Simulation of decoherence in EIT storage and Research on effective information storage

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Keywords: Quantum storage, Electromagnetically induced transparency, Quantum informatics.

Abstract: Quantum storage is an important part of quantum information science. It is the core technology of using quantum logic gate to process quantum information, store, transform and control quantum information. Quantum storage technology is considered as the core technology of storage, transformation and control of quantum information, together with the quantum logic gate. In this paper, we introduce the basic principle of quantum memory, and electromagnetically induced transparency process and the different methods of quantum storage and the performance of them.

1. Introduction

Quantum storage is an essential part of quantum informatics, is regarded as the core technology with storing, transforming and controlling quantum information with quantum logic gates that process quantum information. It is the foundation of efficient quantum communication. In life, information has become an indispensable part.as a result, achieving high density, high speed, good security communication has become the main goal of communication. In classic cases, Calculation and information transmission are completed by the variation of electric potential inside the device. However, the quantum computing, communication, storage is able to guarantee it's high security, better data processing capability and greater information density. In the process of communication, an indispensable procedure would be the storage of information. However, because of the no-cloning theorem of quantum information, the traditional storage methods would destroy the integrity of information. As a result of that, it is needed to find other methods to save those information. At present, the relatively effective method is to use EIT effect, which means that under the action of coupling light, photons can be stored inside atoms as the form of dark-state polariton. Nowadays, it is still challenging using the method since there's an effect called the quantum de-coherence, which prevent us from long time storage of quantum.

This paper is divided into the following parts: the introduction of quantum memory, the basic principle of quantum memory, research methods and objectives, 1EIT introduction and current research needs, Specific research, Result analysis.

2. The basic principle of quantum memory

Quantum memory is the high efficiency, high fidelity storage of quantum information. Basically, it's developed to serve for the indispensable part of quantum communication—the quantum repeater. The development of quantum memory, solved some of the problems in quantum communication. Quantum communication is a part of quantum informatics, absolutely safe in principle. Because if we sent a single quantum state(single photon), the eavesdropper intercepted it, do the quantum measurement and sent a fake one, because the measurement would interfere the quantum state, and the single measurement cannot get all the information, the fake photon can be identified. On another hand, unknown quantum state is not able to clone. It will be illustrated as follows：

Given unitary operators U that can replicate unknown quantum state $|\psi\rangle$ to target bit $|S\rangle$ ：

$$|\psi\rangle \otimes |S\rangle \xrightarrow{U} U(|\psi\rangle \otimes |S\rangle) = |\psi\rangle \otimes |\psi\rangle \quad (1)$$

Again, to unknown state $|\phi\rangle$ we have :

$$|\phi\rangle \otimes |S\rangle \xrightarrow{U} U(|\phi\rangle \otimes |S\rangle) = |\phi\rangle \otimes |\phi\rangle \qquad (2)$$

Calculate the inner product:

$$|\langle \psi | \phi \rangle| = |\langle \psi | \phi \rangle|^2 \qquad (3)$$

We can find that if we want the equation above holds, ψ must equal to or perpendicular to ϕ. So, the clone of unknown quantum state is impossible.

In quantum communication, during the process of single photon transmission, the signal decays exponentially with the propagation distance, which will cause the low efficiency of transmit signals from long distance. In the classic state, This problem can be solved by repeaters that amplify the signal in the middle of propagation. However, because state cannot be cloned, we need to find another method in order to make the quantum repeaters and thus achieve the high efficiency communication.

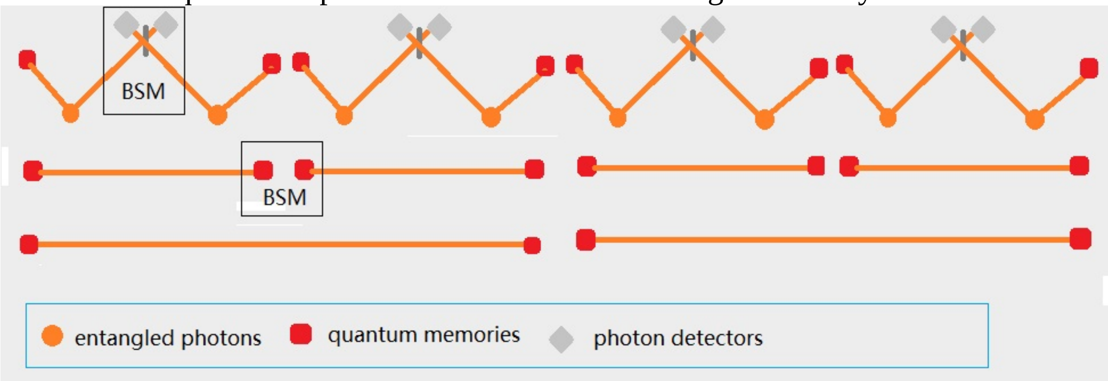

Figure 1 Quantum repeating process

As shown in the figure 1. In the quantum repeating process, we need to upload the state to the quantum memory on the repeater before the signal decays to the threshold. During the process, the transmission distance is divided into small parts. We separate and send entangled photons, one to the memory and the other to measure the Bell state.Before the next transmission link is ready, a quantum will be stored to obtain a longer link.At present, the methods of quantum storage include EIT storage, DLCZ storage and so on.

3. EIT introduction and current research needs

Among them, EIT (electromagnetically induced transparency) is a phenomenon that under the action of external electromagnetic waves, the medium that can absorb optical signals is transparent or greatly reduces the absorption rate.Electromagnetic waves, known as coupling light, have the effect of opening a gap in the Lorentz linear optical absorption line of atoms.The process involves three energy levels, In theory, it can be considered that there are two channel from energy level $|g\rangle$ to $|e\rangle$. the first one is $|g\rangle \to |e\rangle$, the other one is $|g\rangle \to |e\rangle \to |s\rangle \to |e\rangle$. it can be understood as the coherent cancellation of two paths, so the transition will not occur and the medium is transparent.

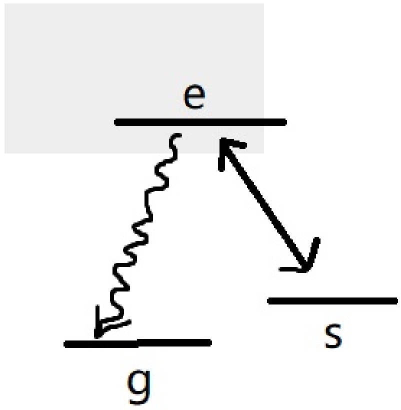

Figure 2 Electromagnetically induced transparency

It has been found that based on this mechanism, the refractive index of the medium can be controlled, the speed of light in the medium can be controlled, so as to realize the operation of slow light and stop light, which can be applied to the storage of photons.

When the light pulse propagates in the medium, its group velocity can be expressed as follows:

$$\mathrm{V_g} = \frac{\mathrm{d}\omega_{\mathrm{p}}}{\mathrm{dk}} = \frac{\mathrm{c}}{\mathrm{n} + \omega \frac{\mathrm{dn}}{\mathrm{dw}}} \tag{4}$$

In the above formula, C represents the speed of vacuum light and N is the refractive index of the medium, $\frac{\mathrm{dn}}{\mathrm{dw}}$ is the change index of refractive index of medium with light frequency.When it is in the EIT window and in the resonance frequency, the refractive index will change and result in the denominator $\mathrm{n} + \omega \frac{\mathrm{dn}}{\mathrm{dw}}$ far less than one. the group velocity of light in the medium is reduced.So we can achieve the storage of optical signal. Therefore, because of this effect, quantum relay and efficient quantum communication are possible.

In 2000, M.Fleischaueret. Proposed the dark state polarizer theory to explain its propagation and proposed the related storage scheme. In 2001, Liu team successfully used EIT process to store and release optical signals in sodium medium. The storage time was 1.5 Ms.In recent years, the efficiency of optical storage has been improved, and the life of optical storage has been increasing. In 2013, Du Shengwang and Yu Yide improved the storage efficiency to seventy eight percent. It provides the possibility and good experimental basis for future quantum communication and storage.However, EIT cannot be stored for a long time because of quantum decoherence. There are three main approaches, Amplitude damping channel, Phase damping channel, and Depolarization channel. In this paper, decoherence process is added in EIT process, and the specific equation is used:

$$\frac{\mathrm{d}\rho}{dt} = \frac{1}{i}[H, \rho] - \kappa(a^{+}a\rho + \rho a a^{+} - a\rho a^{+} - a^{+}\rho a) \tag{5}$$

In the equation, κ is the attenuation coefficient, H is the Hamiltonian of the system, $a^{+}(a)$ is generation (annihilation) operator for light field.The influence of decoherence on EIT process is simulated by Mathematica software.

3.2Specific research

In the calculation, the two energy levels are known as follows:

$$i\frac{dA(t)}{dt} = B(t)\Omega_{AB}(t)\cos(\omega_{AB}t)e^{i(E_A - E_B)t} \tag{6}$$

Ω AB the coupling light’s coupling in it, is described as the function $\Omega = ae^{-(x-b)^2/2c^2}$,Among them, a,b and c are variable coefficients.Here, the frequency is taken as 5, and the three energy levels E1, E2 and E3 are taken as 0, 5 and 10 respectively, which is convenient for calculation. Coupling light is Gaussian light.

Using the numerical method to find the solution of differential equations, the calculation results need to take the square of the modulus is equal to the probability in this state.Draw the image.

4. Results and conclusion

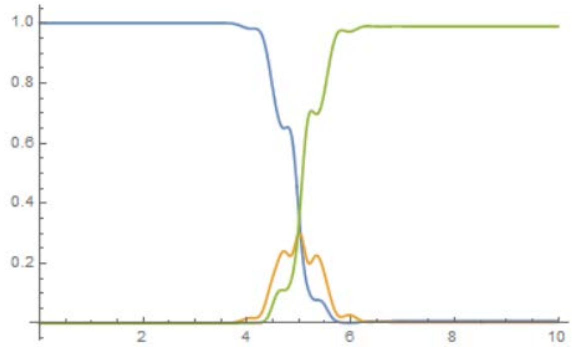

Figure 3 The probabilities of three energy levels

The three colored lines represent the probabilities of three energy levels, as shown in figure 3. The initial condition is that the quantum is in the first level, and the level two and three are zero. The value of the first energy level at the beginning is equal to that at the end of the process, the value of the three energy levels is equal to one, which indicates that the whole process keeps the quantum adiabatic, and no external factors such as loss are added. The inflection point in the image is mainly affected by the duration of the control light and other factors. Adjusting the duration of the control light can partially alleviate this phenomenon.

It can be seen that after the de-coherence effect is added to the EIT simulation in matrix form, the change of the size relationship between the reduce rate and Omega can lead to three representative results.

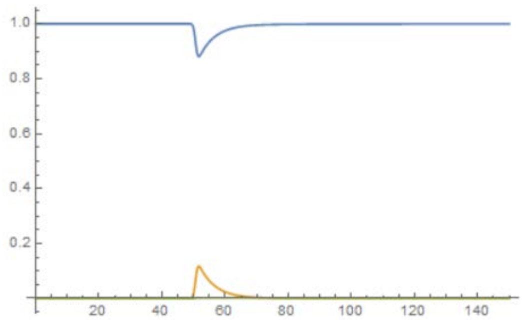

Figure 4 EIT simulation in matrix form

As shown in the figure 4, EIT cannot occur when the decay rate is larger than Omega, because the attenuation is too obvious. It can be seen here that excessive attenuation can hinder the reaction. The first level is always in the position of one, only a small drop occurs and then it returns to one. There is also a small rise in the second level and then a drop to zero. The third level does not change obviously and is in the zero position. During this period, there is no exchange between energy levels, and the coupling is too small, which makes this process cannot meet the EIT storage. Therefore, when the reduce rate is larger than Omega, this process cannot store quantum information effectively.

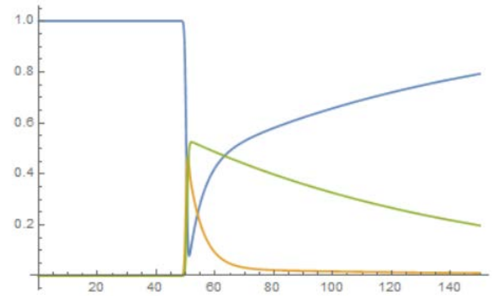

Figure 5 The second energy level is added to the process

When the decay rate is equal to or close to omega, the second energy level is added to the process, as shown in figure 5. In the early stage, it is similar to EIT without de-coherence, but after the reaction, the third level weakens rapidly because of the existence of de-coherence, and then the first level increases until it back to the initial position. Therefore, information storage can be carried out, but it is very inefficient because of the serious attenuation. If they are exactly equal, there is little practical storage available。

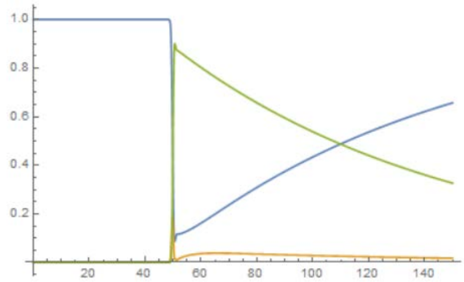

Figure 6 EIT memory scheme with three levels

Decay rate is smaller than Omega. It can be seen that EIT process occurs normally and has a certain duration, which can be used for storage. However, it can be seen that the first level has a continuous upward trend when and after EIT, and the third level also has a downward trend, which indicates that the storage time is still limited. When the time is long enough, the two lines will intersect and return to their original state. Therefore, information can be stored effectively, but the de-coherence effect will still make the information lost over time. This situation is the most feasible EIT memory scheme.

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