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A Wavelength-Tunable Fiber-Coupled Narrow-Band Twin-Photon Source *

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We present a wavelength-tunable narrow-band fiber-coupled source to generate correlated photon pairs at 539 nm and 1550 nm. Using a 10-mm PPLN crystal, we obtain more than 50 mm tunable range near 1550 nm. This source, given its spectral property and tunable property, is well suited for tasks in fiber-optic quantum communication and cryptography networks.

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Photon pairs have become an important resource in experiments on fundamental quantum mechanics and in quantum information science, such as testing Bell inequalities,[1] quantum communications,[2] entangled photon-pair generators,[3,4] heralded sources of single photons,[5] entanglement-based quantum key distribution,[6−9] and so on. Since the first practical and efficient photon pairs source created in a type-Ⅱ BBO bulk crystal,[10] nonlinear optics has experienced great progress, and many important sources have been reported.[11−17] The appearance of periodic poled nonlinear crystals accelerates the process and leads to many exciting results.[18−21] They not only allow us to fully exploit the material's nonlinear properties to obtain more bright sources, but also supply us with a new way to tune the wavelength of the source. This is thanks to their temperature properties and so-called quasi-phase matching (QMP) mechanism. Recently several groups have reported their tunable correlated pair sources,[22−25] and the potential for constructing a quantum network made the tunable source attractive.

However, in most of the previous experiments, cw lasers were used as the pump field, which have good spectral properties. On the other hand, pulsed lasers have good temporal properties, and have been widely used to pump bulk nonlinear crystals to generate good temporal correlated photon sources, such as three photon states,[26] four photon states,[27] and even six photon states.[28] A few attempts[19] have been made to combine the pulse pump and periodically poled nonlinear crystals, which provides a new method to generate wavelength tunable multi-photon states. However, all these sources failed to combine the pulse pump and telecom band together. In this Letter, we report on a novel wavelength tunable photon pair source that may be suitable for applications in future fiber-based quantum networks. We use ultrafast pulse pumped periodically poled lithium niobate (PPLN) to generate photon pairs with wavelengths centered at 1550 nm and 539 nm. Together with the QPM technique, we obtain more than 50 mm tunable range near 1550 nm with a bandwidth of less than 3 nm.

In our source we use picosecond pulses to pump a PPLN crystal. The advantage of a short pulse pump scheme compared with a continuous pump laser is the higher generating rate of multi-photons, which is related to our future work. However, this also brings us a new task of how to control the bandwidth of pairs. A narrow bandwidth is the key factor of the source, for the bandwidth determines the max transmission distance and can decrease the noise of single photon detectors.[29] The theory model shows the band-width is inversely proportional to the pulse width and the length of crystal, so in our experiment we use a long crystal (10 mm) and choose a long pulse (3 ps) as the pump light.

First, we give a brief description of the SPDC process in PPLN. According to the SPDC theory, we can describe the parametric photon pairs generating from PPLN as follows:

$$|\Phi(\omega_i,\omega_s)|^2 \sim |E_p(\omega_p)|^2 \left|\frac{\sin(c\Lambda\Delta\beta/4)\sin\left[N\left(\Delta\beta\frac{\Lambda}{2}-\pi\right)\right]}{\sin\left[\left(\Delta\beta\frac{\Lambda}{2}-\pi\right)/2\right]}\right|^2,$$

where Λ is the period of the PPLN, $N=L/\Lambda$ with L being the length of the crystal, $\omega_{p,s,i}$ are the frequencies of the pump, signal and idler waves, E_p is the pump field amplitude, $\Delta\beta=k_p-k_s-k_i$ is the quantity of the phase mismatch, $k_{p,s,i}$ are the wave vectors of pump, idler and signal waves. In our experiment,

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we use a third order phase matching PPLN crystal of 10 mm length, Λ is 9.675 µm. By setting λ_p at 400 nm, λ_s near 1550 nm, λ_i near 539 nm, where λ_p, λ_s, λ_i are the wavelengths of the pump, signal, and idler waves. Assuming the PPLN being at 329.6 K, we could calculate the signal and idle photons' bandwidth to be 2.46 nm and 0.39 nm respectively. Next we compare the theoretical values with our experimental results. Due to the thermal expansion effect, Λ varies with crystal temperature, and so do the photon-pair wavelengths. The wavelength of the signal approximately linearly varies with the crystal temperature with the slope about 0.88 nm/K.

In the following, we describe our experiment and the results in detail. A schematic drawing of our experimental setup is shown in Fig. 1. The output of the mode-locked Ti:sapphire laser is frequency doubled to generate violet pulses with a width of 3 ps. The full width at half maximum (FWHM) of the spectrum of violet pulses measured by an optical spectrum analyzer (OSA) before the PPLN is about 0.1 nm and the central wavelength is 399.97 nm. Then we use a lens to weakly focus the violet pulses onto the PPLN crystal. After passing through the PPLN crystal, a dichroic mirror (DM) is used to separate the photon pairs and then two low pass filters (LPF) are used to cut the remaining violet pump pulses.

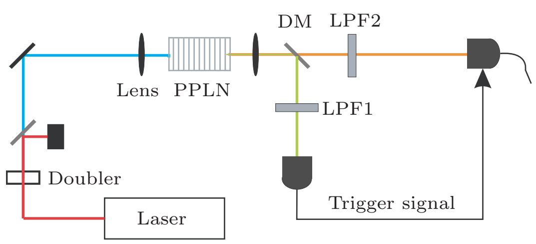

Fig. 1. The experimental setup of our source. Laser: Ti:sapphire laser, doubler: frequency doubler, PPLN: periodically-poled $LiNbO_3$, DM: dichroic mirror, LPF1 and LPF2: low pass filter, L_p and L_s: lens, Si-APD: single-photon detector made of silicon avalanche photon detector, SPD: InGaAs-InP avalanche photodiodes operating in a gated Geiger mode.

Here we briefly give some parameters of the PPLN crystal used in this experiment. The PPLN crystal is cut for type-I phase matching and the grating period is about 9.675 µm, the same as that in our theory model. The size of the crystal is 10 mm $(x)\times 3$ mm$(y)\times$ 0.5 mm(z), where z, y and x are the mean height, width and length, respectively. The crystal is placed in a built-in temperature controller which can vary the temperature between 273 K and 573 K with a stability of 0.1 K.

We measured the spectrum of signal photons by an InGaAs FC-coupled photodetector (Thorlabs, Ltd, SIR5-FC) and the result is shown in Fig. 2. When performing these measurements, we fix the crystal at 330 K, and $\lambda_p = 399.74$ nm. The result is a good approximation for different temperatures because the photons' bandwidth is almost independent of crystal temperature. Figure 2 shows that the FWHM of signal photons is 2.05 nm centered at 1549.28 nm, in good agreement with our theoretical prediction of 2.46 nm (329.6 K, $\lambda_p = 400$ nm).

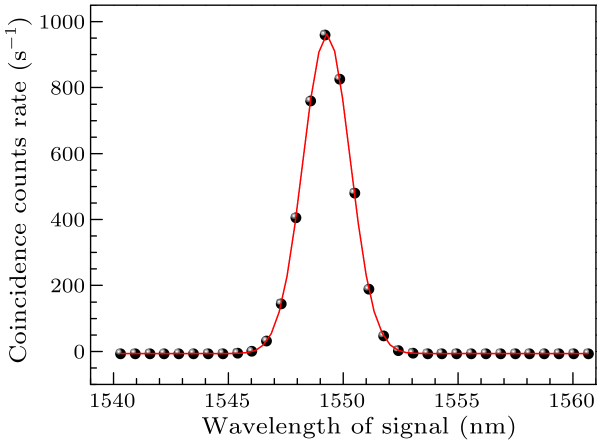

Fig. 2. Spectrum of signal photons.

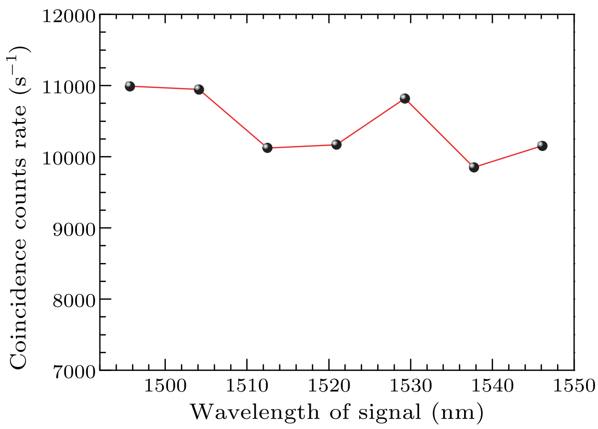

Fig. 3. Coincidence count rate versus the central wavelength of signal photons.

The main advantage of this source is that the wavelength is continuously adjustable, and we have two different methods to tune the wavelength. First, we can vary the temperature of the PPLN crystal to adjust the photon-pair wavelengths. We measured the central wavelength of signal photons from 326 K to 336 K at different temperatures and the result is shown in Fig. 3. The signal photon's wavelength is nearly linearly dependent on the crystal's temperature with a vary rate of 0.84 nm/K. Since the crystal can work from room temperature to 473 K, we can easily reach more than 50 nm tunable range at the telecom band, which is enough for practical applications. Figure 3 shows our experimental results for observing the tuning range of the signal photons at the telecom band. We change the crystal's temperature from 305 K to 365 K, and the signal photon's wavelength varies from

1495 nm to 1546 nm, correspondingly. In the tuning range, we find that the coincidence count rate changes slowly with the wavelength.

Second, we can tune the wavelength of the pump light. The Ti:sapphire laser itself is wavelength tunable. Thus we can tune photon-pair wavelengths easily by adjusting the laser's wavelength. When the pump wavelength $\lambda_p = 399.740$, 399.866, 399.966 nm and setting the crystal temperature at 330 K, the central wavelengths of signal photons are 1549.3 nm, 1546.2 nm, 1545.1 nm respectively. The changing rate of the signal photons is about 35.4 nm(signal)/nm(pump). By using these two tuning methods the source is suitable for the task of tuning a wavelength (e.g., signal photons), while we need to keep another wavelength standing at the same time, and this makes the source more practicable.

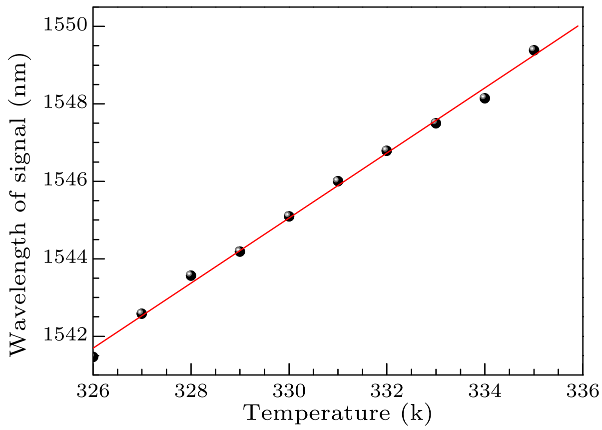

Fig. 4. Central wavelength of signal photons plotted versus the temperature of the PPLN crystal.

For the correction of photon pairs and the coincidence counting rate, we could obtain a coincidence detection count up to 22.4 K/s (with gating time at 2.5 ns) while the idle photon count-rate is 565 K/s when the pump power is 47 mW and crystal is at 329.6 K. This means that the coincidence detection rate is 4%. Considering that our APD's detection efficiency at 539 nm is about 50% and the InGaAs-APD's detection efficiency is about 16%, we can calculate the coupling efficiency of signal photons to be about 25%. Due to the low detection efficiency at the telecom C-band, our source will reach a coincidence rate higher than the degenerate photon sources with the transmit distance. This is the reason why we chose idler photons near 539 nm.

In summary, we have reported a completely new two photon source by using a picosecond pulse to pump the PPLN crystal. The source is a narrow band (< 3 nm) and the wavelength is continuously tunable by varying the temperature of PPLN or tuning the wavelength of the pump photons. By setting the idler photons in the visible band, we obtain another advantage of high coincidence efficiency compared with the degenerate scheme at the telecom band. Our experimental result confirms that the pulse pumped periodically poled nonlinear crystal is also efficient to generate photon pairs. Note that the tunable range at 1550 nm is more than 50 nm, which can fulfill the telecom band at 1550 nm. Together with dense wave division multiplexing technology, the new photon source may be used to construct a quantum network.

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