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Nonlinear Interaction between Two Chirped Broadband Single Photons

*Yuanhua Li, Yiwen Huang, Zhantong Qi, and Xianfeng Chen**

Coherent correlation between two distant broadband single photons can be realized by using the nonlinear optical method, which provides a key technology for spread-spectrum communication in the quantum network. Here, sum-frequency generation (SFG) between two broadband single photons is experimentally demonstrated by using chirp technology. The results show that the efficiency of the SFG is 6.51×10^{-8}, and the visibility of coherent correlation of two distant broadband photons of the telecommunications band is 93.7%. This technique can also be used for other quantum applications, such as quantum entanglement swapping and quantum communication.

1. Introduction

Coherent correlation[1] of two long-distance photons is the basis for building a large-scale quantum network.[2] Both quantum repeaters[3,4] and distributed quantum computing[5,6] are premised on the work of high-visibility coherent correlation between two distant photons. At present, there are two methods to achieve a coherent correlation between two photons at a long distance. One is the linear optical method using the post-selection process, which requires two narrow bandwidth single photons, close to the single frequency, to complete the coherent correlation, and this correlation method is probabilistic.[7,8] The other is based on a nonlinear optical method, which does not require post-selection and can achieve a deterministic coherent correlation of two long-distance photons.[9] In order to ensure the characteristics of single photon and low noise in the quantum communication process, the brightness of each channel of the quantum network to manipulate the photon is limited, which directly affects the communication rate and the longest distance of transmission.[10] For the purpose of improving the communication rate and transmission distance, the spread-spectrum method can be used, which is to make more photons of different frequencies for communication tasks. This spread-spectrum scheme not only improves the brightness of photons during the communication process, but also does not change the characteristics and noise of any single-frequency photon in the spectrum after spreading. However, the spread spectrum will cause the bandwidth of single photons to become larger and the coherence time to become smaller. Therefore, spread spectrum reduces the visibility of the coherent correlation of two distant photons, and at the same time increases the difficulty of the coherent correlation of two distant photons. Obviously, the linear optics-based method cannot achieve the high-visibility coherent correlation of two broadband photons. After preliminary research, it was found that it is possible to achieve the coherent correlation of two long-distance broadband single photons by using nonlinear optical technology.

It has been theoretically proved that the sum-frequency generation (SFG) between two photons can establish a deterministic coherent correlation between two distant photons.[9] Similar experimental results have been demonstrated based on narrowband single photons, including the SFG between a narrowband single photon coherent state and a true narrowband single photon,[11] and between two true narrowband single photons.[12] The efficiency of SFG of both experiments is $\approx 1.5 \times 10^{-8}$, and such an efficiency can achieve the visibility of 87% of coherent correlation between two distant photons in theory. However, the generated photon pair of the visible wavelength regime of coherent correlation cannot be used for the optical fiber network, and the visibility of the coherent correlation of the generated photon pair is also limited by the efficiency of SFG. Fortunately, we have experimentally realized the SFG of two broadband single-photon-level coherent states based on chirp technology, and the efficiency of SFG has been greatly improved.[13] This technique can be used to complete the SFG of two true broadband single photons and can be used to establish the high-visibility coherent correlation of two distant broadband single photons of the telecommunications band.

Y. Li
Department of Physics, Shanghai Key Laboratory of Materials Protection and Advanced Materials in Electric Power
Shanghai University of Electric Power
Shanghai 200090, China

Y. Li, Y. Huang, Z. Qi, X. Chen
State Key Laboratory of Advanced Optical Communication Systems and Networks, Department of Physics and Astronomy
Shanghai Jiao Tong University
Shanghai 200240, China
E-mail: xfchen@sjtu.edu.cn

X. Chen
Shanghai Research Center for Quantum Sciences
Shanghai 201315, China

X. Chen
Collaborative Innovation Center of Light Manipulations and Applications
Shandong Normal University
Jinan 250358, China

The ORCID identification number(s) for the author(s) of this article can be found under https://doi.org/10.1002/qute.202300175

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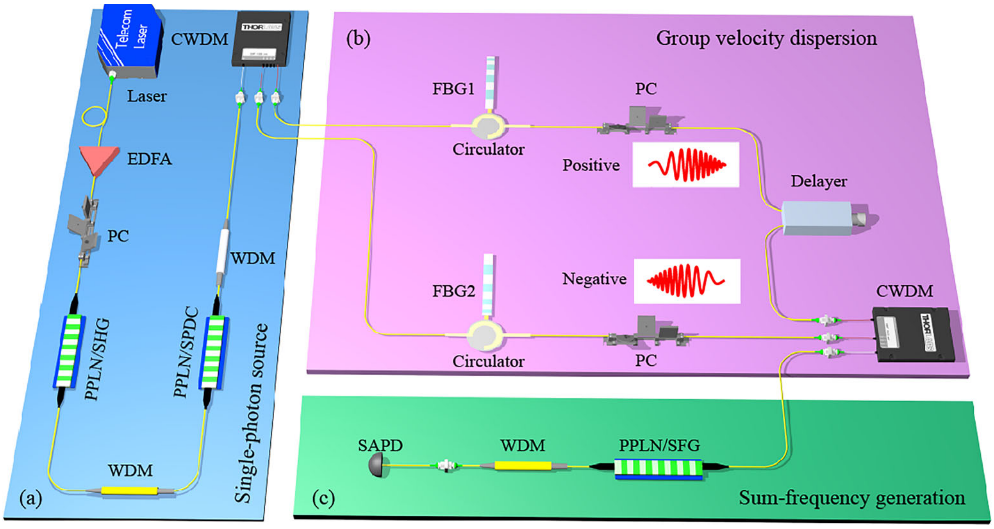

Figure 1. Experimental set-up. a) Single-photon source. b) Group velocity dispersions of two broadband single photons. c) SFG between two chirped broadband single photons. Delayer, optical adjustable delay fiber; PC, polarization controller; Circulator, optical fiber circulator.

Here, we experimentally achieved the SFG between two true broadband single photons by using the chirp technique. Our results show that the efficiency of generated SFG can achieve a visibility of 93.7% of the coherent correlation of two long-distance broadband single photons of the telecommunications band. Our method can directly improve the brightness of the photons in each channel and speed up the communication rate improving the transmission distance, which paves the way for quantum entanglement swapping and quantum communication.

2. Experimental Section

Next, the feasibility of the approach was experimentally demonstrated by using a generated single-photon source.[14] The experimental setup is shown in **Figure 1**. A continuous laser with a central wavelength of 1551.72 nm was first amplified to 180 mW by an erbium-doped fiber amplifier. The amplified laser passed through the first periodically polarized Lithium niobate (PPLN) waveguide, which converted its wavelength to the near-infrared region through nonlinear second harmonic generation (SHG). The generated SHG laser was used as the pump light for the spontaneous parametric down-conversion (SPDC) process, which could be achieved through a second PPLN waveguide. The first wavelength division multiplexing (WDM) was used to isolate continuous light with a center wavelength of 1551.72 nm, while the second WDM was used to isolate the SHG generated by the first PPLN waveguide. Both WDMs had an extinction ratio of 180 dB. In order to obtain more single photons, the experiment keeps the maximum output of the pump laser unchanged. In this case, the second-order correlation function $g^{(2)}(0)$ and the coincidence-to-accidental ratio (CAR) of the single-photon source were 0.08 and 10, respectively, and hence the characteristics of the single photon and the good signal-to-noise ratio were guaranteed.

To implement the approach architecture, the generated single-photon source was then split by a 647.6-GHz coarse wavelength division multiplexing (CWDM) with high-isolation, which had two frequency correlation channels. Then the broadband photon pair with central wavelengths of 1555.75-nm (CH27) and 1547.72-nm (CH37) were obtained, which had a FWHM bandwidth of 5.2 nm, as shown in **Figure 2**. The number of photons per channel was $\approx 1 \times 10^9$. Photons in CH27 channel were sent to a fiber Bragg grating 1 (FBG1), and photons in the other channel were coupled into the fiber Bragg grating 2 (FBG2). FBG1 and FBG2 were the two gratings with identical parameters. The central wavelength of these two gratings was 1547 nm, the full width at half maxima (FWHM) bandwidth was 39 nm, and the chirp rate was 5 nm cm^{-1}. In the experiment, FBG1 was used to generate positively chirped photons, while FBG2 was used to generate negatively chirped photons. Therefore, the photons in Channel 1 (CH1) channel would have a relatively front phase when reflected by the positive chirped gratings (FBG1), while the photons in the Channel 2 (CH2) channel would have a relatively later phase when reflected by the negatively chirped gratings (FBG2). Because two FBGs were used, group velocity dispersion was introduced into the two channels, so that all photons in the spectrum in the two channels could be used to generate SFG photons.

The positive or negative dispersion caused by FBG depended on the port of reflected photons. When two true broadband single photons were simultaneously sent to FBG1 and FBG2, the frequencies of these two broadband photons were $\omega_1(t) = \omega_1 + At$ and $\omega_2(t) = \omega_2 - At$, respectively (where A is the linear chirp parameter). All of the positively and negatively chirped single photons were simultaneously coupled into the third PPLN waveguide to create the SFG photons. The optimum SFG phase matching temperature was 29 °C. The SFG between two true broadband single photons could be simply described as $\omega_{SFG} = \omega_1 + \omega_2$, ω_{SFG} is the frequency that most satisfies the SFG phase matching. Thus, the narrowband SFG photon was realized. In the experiment, three identical 5.2 cm long 0-type PPLN waveguides were used, and the quasi-phase-matching polarization period of the three PPLN waveguides was 19.6 μm. Two broadband single photons were detected and calibrated using a single photon detector, with a detection efficiency of 10% and a dark counting rate of 370 Hz. Finally, a 108 dB WDM was used to isolate these two

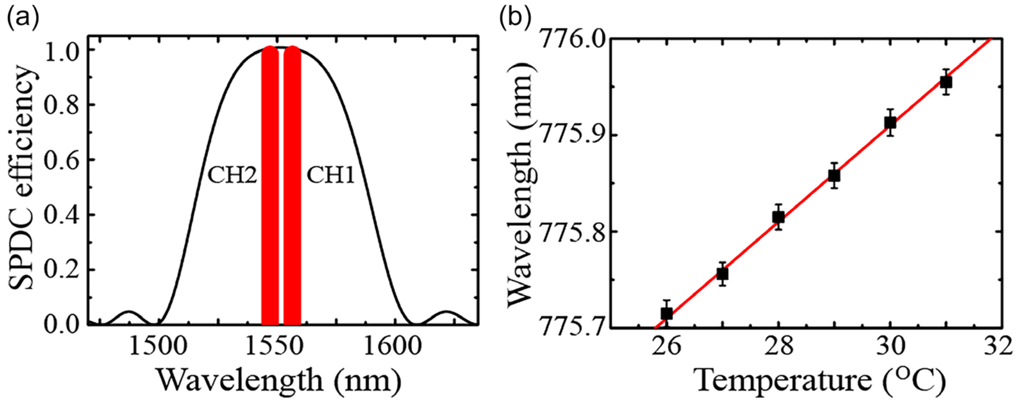

Figure 2. a) Spectrum of signal (higher-wavelength) and idler (lower-wavelength) photons, the color-coded bars (CH1 and CH2) represent pairs of signal and idler photons. The spectrum of the source (black curve) was obtained according to the SPDC process.[15] b) Relationship between the center wavelength of SFG photons and the temperature of the PPLN waveguide.

broadband single photons, and all SFG photons could be detected with a silicon avalanche photodiode (SAPD), whose detection efficiency is 60% and dark count rate is 26 Hz.

3. Results and Discussion

In our experiment, the positively and negatively chirped broadband single photons are simultaneously coupled into the third PPLN waveguide, and the number of the SFG photons can be measured. We note that when the positively chirped single photons (or negatively chirped single photons) are sent to the waveguide alone, the photons of SHG are close to the dark count and cannot be detected. Thus, the generated photons are all SFG photons. Here, we can obtain the center wavelength of SFG photons by adjusting the temperature of the PPLN waveguide.

By using two single-frequency lights with adjustable wavelengths, we obtain the relationship between the center wavelength of the SFG photons and the temperature, that is, $\lambda(T) = 774.41 + 0.05T$, as shown in Figure 2. The relationship is linear, that is, when the temperature changes by 0.2 °C, the center wavelength of the SFG photons will change by 0.01 nm. Therefore, we can obtain the number of SFG photons in different situations by adjusting the temperature of the PPLN waveguide.

In our experiment, the number of single photons of CH1 and CH2 channels simultaneously coupled to the third PPLN waveguide was reduced to 1.53×10^8 due to losses through FBGs and other devices. In this case, the maximum SFG photons are obtained. The maximum efficiency of SFG of 6.51×10^{-8} is realized, where dark counts of 2.6 Hz have been subtracted and the total losses of ≈4.9 dB have been taken into account.

It is shown that the theoretical SFG efficiency is given by $\eta'_{SFG} = (\xi L^2 h\nu \Delta\nu)/tbp$, where ξ represents the efficiency of SFG, L is the length of waveguide, $\Delta\nu$ denotes the input photon bandwidth, and tbp represents the time-bandwidth product. Here, we consider that $\xi = 15\%/(W \cdot \mathrm{cm}^2)$, $tbp = 0.66$, and $\Delta\nu = 647GHz$, thus the theoretical efficiency of SFG is $\eta'_{SFG} \approx 7.8 \times 10^{-8}$. Therefore, our experimental efficiency of SFG is in agreement with the theoretical result.

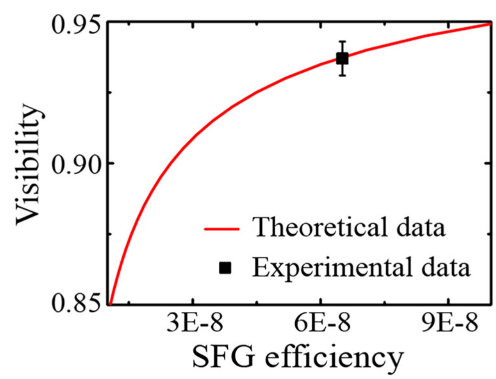

Figure 3. The visibility of the coherent correlation of two long-distance broadband photons.

According to the proposed theories,[7,17] we can obtain the equation for the visibility of the coherent correlation of two long-distance broadband photons, which is given by

$$P = \frac{1}{128}\eta_c^2\eta^2\eta_{SFG}(1-V)^2(7-3V) \quad (1)$$

where P denotes the success probability for the fourfold coincidence, η_c represents the overall coupling efficiency, and η is the efficiency of single photon detection. When $P = 3 \times 10^{-12}$ and $\eta_c = \eta = \sqrt{0.6}$, we can obtain the visibility based on the efficiency of SFG, as shown in **Figure 3**. In our work, the visibility of $V^{EXP} = (93.7 \pm 1.6)\%$ is obtained, which is in agreement with the theoretical result.

We note that the visibility of the coherent correlation increases nonlinearly with the efficiency of SFG, as shown in Figure 3. When one uses the high-quality frequency conversion device presented in Ref. [18] [6-mm-long nonlinear waveguide, $\xi = 3061\%/(W \cdot \mathrm{cm}^2)$], the efficiency of SFG may increase to 3.8×10^{-7}. Thus, the visibility of the coherent correlation of 97% can be obtained in theory.

4. Conclusion

We have successfully demonstrated the feasibility of our approach by using a single photon source. In our experiment, we have demonstrated the SFG between two broadband photons, where the efficiency of the SFG is 6.51×10^{-8}. Therefore, we can establish the high-visibility (93.7%) coherent correlation of two long-distance broadband single photons based on SFG. This technique in our approach marks a critical step toward the implementation of spread-spectrum communication in the quantum network and also has potential applications in quantum entanglement swapping and quantum communication.[19,20]

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Conflict of Interest

The authors declare no conflict of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Keywords

nonlinear optics, single photons, sum-frequency generation

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