第 34 卷第 2 期
2015 年 4 月

红 外 与 毫 米 波 学 报
J. Infrared Millim. Waves

Vol. 34, No. 2
April, 2015

文章编号: 1001 - 9014(2015)02 - 0157 - 04

DOI:10. 11972/j. issn. 1001 - 9014. 2015. 02. 006

The switching of single photon in near-infrared quantum communication networks

ZHAO Nan*, ZHU Chang-Hua, PEI Chang-Xing, QUAN Dong-Xiao

(State Key Laboratory of Integrated Service Networks, Xidian University, Xi'an 710071, China)

Abstract: A new scheme of wavelength switching in multiuser near-infrared quantum cryptography networks has been proposed. Solution is provided for information exchange in quantum network, the unchanged polarization in the course of switching is also analyzed. In addition, the relation between conversion efficiency and pump power is simulated. The results show that this scheme is feasible and effective.

Key words: near-infrared, quantum cryptography, wavelength switching, unchanged polarization
PACS: 03. 67. Dd, 42. 50. Dv

近红外量子通信网中单光子波长交换研究

赵 楠*, 朱畅华, 裴昌幸, 权东晓
(西安电子科技大学 综合业务网理论与关键技术国家重点实验室,陕西 西安 710071)

摘要:提出了一种新的近红外多用户量子密钥分发中波长交换方案,解决了量子网络中信息交互难题;分析了交换过程中近红外单光子束的偏振变换;仿真了波长交换效率和泵浦光功率之间关系.仿真结果表明,该方案可行并且高效.

关 键 词:近红外;量子密钥分发;波长交换;偏振不变

中图分类号:TN918.91,TN219 **文献标识码**:A

Introduction

Network of quantum cryptography is a key research area, where networking provides users much wider scopes of communication. Usually a whole network consists of several subnets with different communication wavelength/frequency. There are some suitable wave bands with the central wavelength around 1 310 nm or 1 550 nm for quantum communication[1-5]. However, a thorny problem is keeping the information secure by different wavelengths in a whole quantum network. In recent years, remarkable progress has been made on quantum wavelength conversion and detection[6-9]. Several important experiments have already been reported. However, the changing of quantum polarization is not considered in these theoretical and experimental studies. A novel scheme of quantum switching is proposed in this paper, and the characteristic of polarization in the scheme is analyzed.

1 Scheme of the switching in multiuser quantum cryptography

Single photon is a perfect carrier of information in quantum cryptography. The energy of single photon is faint, and the measurement is forbidden except legal receiver. When measuring happens, the quantum state must be destroyed to unknown collapse[10-15]. For resolving it, we propose a scheme to complete quantum switching.

Quantum switching includes sum-frequency generation (SFG) and difference-frequency generation (DFG). SFG combined with DFG is a novel application, which can resolve the problem about high pump power in the process of switching. The course of wavelength conversion is finished by PPLN (Periodically poled lithium niobate), which is used to correct the

Received date: 2014 - 02 - 25, **revised date**: 2015 - 01 - 22 **收稿日期**: 2014 - 02 - 25, **修回日期**: 2015 - 01 - 22

Foundation items: Supported by National Nature Science Foundation of China(61301171, 61372076), the Fundamental Research Funds for the Central Universities, China(K5051301018), and the 111 Project(B8038)

Biography: ZHAO Nan(1980-), male, Shanxi Xi'an, Ph. D. Research area is optical communication, quantum communication, quantum information. E-mail: zhaonan@xidian. edu. cn

* **Corresponding author**: E-mail: zhaonan@xidian. edu. cn

phases of light beam by the periodical structure of crystal. Nonlinear coefficient will be reversed when light beam propagates a coherent distance; phases are reversed when ratio of efficient conversion reaches to the maximum value. The phase relation needs to be kept unchanged to make energy flow to the target wave. The characteristic of PPLN is used to realize the fundamental wavelength conversion.

Single-photon wavelength conversion is implemented by three-wave-mixing effect. A single-photon signal(λ_s) interacts with a pump light(λ_p) to produce a target single-photon signal (λ_v). SFG course occurs, the three wavelengths subject to the formula$1/\lambda_v = 1/\lambda_p + 1/\lambda_s$. DFG course occurs, the three wavelengths subject to the formula$1/\lambda_v = 1/\lambda_s - 1/\lambda_p$. In this scheme, PPLN waveguide consists of MgO-doped lithium niobate as the waveguide core and lithium tantalite as the cladding layer. The type of PPLN decides the occurrence of SFG or DFG. The phase-matching is satisfied by quasi-phase-matching technique. The basic process of wavelength conversion at the switching node is shown in Fig. 1.

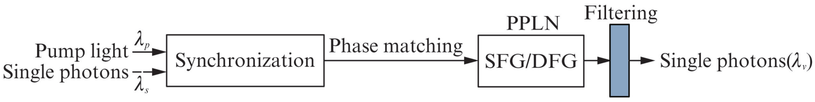

Fig. 1 Functional block of wavelength conversion
图1 波长变换流程框图

In Fig. 1, pump light (λ_p) and single photons (λ_s) are coupled into PPLN, then they are adjusted to satisfy phase matching through synchronous triggering. SFG or DFG can be completed by PPLN according to the requirement. Finally, the target single photons (λ_v) can be obtained after optical filtering.

For quantum cryptography, polarizations of quantum states need to remain unchanged in the propagation.

A novel scheme is proposed to complete quantum wavelength switching. Because the incident waves must satisfy polarization dependent, we use some optical devices to realize the multi-wavelength conversion. The scheme of quantum states wavelength switching is shown in Fig. 2. The optical devices include reflector mirror, wave plate and beam splitter.

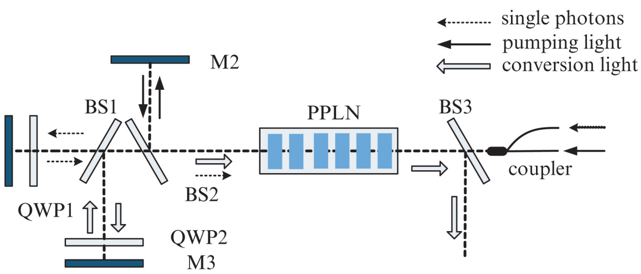

Fig. 2 Wavelength switching of quantum states
图2 量子态波长交换方案

The scheme proposed is based on BB84 protocol, in which four different kinds of polarization states are prepared. It is unknown for the node of switching to definite the polarization direction. In fact, neither central node has permission to measure the quantum states to ensure the security of quantum communication. First, single photons with four different quantum states input the PPLN crystal with pump light. Second, only the wavelength with one polarization direction is converted, because PPLN has the characteristic of polarization coherent. Then the single photons propagate through the 1/4 wave plate (QWP), beam splitter (BS), and reflector mirror (M) in turn. Reflector mirror is used to reflect light, beam splitter to split two orthogonal quantum states, and 1/4 wave plate to change the polarization direction of quantum states about 45°. In fact, each process of wavelength conversion only converses single photons with one polarization direction to the target wavelength. In this scheme, single photons with four polarization directions can be conversed respectively to the target wavelength through the devising of wave plates and beam splitters. The combination of these devices is used to complete the whole wavelength conversion by one piece of PPLN. The components used to amplify power and filter are ignored in Fig. 2. In the experiment, for the demand of quasi-phase-matching, the pump power needs to be amplified by Erbium-doped optical fiber amplifier before wavelength conversion occurs.

In the scheme above, the polarization direction needs to retain unchanged. At the end of sending, quantum states are prepared randomly. At the node of switching, polarization direction is unknown. The scheme here is a solution to single photons switching. For each wavelength conversion, it needs to prove whether the polarization direction is unchanged or not.

2 Proof of unchanged polarization in quantum switching

There are some descriptions about quantum states according to different theories. We adopt the electrical field theory of quantum states and analyze the courses of SFG and DFG separately.

For the system of wavelength conversion, annihilation operators are the proper description of physical quantity. Let $\hat{a}_p$, $\hat{a}_1$and $\hat{a}_2$ be pump light, input single photons and output photons respectively. According to energy conservation, the processes of SFG and DFG can be described by

$$\hat{a}_2^{\dagger} = a_{\hat{p}}\,\hat{a}_1^{\dagger} \quad . \qquad (1)$$

Through length of PPLN crystal, the wavelength of single photons is changed. L is the length of crystal equal to the distance of nonlinear reaction.

The real quantum communication system interacts with the outside. The interaction is regarded as noise, which can make the magnitude and phase of near-infrared photon changed. Because the energy of photon is weak, the noise is from many aspects, including nonideal equipments, birefrigent effect, temperature, and so on. It is a straight method to transform complex and abstract physical process into mathematical model. The mathematical formulation of quantum operation is used to describe the dynamics processes of quantum communication system. We use operator-sum representation and mechanics quantity operator to describe the process of quantum switching.

The Hamiltonian of the system can be separated into H_0 and H'. H_0 represents the part with no disturbance and H' represents the other with disturbance. They both obey Schrodinger equation,

$$i\hbar \frac{\partial \varphi}{\partial t} = H\varphi \quad , \quad (2)$$

$$H = H_0 + H'(t) \quad , \quad (3)$$

$$H_0 \phi_n = \varepsilon_n \phi_n \quad . \quad (4)$$

The wave function of H_0 is $\Phi_n = \phi_n(x) e - \frac{i}{\hbar}\varepsilon_n t$.

In the process of wavelength switching, the polarization direction of quantum states needs to be unchanged. It is assumed that the changed part of polarization is described by H', which is related to L. L is changed with t, so H' can be given as $H'(t)$. Based on BB84 protocol, if the polarization is changed, the transition probability of system from one quantum state to another is not zero.

Expanse the eignstate according to Φ_n, and take it to formula (1). Let Φ_m^* left multiplies the result according to the orthogonality of eignfunction assemble,

$$i\hbar \frac{\mathrm{d}a_m(t)}{\mathrm{d}t} = \sum_n a_n(t) H'_{mn} \mathrm{e}^{j\omega_{mn}t} \quad , \quad (5)$$

where, $H'_{mn} = \int \phi_m^* H' \phi_n \mathrm{d}\mathbf{r}, \omega_{mn} = \frac{1}{\hbar}(\varepsilon_m - \varepsilon_n)$.

Describing the part with interference, $H'(t)$ can be solved by the way of successive approximations. Initial states of the system are the k-th eignstate of H_0. When $t = 0$, $a_n(0) = \delta_{nk}$, from Eq. 5,

$$i\hbar \frac{\mathrm{d}a_m(t)}{\mathrm{d}t} = H'_{mn} \mathrm{e}^{j\omega_{mn}t} \quad , \quad (6)$$

so $a_m(t) = \frac{1}{i\hbar}\int_0^t H'_{mn} \mathrm{e}^{j\omega_{mn}t'} \mathrm{d}t'$.

$a_m(t)$ is the wave function of system at t, $|a_m(t)|^2$ is the probability that system changes in the course of wavelength conversion. Approximately, the result is given as

$$P = |a_m(t)|^2 = \frac{|a_m(L)|^2}{c^2} = \frac{1}{\hbar c^2}\left|\int_0^L H'_{mn} \mathrm{d}L\right|^2 \quad . (7)$$

It is assumed that single photons propagate by a straight line.

Take the DFG as an example, according to the results from Ikuta[14], the DFG process at the single-photon level can be described by the following Hamiltonian,

$$H'_{mn} = i\hbar(\xi^* \hat{a}_p \hat{a}_2^\dagger - \xi \hat{a}_2 \hat{a}_p^\dagger) \quad . \quad (8)$$

The coupling constant ξ of nonlinear medium is given as $\xi = |\xi| e^{i\varphi'}$, where the phase of pump light φ' is proposed as zero.

According to the theories of electromagnetic field, ξ can be given as $\xi = |gE_p|$, where E_p is the electric field intensity. The nonlinear coupling coefficient in DFG process g is defined as

$$g = 2\pi d_{\mathrm{eff}}(\sqrt{n_p n_2 \lambda_p \lambda_2})^{-1} \quad , \quad (9)$$

n_p and n_2 represent the fractive index of single pump light and photons in the crystal respectively.

By Heisenberg representation $\hat{a}_{2/p}(l) \equiv U^\dagger \hat{a}_{2/p} U with U \equiv \exp(-iHL/\hbar)$, the annihilation operators of output single photons and pump light are shown as

$$\begin{aligned} \hat{a}_p(L) &= \cos(|gE_p|L)\hat{a}_p - \sin(|gE_p|L)\hat{a}_2 \\ \hat{a}_2(L) &= \sin(|gE_p|L)\hat{a}_p + \cos(|gE_p|L)\hat{a}_2 \end{aligned} \quad . (10)$$

From Eq. 1, $\hat{a}_2{}^\dagger(L) = \hat{a}_p(L)\hat{a}_1{}^\dagger(L)$

From Eq. 7 – 8 and 10,

$$P_{\mathrm{system}} = \frac{1}{\hbar c^2}\left|\int_0^L H'_{mn} \mathrm{d}L\right|^2$$

$$= \frac{1}{\hbar c^2} \cdot \{\hbar[\cos^2(|gE_p|L) + \sin^2(|gE_p|L)]\}^2 \quad , (11)$$

where E_p is proportional to the energy of single photon (4.2×10^{-19} J), L is about several centimeters. For $\hbar \approx \frac{1}{2\pi} \cdot 6.63 \times 10^{-34}$ J · s, $c \approx 3 \times 10^8$ m/s, so $P_{\mathrm{system}} \propto 1/(10^{34} \cdot 10^{16})$, $P_{\mathrm{system}} \approx 0$. It is obvious that there's no change of polarization direction through the process of wavelength conversion. The analysis of the change of polarization in SFG is similar to that in DFG. In SFG, $P_{\mathrm{system}'} \approx 0$.

In the process of quantum wavelength conversion (SFG and DFG), the characteristic of polarization remains unchanged. The scheme of quantum wavelength conversion is feasible to change the wavelength of single photons with polarization-independent. The next step is to estimate the efficiency of conversion from the single photons to the conversion photons. Efficiency is the foundation of application. In PPLN crystal, the single photons and pump light have non-liner mutual function completely to produce conversion photons under ideal conditions. However, the conversion efficiency is unequal to 100% due to some reasons, such as, ideal devices, channel loss.

3 Simulation and performance

The energy of single photons is proportional to the number of them, so the loss in the process of wavelength conversion can be measured by the number of single photons lost.

In Eq. 1, annihilation operators can describe the process of energy conversion, $\hat{a}_2$ is the annihilation operator of output photons.

The number of single photons is given by

$$N(L) = \langle \hat{a}_2^\dagger(L) \hat{a}_2(L) \rangle$$

$$= \langle \phi | [\sin(|gE_p|L)\hat{a}_p^\dagger + \cos(|gE_p|L)\hat{a}_2^\dagger] \cdot [\sin(|gE_p|L)\hat{a}_p + \cos(|gE_p|L)\hat{a}_2 | \phi\rangle \quad , (12)$$

For satisfying the demand about the wavelength in PPLN,

$$\langle \hat{a}_p | \hat{a}_2 | \hat{a}_p \rangle = \langle \hat{a}_p^\dagger | \hat{a}_2^\dagger | \hat{a}_p^\dagger \rangle = 0 \quad . (13)$$

From Eq. 12 – 13, the number of single photons is given as

$$\begin{aligned} N(L) &= |\sin(|gE_p|L)\langle \phi | \hat{a}_p^\dagger \hat{a}_p | \phi \rangle| \\ &= |\sin(|gE_p|L) N_p(0)| \end{aligned} \quad . \quad (14)$$

So the frequency of wavelength conversion is

$$\eta = N(L)/N_p(0) = |\sin(|gE_p|L)| . \quad (15)$$

The electrical field intensity E_p is given as

$$E_p = \sqrt{2P_p / cn_p \varepsilon_0 A_{\text{eff}}} . \quad (16)$$

Finally, from Eqs. 14 – 16, η is given as

$$\eta = \sin(2\pi d_{\text{eff}} L \sqrt{2P_p / c\varepsilon_0 A_{\text{eff}} n_1 n_2 n_p \lambda_1 \lambda_2}) . (17)$$

The analytical method about η in DFG can be used to analyze the change of photon number in SFG. We simulate the courses of DFG and SFG to describe the relation between η and the pump power. Consider the conventional values of the parameters in Eq. 17, the simulation results is shown in Fig. 3.

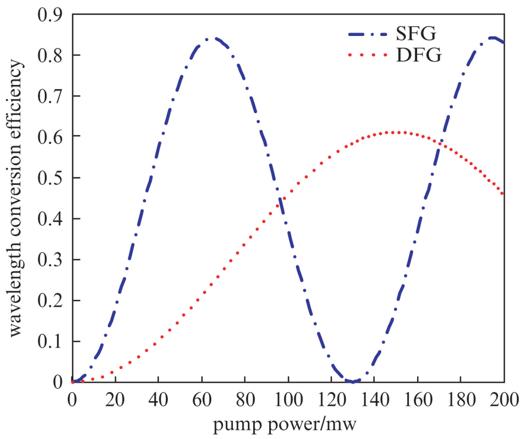

Fig. 3 The relation between pump power and the wavelength conversion efficiency
图3 波长变换效率与泵浦功率关系曲线

In Fig. 3, the vertical axis shows the wavelength conversion efficiency, whereas the horizontal axis shows the pump power(mW). The scope of wavelength conversion is from 1 350 nm to 1 310 nm, the maximum efficiency of DFG 61%. Accordingly, the power of pump is 148 mW, the maximum efficiency of SFG 85% , and the power of pump 67 mW. η does not reach to 100% because of the nonideal environment and it can be closed to 100% by improving the experiment devices.

4 Conclusions

The scheme of quantum switching is proposed. The polarization direction of quantum states in SFG and DFG is analyzed, the relation between conversion efficiency and pump power is simulated. This scheme is feasible to complete information switching without being measured in quantum network. Based on this scheme, the experimental platform will be constructed to make further research.

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