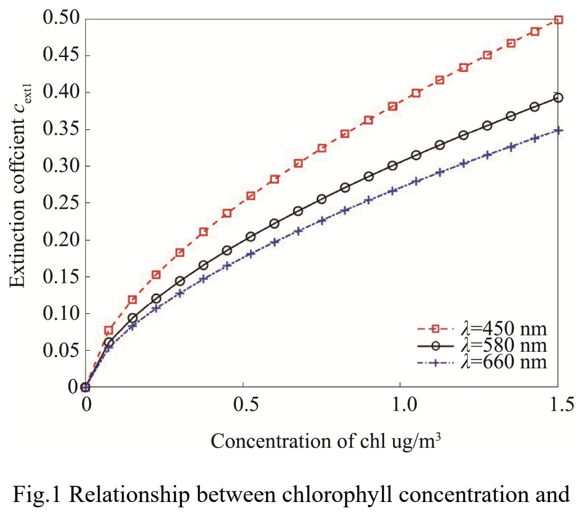

Fig.1 Relationship between chlorophyll concentration and scattering coefficient of algal particles at different wavelengths

In Fig.1, the chlorophyll concentration ranges from 0 to 1.5 ug/m^3, and the extinction coefficient gradually increases with the increase of chlorophyll concentration when the incident wavelength is certain. The larger the incident wavelength, the more significant the trend of the extinction coefficient of planktonic algal particles with the increase of chlorophyll concentration. In Fig.2, the number density of particles ranges from 0 to 10×10^6/m^3, and the extinction coefficient gradually increases with the increase of the number density of planktonic algal particles when the incident wavelength is certain. The larger the incident wavelength, the more significant the trend of the extinction coefficient of the planktonic algal particles with the increase of particle density. Therefore, the chlorophyll concentration and population density of marine planktonic algal particles have a great influence on the extinction characteristics of planktonic algal particles, and the change of incident light wavelength also affects the extinction effect of planktonic algal particles.

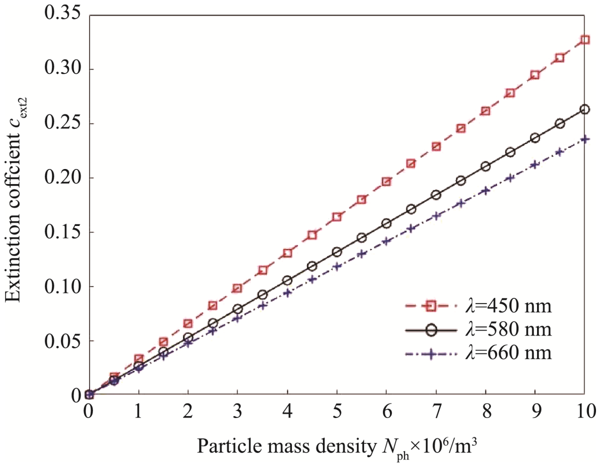

Fig.2 Relationship between particle density and extinction coefficient of planktonic algae at different wavelengths

2 Effects of Marine Planktonic Algal Particles on the Attenuation of Underwater Quantum Communication Links

When the optical quantum signals sent by the transmitter of a quantum communication system are transmitted between communication links in the marine environment, the photon energy is attenuated due to the absorption and scattering effects of planktonic algal particles. When the optical quantum signal is transmitted in seawater, the energy attenuation due to marine planktonic algal particles[22] is expressed as follows

$$I=I_0\exp(-c_{\text{exti}}\cdot L), \quad (9)$$

where L is the transmission distance of the quantum signal, I is the remaining energy after the underwater transmission distance, and I_0 is the energy of the quantum signal at the initial moment. Using logarithmic operation, the link attenuation factor caused by the planktonic algae particles during the transmission of the optical quantum signal in the underwater channel is

$$Q_{att}=10\cdot\lg\frac{I_0}{I}=10\cdot L\cdot c_{\text{exti}}\cdot\lg e\,. \quad (10)$$

Selection of the incident wavelength of the optical signal λ=580 nm. According to Eq. (10), numerical simulations of the effects of marine planktonic algal particles chlorophyll concentration, particle population density and transmission distance on link attenuation were carried out, respectively, and the results are shown in Figs.3, 4.

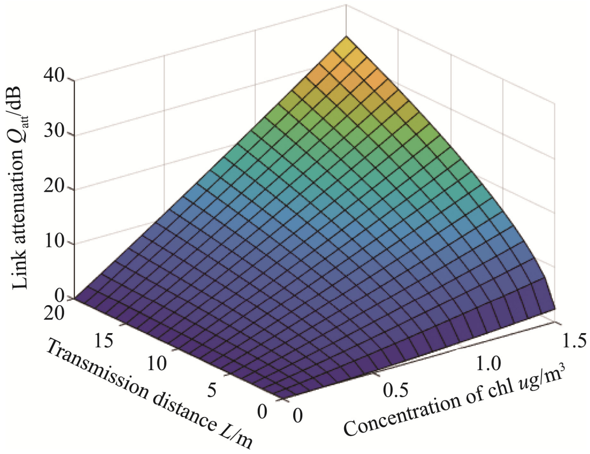

Fig.3 Relationship among link attenuation, chlorophyll concentration of marine planktonic algae and transmission distance

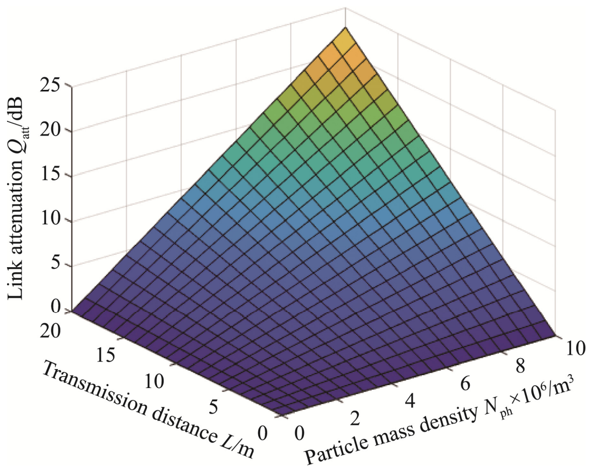

Fig.4 Relationship among link attenuation, particle number density of marine planktonic algae and transmission distance

As can be seen in Fig.3, when the chlorophyll concentration is 0.6 ug/m^3, the transmission distance is increased from 10 m to 20 m, and the link attenuation increases from 8.792 dB to 23.040 dB; when the transmission distance is 15 m, and the chlorophyll concentration is boosted from 0.75 ug/m^3 to 1.5 ug/m^3, the link attenuation is raised from 14.050 dB to 28.950 dB; and when the link attenuation reaches the maximum value of 34.140 dB. It can be seen that the transmission of the quantum communication link is greatly affected by the increase in transmission distance and chlorophyll concentration.

As can be seen in Fig.4, when the particle number density of particles is 6×10^6/m^3, the transmission distance increases from 10 m to 20 m, and the link attenuation increases from 6.836 dB to 13.670 dB; when the transmission distance is 10 m and the particle number concentration increases from 4×10^6/m^3 to 10×10^6/m^3, the link attenuation increases from 4.558 dB to 11.390 dB;

and the link attenuation reaches a maximum value of 22.97 dB when L=20 m and $N_{ph}=10\times10^6/m^3$. From the simulation results, it can be seen that with the increase of transmission distance and particle number concentration, the optical quantum energy is attenuated, which leads to the increase of link attenuation in quantum communication.

3 Effects of Marine Planktonic Algal Particles on the Fidelity of Underwater Quantum Communication Links

The fidelity describes how similar the state of the quantum signal after output is to the initial state. The fidelity of an optical signal after transmission through a channel is defined as[23]

$$F=\mathrm{Tr}(\boldsymbol{\rho}^{1/2}\boldsymbol{\rho}'\boldsymbol{\rho}^{1/2})^{1/2}, \tag{11}$$

where $\boldsymbol{\rho}$ is the final state of the quantum state interacting with the free-space environment, and $\boldsymbol{\rho}'$ is the evolution of the density operator after the input character. Let the quantum system$\{p_i, \boldsymbol{\rho}_i\}$, denote the probability that the quantum system is in state $\boldsymbol{\rho}_i$ as p_i, and the input characters $\boldsymbol{\rho}_1=|0\rangle\langle 0|, \boldsymbol{\rho}_2=|1\rangle\langle 1|$. There are

$$\boldsymbol{\rho} = p_1\boldsymbol{\rho}_1 + (1-p_1)\boldsymbol{\rho}_2 = \begin{bmatrix} p_1 & 0 \\ 0 & 1-p_1 \end{bmatrix}, \tag{12}$$

$$\boldsymbol{\rho}' = \begin{bmatrix} \dfrac{p_1+2(1-p_1)p}{2} & 0 \\ 0 & \dfrac{p_1+2(1-p_1)(1-p)}{2} \end{bmatrix}, \tag{13}$$

where p is the probability of losing a light quantum during quantum link transmission due to the influence of marine planktonic algal particles, $p=1-\exp(-c_{exti}\cdot L)$. The fidelity of the channel is obtained as

$$\begin{aligned} F=\mathrm{Tr}(\boldsymbol{\rho}^{1/2}\boldsymbol{\rho}'\boldsymbol{\rho}^{1/2})^{1/2} &= \mathrm{Tr}\begin{bmatrix} \sqrt{p_1\left(\dfrac{p_1+2(1-p_1)p}{2}\right)} & 0 \\ 0 & \sqrt{(1-p_1)\left(\dfrac{p_1+2(1-p_1)(1-p)}{2}\right)} \end{bmatrix} \\ &= \sqrt{\frac{p_1}{2}+(1-p_1)pp_1} + \sqrt{\frac{p_1}{2}+(1-p_1)(1-p)(1-p)} \end{aligned} \tag{14}$$

Taking p_1 as 0.1, the relationship between planktonic algal particles at different chlorophyll concentrations or particle number densities, transmission distances and quantum channel fidelity was simulated and the results are shown in Fig.5~6.

In Fig.5~6, the X-axis represents the chlorophyll concentration and particle number density of the planktonic algal particles; the Y-axis is the transmission distance; and the Z-axis is the quantum channel fidelity, with a range of 0.3~1. From Fig.5~6, we can see that, with the higher chlorophyll concentration and particle number density of the planktonic algal particles in the ocean and the increase of the transmission distance, the more extinction effect is stronger, and the more distortion of the state of the quantum signal output, the greater the impact on the channel fidelity, and the more the channel fidelity is decaying. The more powerful the effect, the channel fidelity decays. When the transmission distance is small, the fidelity with chlorophyll concentration trend is more significant, with the particle number density increasing and the attenuation trend is more gentle; when the transmission distance is more than 10 m, the fidelity with chlorophyll concentration increases and the trend slows down, with the particle number density changing and the trend is faster. At L=20 m, the channel fidelity reaches a minimum value of 0.334 at $C_{chl}=1.5$ ug/m^3; the channel fidelity reaches a minimum value of 0.374 at $N_{ph}=10\times10^6/m^3$.

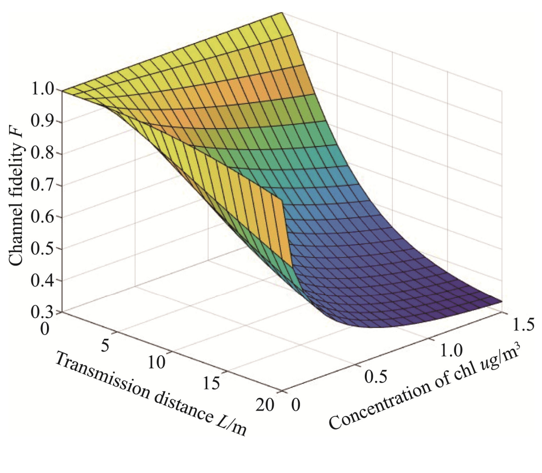

Fig.5 Relationship among channel fidelity, chlorophyll concentration marine planktonic algal and transmission distance

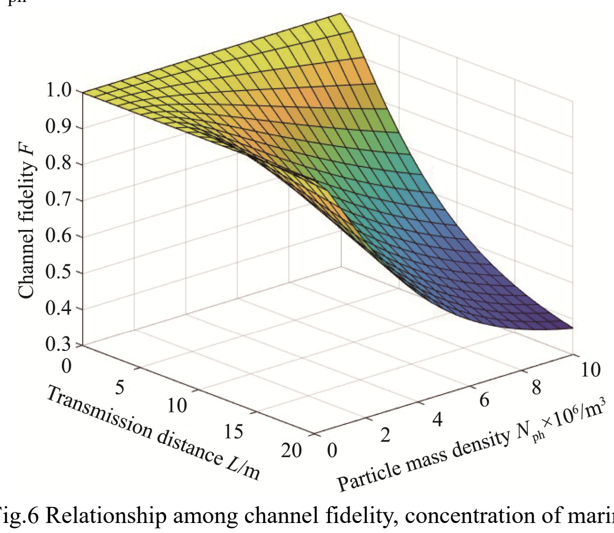

Fig.6 Relationship among channel fidelity, concentration of marine planktonic algal and transmission distance of marine algal particle

4 Effects of Marine Planktonic Algal Particles on the Security Key Generation Rate of Underwater Quantum Communication Links

Security key generation rate is one of the key parameters to measure quantum communication performance. Based on the BB84 protocol, the quantum key distribution system generally adopts a weak coherent state light source instead of an ideal single photon source. The signal photons are measured in the Bell state after the encoding, and the number of its photons obeys the Poisson distribution. Then the probability of containing one photon in each light quantum pulse[24] is

$$P(n) = \exp(-x)\frac{x^n}{n!}, \tag{15}$$

where n represents the number of photons and x represents the optimal value of the average optimal number of photons for the light source.

In an underwater quantum communication system, the secure key generation rate for quantum key distribution can be expressed as[25]

$$R \geqslant \alpha Y_1[1-H(e_1)]-Q_u f(E_u)H(E_u), \tag{16}$$

where α is the transmission efficiency of a single-photon pulse from the transmitter to the receiver; Y_1 is the single-photon count rate, e_1 is the single-photon BER; Q_u and E_u are the total count rate and BER of the system at the transmitter signal state, respectively; $f(E_u)$ is the error-correction efficiency function; $H(x)$ is the binary Shannon entropy function, $H(x)=-x\log_2 x-(1-x)\log_2(1-x)$.

According to the BB84 quantum key distribution protocol, the passage rate η_n of the pulse when n photons are transmitted in an underwater channel is expressed as

$$\eta_n = 1-(1-\eta_p)^n, \tag{17}$$

Where η_p is the transmission efficiency of the optical signal under the influence of the marine planktonic algal particle environment, which is related to the attenuation coefficient of the planktonic algal particles, expressed as

$$\eta_p=10^{-(Q_{att}\cdot L)/100}. \tag{18}$$

Considering the dark counts at the receiving end of the communication system, the count rate and BER of a single photon at the receiving end is expressed as

$$Y_n=\eta_t(\eta_n+Y_0-\eta_n Y_0), \tag{19}$$

$$e_n = \frac{e_0 Y_0 + e_t(1-\eta_n)}{Y_n} = \frac{e_0 Y_0 + e_t(1-\eta_n)}{\eta_t(\eta_n + Y_0 - \eta_n Y_0)}, \tag{20}$$

Where η_t is the detection efficiency of the detector; Y_0 is the dark count rate of the single-photon detector; e_0 is the BER caused by background optical noise; and e_t is the BER caused by detector noise.

Then the total count rate and BER of the system for a single photon state signal (n=1) are denoted as

$$Q_u=Y_1 P(n=1)= \eta_t(Y_0+\eta_p-Y_0\eta_p)x\exp(-x), \tag{21}$$

$$E_u = \frac{e_0 Y_0 + e_1[1-\exp(-\eta_p x)]}{Q_u}. \tag{22}$$

In the working process of quantum key distribution system, the size of the security key rate is closely related to the system parameters, and the values of some parameters are as shown in Table 1[26].

Table 1 Parameters values of the system security key generation rate

Parameter	x	α	$F(E_u)$	η_t	e_t	Y_0	e_0
Value	0.1	0.5	1.16	0.4	1.5%	10^{-5}	0.5

In summary, the relationship between planktonic algal particles at different chlorophyll concentrations or particle number densities, quantum state transmission distances and quantum security key generation rates is simulated and calculated, and the results are shown in Fig.7~8.

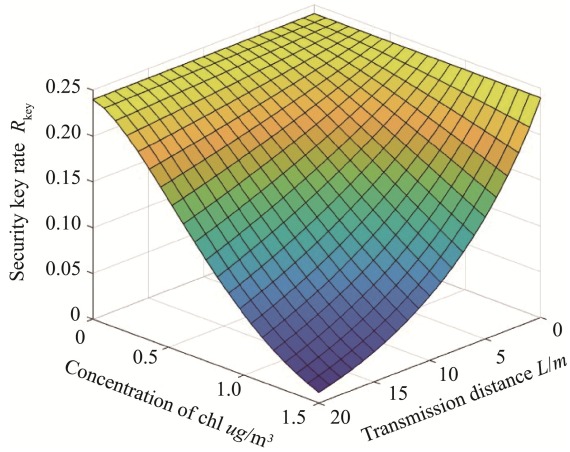

Fig.7 Relationship among security key generation rate, chlorophyll concentration of marine planktonic algal particles and transmission distance

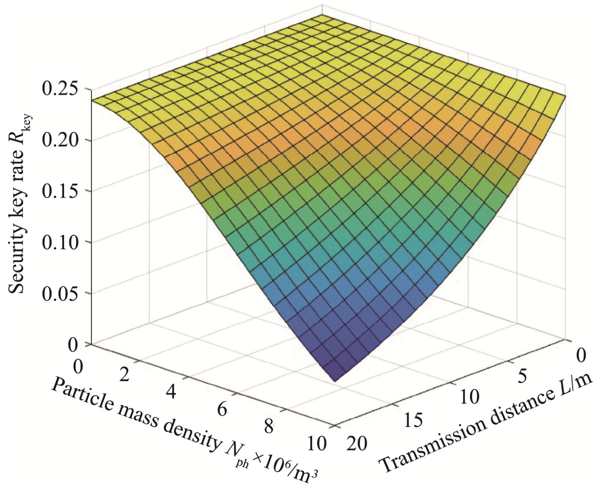

Fig.8 Relationship among security key generation rate, particle number density of marine planktonic algae and transmission distance

As shown in Fig.7,8, the influence of chlorophyll concentration of planktonic algal particles, particle number density, and transmission distance of light quanta during channel transmission all leads to quantum security key rate attenuation. When the chlorophyll concentration and particle number density of the particles are small, the generation of security keys is less affected by transmission distance. With the increase in chlorophyll concentration and particle number density of planktonic algal particles, the effect of transmission distance on security key rate is gradually significant. When the transmission distance is 20 m, the security key generation rate decreases from 0.240 to 0.012 when the chlorophyll concentration of planktonic algal particles increases from 0 ug/m^3 to 1.5 ug/m^3; and the security key generation rate decreases from 0.240 to 0.043 when the particle number density of planktonic algal particles increases from 0×10^6/m^3 to 10×10^6/m^3. It can be seen that the security key generation rate can be improved by reducing the chlorophyll concentration and particle number density of planktonic algal particles.

5 Effects of Marine Planktonic Algal Particles on Underwater Quantum Communication Channel Utilization

In a quantum communication link, assuming that the length of each data frame is fixed, the transmission time is t_d, the voice response delay is t_b, the transmission delay interval is t_a, and the transmission period of each data frame can be denoted as $t_d+t_a+t_b+t_a$. The average number of times a data frame is transmitted (the first time is the initial transmission state, and the rest is the repeated transmission state) is denoted as d. Given an arbitrary data frame, it must be retransmitted several times to ensure the successful transmission of the data frame, taking N to denote the total average number of transmissions of this data frame (the first time is the initial transmission state, and the remaining N–1 is the repetitive transmission state). N is expressed as

$$N = \sum_{n=1}^{\infty} n r^{n-1}(1 - r') = \frac{1}{1 - r'}, \quad (23)$$

where r' is the BER of the information bit and is taken as r=0.05. The average link utilization when transmitting in a quantum channel can be obtained as[27]

$$U = \frac{t_d}{N(t_d + t_a + t_b + t_a)} = \frac{1 - r'}{1 + 2\frac{t_a}{t_d} + \frac{t_b}{t_d}}. \quad (24)$$

When optical quantum signals are transmitted over an underwater quantum communication channel, the quantum channel link utilization under the influence of chlorophyll from planktonic algal particles is defined as

$$U_{\mathrm{chl}} = \alpha \frac{1 - r'}{1 + \frac{C_{\mathrm{chl}}}{C_{\mathrm{m}}} + \frac{\lambda}{\lambda_{\mathrm{m}}} + \frac{L}{L_{\mathrm{m}}}}, \quad (25)$$

where C_{m} is the maximum value of the chlorophyll concentration range of planktonic algal particles, take C_{m}=1.5 ug/m^3; λ_{m} is the maximum value of the wavelength range of incident light in seawater, take λ_{m}=800 nm; L_{m} is the maximum value of the transmission distance range of underwater quantum communication, take L_{m}=200 m. Considering that the extinction coefficient of the chlorophyll concentration is greatly affected by the wavelength, therefore, take L=10 m. Numerical simulation is carried out on the relationship between the utilization rate of the quantum channel, chlorophyll concentration of planktonic algal particles in the ocean and the wavelength of the incident light and the results are shown in Fig.9.

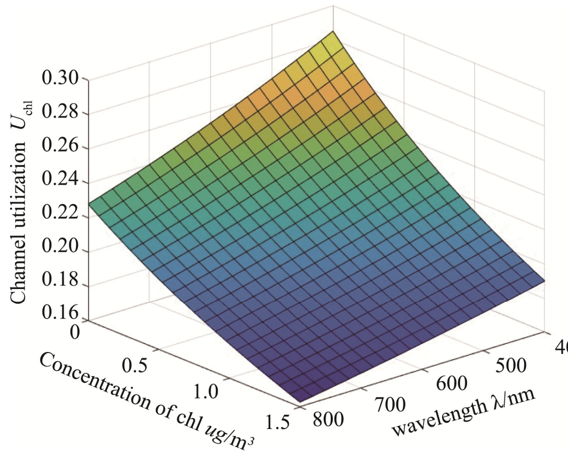

Fig.9 Relationship among channel utilization, chlorophyll concentration of marine phytoplankton particles and incident light wavelength

As can be seen in Fig.9, when the chlorophyll concentration of planktonic algal particles remains constant, with the increase of incident light wavelength, the transmittance of light quanta through the environment of marine planktonic algal particles decreases, and the quantum channel utilization also decreases; when the incident light wavelength is kept constant, with the increase of the chlorophyll concentration, the greater the absorption effect caused by photosynthesis of planktonic algal particles, the quantum channel utilization deteriorates substantially, and the channel utilization is The channel utilization rate is greatly affected by the chlorophyll concentration of the algal particles and decays faster with the change of chlorophyll concentration. The channel utilization reaches a minimum value of 0.163 at L=20 m and C_{chl}=1.5 ug/m^3.

When optical quantum signals are transmitted over an underwater quantum communication channel, the quantum channel link utilization subject to the number density of planktonic algal particles is defined as

$$U_N = \alpha \frac{1 - r'}{1 + \frac{N_{\mathrm{ph}}}{N_{\mathrm{phm}}} + \frac{\lambda}{\lambda_{\mathrm{m}}} + \frac{L}{L_{\mathrm{m}}}}, \quad (26)$$

where N_{phm} is the maximum value of the range of planktonic algal particle number density, take N_{phm}= 10×10^6/m^3. Considering that the extinction coefficient of the planktonic algal particle number density is less affected by the wavelength, take λ=580 nm. Numerical simulation of the relationship between quantum channel utilization and the density of planktonic algal particles in the ocean and the transmission distance is carried out, and the results are shown in Fig.10.

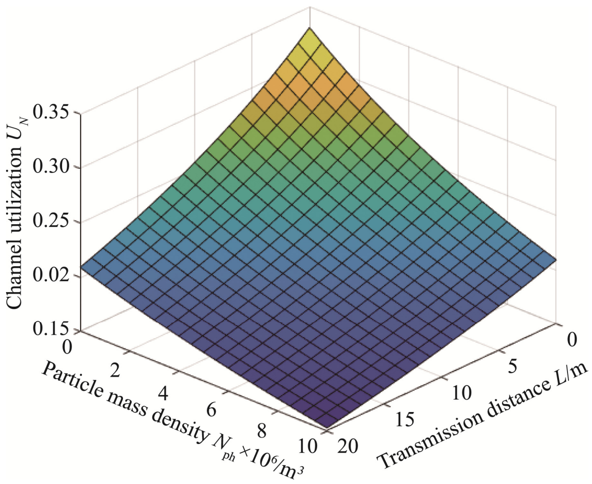

Fig.10 Relationship among channel utilization, particle number density of marine planktonic algae and transmission distance

As shown in Fig.10, when the number density of planktonic algal particles is kept constant, the channel utilization decreases as the transmission distance increases; when the transmission distance is kept constant, as the number density of planktonic algal particles increases, the more absorption and scattering effect occurs when the light quantum passes through the environment of marine planktonic algal particles, and the channel utilization decreases greatly. At L=20 m and N_{ph}=10×10^6/m^3, the channel utilization reaches a minimum value of 0.153.

Therefore, under the influence of marine planktonic algae particles, to ensure a better performance of quantum communication, it can be adjusted according to the size of the chlorophyll concentration and particle number density of planktonic algae particles as well as the wavelength of light to obtain better channel utilization.

7 Conclusion

In this paper, the effects of marine planktonic algal particles on underwater quantum communication links are investigated. Based on the Bricaud and Loisel models and the Mie scattering theory, the relationship between the extinction coefficient of marine planktonic algal particles and the variation of chlorophyll concentration and particle size distribution under different incident wavelengths is Based on the extinction characteristics of ocean planktonic algal particles, the relationships between chlorophyll concentration and particle number density of planktonic algal particles and link attenuation, channel fidelity, security key generation rate and channel utilization are established and simulated.

The results show that with the increase in chlorophyll concentration and particle number density of marine phytoplankton particles, the attenuation of the quantum communication link show an increasing trend, while generation rate of secure keys, channel fidelity and utilization rates exhibit varying degrees of decline. Moreover, compared with other parameters, the influence of changes in chlorophyll concentration of marine phytoplankton particles is more significant, leading to greater interference with communication quality. In contrast, the change in the planktonic algal particles' chlorophyll concentration in the ocean has a more significant impact on the link parameters. This interferes with the quality of communication more. Therefore, the effects of chlorophyll concentration and particle number density of planktonic algal particles on the performance of the communication link, especially the effect of chlorophyll concentration, must be fully considered when performing underwater quantum communication.

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All data supporting the results of this study are included in the manuscript and are available upon request.

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