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基于和频与差频级联的全光单光子波长变换

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摘　要：基于周期极化铌酸锂波导，提出了一种采用和频产生与差频产生级联的全光单光子波长变换方案.在海森堡绘景下，通过非线性变换过程的哈密顿量求解了目标单光子信号的湮灭算子，进而根据变换前后的光子数算符之比得到了单光子波长变换的效率.分析了和频产生过程以及差频产生过程中单光子的转换效率与泵浦功率之间的关系，证明了存在最佳泵浦功率使得量子态能够完全转移.数值分析结果表明，当上变换(和频产生)泵浦光功率为 65 mW、下变换(差频产生)泵浦光功率为 150 mW 时，由 1 550 nm 到 1 530 nm 的单光子波长变换可达到 61%的转换效率.给出了级联单光子波长变换的实验装置，包括周期极化铌酸锂波导、泵浦激光、准单光子信号源、滤波等光学元器件、单光子探测器和同步线路.

关键词：全光单光子波长变换；和频产生；差频产生；周期极化铌酸锂波导
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All-optical Single-photon Wavelength Conversion Based on Cascaded Sum-frequency Generation and Difference-frequency Generation

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Abstract: Based on periodically poled lithium niobate (PPLN) waveguides, an all-optical single-photon wavelength conversion scheme is proposed, in which a cascaded sum-frequency generation (SFG) and difference-frequency generation (DFG) are applied. In the Heisenberg picture, the annihilation operators of target photon are obtained by using the Hamiltonian of nonlinear conversion process. According to the efficiency of the single-photon wavelength converter, that is, the ratio of the value of photon number operator after conversion to the value before conversion, the relation of the efficiencies of the single-photon wavelength converters in the SFG and DFG process with the pump power are analyzed. The result that there exists an optimum pump power with which the quantum state can be transferred completely is demonstrated. Numerical analysis results show that the efficiency of single-photon wavelength conversion from 1 550 nm to 1 530 nm is about 61% when the pump power of up-converter is 65 mW and the pump power of the down-converter is 150 mW, respectively. In addition, an experimental setup is also proposed, which consists of PPLN waveguides, pump lasers, quasi-single photon source, optical components, e.g. filtering, single photon detector (SPD) and synchronization circuit.

Key words: All-optical single-photon wavelength conversion; Sum-Frequency Generation(SFG); Difference-Frequency Generation(DFG); PPLN waveguide

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0 Introduction

All-optical wavelength conversion at the single-photon level is known as a potential technique which can be used to quantum switch for building multi-user quantum networks[1]. By this technique, the capacity of wavelength division multiplexing (WDM) network can be increased greatly, wavelength competition can be avoided and the management of communication network may be more flexible and rational[2]. Generally, Single-photon wavelength conversion is implemented by three-wave-mixing effect, especially sum-frequency generation (SFG)[3-4] and difference-frequency generation (DFG)[5-6]. In fact, the single-photon wavelength conversion in WDM network can be implemented by DFG directly: a single-photon signal at wavelength λ_s interacts with a pump light at wavelength λ_p, and then the target single-photon signal at wavelength λ_c ($1/\lambda_c = 1/\lambda_p - 1/\lambda_s$) is generated. To operate within the third optical tele-communication spectral window, both the wavelengths of the input and target signal are required in the 1.5 μm band. Therefore, the pump light has to be in the 780 nm range. This DFG-based scheme is simple but suffered from manufacturing the high-power and low-linewidth pump laser in the 780 nm range. To overcome this, a novel quantum wavelength conversion scheme based on the cascaded SFG and DFG in two respective PPLN waveguides is proposed.

The rest of this paper is organized as follows: the proposed scheme is described in section 1, followed by the theoretical analysis and numerical results in Section 2 and 3, an experimental setup is also proposed in section 4, and a conclusion is given in Section 5.

1 The proposed scheme

As illustrated in Fig. 1: a single-photon signal at wavelength λ_s interacts with a pump light at wavelength λ_{p_1} in the first PPLN waveguide to produce visible single-photon signal at λ_v ($1/\lambda_v = 1/\lambda_s + 1/\lambda_{p_1}$), and then the generated single-photon signal combines with the pump light at wavelength λ_{p_2} in the second PPLN waveguide where the target single-photon signal at λ_c ($1/\lambda_c = 1/\lambda_v - 1/\lambda_{p_2}$) is achieved.

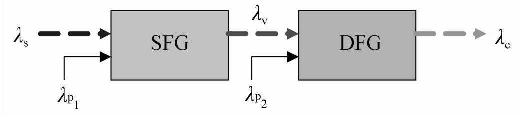


Fig. 1 The schematic of proposed conversion scheme

In this scheme, the PPLN waveguide consists of MgO-doped lithium niobate as the waveguide core and lithium tantalite as the cladding layer[7]. The phase-matching is satisfied by quasi-phase-matching (QPM) technique[8], and the pump power with which an efficient transfer of quantum state can be ensured is figured out in Section 2. In addition, for wavelength conversion at the single photon level it is known that large excess noise derives from either spontaneous Stocks Raman scattering or spontaneous parametric down-conversion (SPDC) of the pump light[9]. To minimize these noises, long-wavelength pump source is employed[10].

2 Theoretical Analysis

In this wavelength conversion scheme, the SFG and DFG are separated, hence, they can be analyzed independently. Some hypotheses have to be made before theoretical analysis

1) The phase matching is supposed to be perfect.

2) In the case of a strong pump, there is negligible depletion for the pump field and the amplitude of which can be treated classically as electrical field intensity.

3) The pump light is assumed to be ideal uniform plane wave.

4) The propagation loss is neglected.

5) The pump light occupies the extraordinarily polarized TM_{00} mode.

2.1 Process of sum-frequency generation

A theoretical model of the SFG process is given in Ref. [11]. In this model, the frequency up-conversion efficiency η_1 is expressed as

$$\eta_1 = \sin^2(|g_1 E_{p_1}| L_1) \tag{1}$$

where E_{p_1} is the electrical field intensity of pump light at wavelength λ_{p_1} and L_1 is the interaction length in the second-order nonlinear medium. The nonlinear coupling coefficient g_1 is defined as

$$g_1 = 2\pi d_{\mathrm{eff}} (\sqrt{n_s n_v \lambda_s \lambda_v})^{-1} \tag{2}$$

where n_s and n_v are the refractive indexes of the input and output single-photon signal in the first waveguide . The effective nonlinear coefficient d_{eff}

is defined as $d_{\mathrm{eff}}=(2d_{33}/\pi)\sin(\pi D)$ where D denotes the poling duty cycle[12] and d_{33} is maximum nonlinear coefficient of the nonlinear medium.

The relationship between E_{p_1} and light field intensity I_{p_1} is given as

$$I_{\mathrm{p}_1}=\frac{1}{2}n_{\mathrm{p}_1}\sqrt{\varepsilon_0/\mu_0}\,|E_{\mathrm{p}_1}|^2 \tag{3}$$

Due to the assumption that pump light is plane wave, the pump power at wavelength λ_{p_1} is simply written as

$$P_{\mathrm{p}_1}=I_{\mathrm{p}_1}A_{\mathrm{eff}} \tag{4}$$

where A_{eff} is the section area of effective pump light beam. By Eqs. (3) and (4), E_{p_1} can be given by

$$E_{\mathrm{p}_1}=\sqrt{2P_{\mathrm{p}_1}/cn_{\mathrm{p}_1}\varepsilon_0 A_{\mathrm{eff}}} \tag{5}$$

where n_{p_1} is refractive index of the pump light at wavelength λ_{p_1} in the nonlinear medium, ε_0 and μ_0 represent permittivity and permeability in vacuum respectively , and c is the light velocity in free space.

Under the conditions of Eqs. (2) and (5), Eq. (1) is modified as

$$\eta_1=\sin^2(2\pi d_{\mathrm{eff}}L_1\sqrt{2P_{\mathrm{p}_1}/c\varepsilon_0 A_{\mathrm{eff}}n_{\mathrm{s}}n_{\mathrm{v}}n_{\mathrm{p}_1}\lambda_{\mathrm{s}}\lambda_{\mathrm{v}}}) \tag{6}$$

The pump power with which the conversion efficiency of 100% can be achieved is given as

$$P_{\mathrm{p}_1}=\frac{c\varepsilon_0 A_{\mathrm{eff}}n_{\mathrm{s}}n_{\mathrm{v}}n_{\mathrm{p}_1}\lambda_{\mathrm{s}}\lambda_{\mathrm{v}}}{32d_{\mathrm{eff}}^2L_1^2h} \tag{7}$$

where proportional factor h denotes the decline of pump power introduced by the incomplete coincidence of light beam[13].

2.2 Process of difference-frequency generation

According to the results in Ref. [14], the DFG process at the single-photon level can be described by the following Hamiltonian

$$\hat{H}=\mathrm{i}\hbar(\xi^*\hat{a}_{\mathrm{v}}\hat{a}_{\mathrm{c}}^{\dagger}-\xi\hat{a}_{\mathrm{c}}\hat{a}_{\mathrm{v}}^{\dagger}) \tag{8}$$

where $\hat{a}_{\mathrm{v}}$ and $\hat{a}_{\mathrm{c}}$ are annihilation operators corresponding to the visible signal at wavelength λ_{v} and the target signal at wavelength λ_{c}, respectively. The coupling constant ξ of nonlinear medium is given as $\xi=|\xi|\mathrm{e}^{\mathrm{i}\varphi}$, where we suppose the phase of pump light φ is zero.

The amplitude of the pump field at wavelength λ_{p_2} can be treated classically as electric field intensity E_{p_2}. So, ξ is rewritten as

$$\xi=|g_2E_{\mathrm{p}_2}| \tag{9}$$

The nonlinear coupling coefficient in DFG process g_2 is given by

$$g_2=2\pi d_{\mathrm{eff}}(\sqrt{n_{\mathrm{v}}n_{\mathrm{c}}\lambda_{\mathrm{v}}\lambda_{\mathrm{c}}})^{-1} \tag{10}$$

where n_{c} is the refractive index of the target single-photon signal in the medium.

By Heisenberg representation $\hat{a}_{\mathrm{v(c)}}(l)\equiv\hat{U}^{\dagger}\hat{a}_{\mathrm{v(c)}}\hat{U}$ with $\hat{U}\equiv\exp(-\mathrm{i}\hat{H}l/\hbar)$, the annihilation operators of visible and target single-photon signal are achieved as

$$\begin{aligned}\hat{a}_{\mathrm{v}}(L_2)&=\cos(|g_2E_{\mathrm{p}_2}|L_2)\hat{a}_{\mathrm{v}}-\\&\quad\sin(|g_2E_{\mathrm{p}_2}|L_2)\hat{a}_{\mathrm{c}}\\\hat{a}_{\mathrm{c}}(L_2)&=\sin(|g_2E_{\mathrm{p}_2}|L_2)\hat{a}_{\mathrm{v}}+\\&\quad\cos(|g_2E_{\mathrm{p}_2}|L_2)\hat{a}_{\mathrm{c}}\end{aligned} \tag{11}$$

where L_2 is the interaction length of the nonlinear medium.

If the quantum state at the input of the second waveguide is given by

$$|\phi\rangle=|\Psi,0\rangle \tag{12}$$

where $|\Psi\rangle$ represents the state of the photon generated by SFG and $|0\rangle$ represents the vacuum state at λ_{p_2}, the expected value of photon number operator for the target single-photon signal is given as

$$\begin{aligned}N_{\mathrm{c}}(L_2)&=\langle\hat{a}_{\mathrm{c}}^{\dagger}(L_2)\hat{a}_{\mathrm{c}}(L_2)\rangle=\phi|[\sin(|g_2E_{\mathrm{p}_2}|\cdot\\&\quad L_2)\hat{a}_{\mathrm{v}}^{\dagger}+\cos(|g_2E_{\mathrm{p}_2}|L_2)\hat{a}_{\mathrm{c}}^{\dagger}][\sin(|g_2E_{\mathrm{p}_2}|\cdot\\&\quad L_2)\hat{a}_{\mathrm{v}}+\cos(|g_2E_{\mathrm{p}_2}|L_2)\hat{a}_{\mathrm{c}}|\phi\rangle\end{aligned} \tag{13}$$

Since the pump mode at the input is in the vacuum state, it is clear that

$$\langle 0|\hat{a}_{\mathrm{c}}^{\dagger}|0\rangle=\langle 0|\hat{a}_{\mathrm{c}}|0\rangle=0 \tag{14}$$

Then Eq. (13) can readily be simplified to

$$\begin{aligned}N_{\mathrm{c}}(L_2)&=\sin^2(|g_2E_{\mathrm{p}_2}|L_2)\langle\Psi|\hat{a}_{\mathrm{v}}^{\dagger}\hat{a}_{\mathrm{v}}|\Psi\rangle=\\&\quad\sin^2(|g_2E_{\mathrm{p}_2}|L_2)N_{\mathrm{v}}(0)\end{aligned} \tag{15}$$

So, the frequency down-conversion efficiency η_2 is given by

$$\eta_2=N_{\mathrm{c}}(L_2)/N_{\mathrm{v}}(0)=\sin^2(|g_2E_{\mathrm{p}_2}|L_2) \tag{16}$$

where the electrical field intensity can also be written as

$$E_{\mathrm{p}_2}=\sqrt{2P_{\mathrm{p}_2}/cn_{\mathrm{p}_2}\varepsilon_0 A_{\mathrm{eff}}} \tag{17}$$

Under the conditions of Eqs. (10) and (17), Eq. (16) can be modified as

$$\eta_2=\sin^2(2\pi d_{\mathrm{eff}}L_2\sqrt{2P_{\mathrm{p}_2}/c\varepsilon_0 A_{\mathrm{eff}}n_{\mathrm{v}}n_{\mathrm{c}}n_{\mathrm{p}_2}\lambda_{\mathrm{v}}\lambda_{\mathrm{c}}}) \tag{18}$$

The pump power with which the down-conversion efficiency of 100% can be achieved is given as

$$P_{\mathrm{p}_2}=\frac{c\varepsilon_0 A_{\mathrm{eff}}n_{\mathrm{v}}n_{\mathrm{c}}n_{\mathrm{p}_2}\lambda_{\mathrm{v}}\lambda_{\mathrm{c}}}{32d_{\mathrm{eff}}^2L_2^2h} \tag{19}$$

3 Numerical results

In Eqs. (7) and (19), the efficient nonlinear coefficient, the length of nonlinear medium, refractive index, wavelength, and pump power etc. are all classical quantities which means that if suitable conditions are available , quantum state

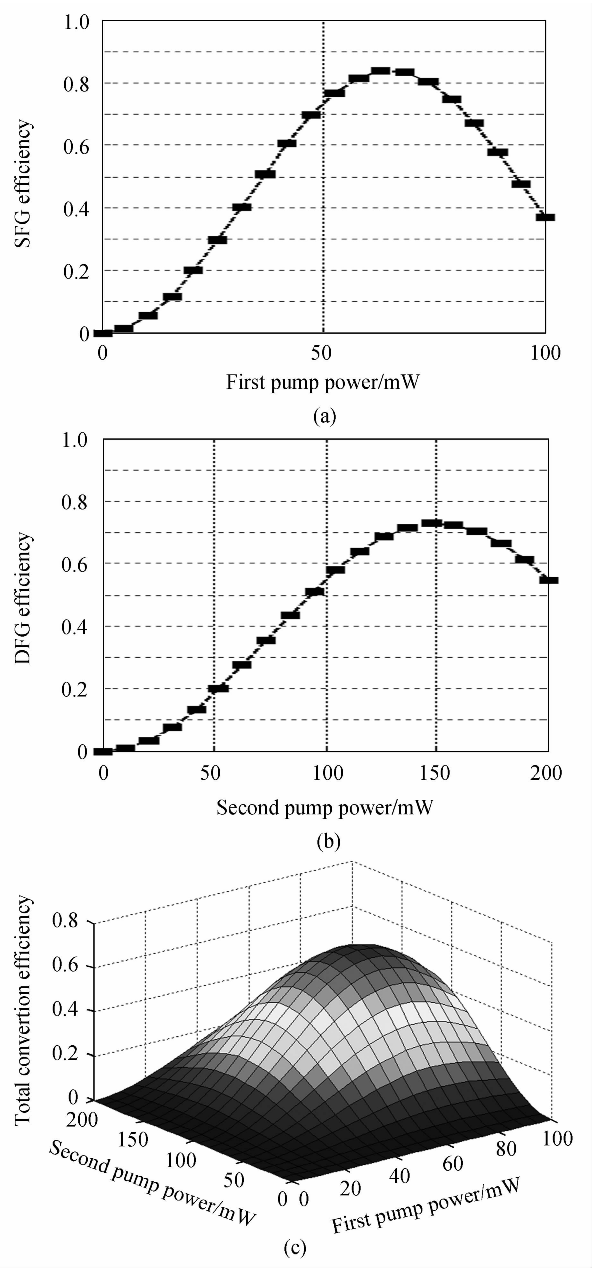


Fig. 2 The relations of P_{p_1} and the conversion efficiency of SFG process(a), P_{p_2} and the conversion efficiency of DFG process(b), and two pump powers and total conversion efficiency(c)

can be efficiently transferred from one telecommunication channel to another. The SFG efficiency η_1 is obtained by Eq. (6) as well as the DFG efficiency η_2 by Eq. (18). The total conversion efficiency η is

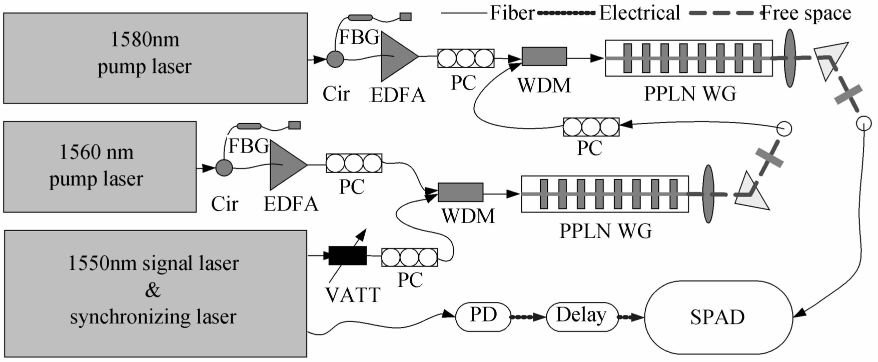
$$\eta=\eta_1\eta_2 \tag{20}$$

The numerical results of the conversion from the wavelength 1 550 nm to 1 530 nm are shown in Fig. 2. The SFG process reaches a maximum efficiency of 84% in the first waveguide, and DFG has a maximum efficiency of 73% in the second waveguide. It also shows that the total conversion efficiency of 61% is obtained when P_{p_1} is about 65 mW and P_{p_2} is about 150 mW.

4 Experimental setup

As illustrated in Fig. 3, an experimental setup is also proposed. It is mainly composed of five parts: quasi-single photon source, pump system, PPLN waveguide, filter system, and detection system. A FBG is used to spectrally filter the light from pump laser in order to approach the QPM bandwidth of PPLN waveguide. The FBG reflection is amplified by an EDFA as the pump light. The single-photon signal at wavelength 1 550 nm and the pump light at wavelength 1 560 nm are coupled into the PPLN waveguide, in which a visible single-photon signal at wavelength 778 nm is generated due to SFG process.

Subsequently, the generated single photon mixes with the pump light at 1 580 nm in the other PPLN waveguide, in which target single-photon signal at 1 530 nm is generated by DFG process. The PPLN waveguide outputs are separated using a lens, a prism, a split, and an interference filter. The target single-photon signal is detected by InGaAs/InP single photon avalanche diodes (SPAD).



Abbreviations: Cir, circulator; FBG, fiber bragg gating; EDFA, erbium-doped fiber amplifier; PC, polarization controller; WDM, wavelength-division multiplexer; VATT, variable attenuator; SPAD, single photon avalanche diodes

Fig. 3 Experimental setup for the proposed conversion scheme

5 Conclusion

In conclusion, an all-optical single-photon wavelength conversion scheme based on a cascaded SFG process and DFG process is proposed. The two processes are performed in two respective PPLN waveguides. Long-wavelength pump source is employed in this scheme to minimize excess noise. The pump power with which the quantum state of single-photon can be kept and the corresponding conversion efficiency are deduced in each process by quantum theory. By the deduced results, the single-photon wavelength conversion from 1 550 nm to 1 530 nm is analyzed. Numerical analysis results show that, the total conversion efficiency of 61% is obtained when P_{p_1} is about 65 mW and P_{p_2} is about 150 mW. Finally, the experimental arrangement of the proposed scheme is introduced.

References

[1] KIMBLE H J. The quantum internet[J]. *Nature*, 2008, **453** (7198): 1023-1030.

[2] YOS J B O. Wavelength conversion technologies for WDM network applications[J]. *Lightwave Technology*, 1996, **14** (6): 955-966.

[3] RAKHER M T, MA L, SRINIVASAN K, *et al*. Quantum transduction of telecommunications-band from quantum dot by frequency upconversion[J]. *Nature Photonics*, 2010, **4**(11): 786-791.

[4] PORAT G, SILBERBERG Y, SUCHOWSKI H, *et al*. Two photon frequency conversion[J]. *Optics Express*, 2012, **20** (4): 3613-3619.

[5] ZASKE S, LENHARD A, BECHER C. Efficient frequency down conversion at the single photon level from the red spectral region to the telecommunications C-band[J]. *Optics Express*, 2011, **19**(13): 12825-12836.

[6] TAKESUE H. Single-photon frequency down-conversion experiment[J]. *Physical Review A*, 2010, **82**(1): 013833.1-013833.5.

[7] TANZILLI S, TITTEL W, de RIEDMATTEN H, *et al*. PPLN waveguide for quantum communication [J]. *The European Physical Journal D*, 2002, **18**(2): 155-160.

[8] HUM D S, FEJER M M. Quasi-phasematching[J]. *Comptes Rendus Physique*, 2007, **8**(2): 180-198.

[9] SPELC J, LANGROCK C, FEJER M M, *et al*. Influence of domain disorder on parametric noise in quasi-phase-matched quantum frequency converters[J]. *Optics Letters*, 2010, **35** (16): 2804-2806.

[10] PELC J S, MA L, FEJER M M, *et al*. Long-wavelength-pumped upconversion single-photon detector at 1550 nm: performance and noise analysis[J]. *Optics Express*, 2011, **19** (22): 21445-21456.

[11] GU X R, HUANG K, ZENG H P, *et al*. Photon correlation in single-photon frequency upconversion[J]. *Optics Express*, 2012, **20**(3): 2399-2407.

[12] ROUSSEV R V, LANGROCK C, FEJER M M, *et al*. Periodically poled lithium niobate waveguide sum-frequency generation for efficient single-photon detection at communication wavelengths[J]. *Optics Letters*, 2004, **29** (4): 1518-1520.

[13] ALBOTA M A, WONG F N C. Efficient single-photon counting at 1.55 μm by means of frequency upconversion[J]. *Optics Letters*, 2004, **29**(13): 1449-1451.

[14] IKUTA R, KUSAKA Y, IMOTO N, *et al*. Wide-band quantum interface for visible-to-telecommunication wavelength conversion[J]. *Nature Communications*, 2011, **2**: 537.