Generation of pulsed polarization entangled photon pair via a space cascaded two-crystal geometry

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The generation of pulsed polarization entangled photon pair has been realized using type-I phase matching in the spontaneous parametric downconversion process in a space cascaded two-crystal geometry. The optical axes of the crystal are aligned in such a way that the horizontal polarization photon pair is produced from up crystal, and the vertical polarization photon pair is produced from down crystal. These two processes are simultaneous, but are separable in space. We get the high entangled polarization photon pair by using the single mode fiber to erase the spatial information between these two processes. This photon pair exhibits more than 86% high-visibility quantum interference for polarization variable without the narrowband filter and temporal compensation.

Quantum entanglement is one of the most striking features of quantum mechanics. Entangled states of two or more particles not only provide possibilities to test basic concepts of quantum mechanics[1], but also form the basis of quantum information, make such phenomena as quantum cryptography [2], teleportation [3], dense coding [4] and quantum computation [5] possible. So, it is clear that preparation of maximally entangled state, or Bell state, is an important subject in modern experiment quantum optics. At present, the most accessible and controllable source of entanglement is the process of Spontaneous Parametric Down-Conversion (SPDC) in a nonlinear crystal. [6-10] SPDC can be used to generate the entangled photon states using type-I or type-II phase matching. In type-I phase matching, the two paired down-converted photons have the same polarizations and they emitted along concentric cones around the direction of pump beam. In type-II phase matching, the down-converted photons have orthogonal polarizations. Those differently polarized photons are emitted along two different cones with cone axes at opposite sides of the pump beam. For two particular emission directions, the correlated photons are produced in the state $|HV\rangle + |VH\rangle$ [10]. Recently, Kwiat et. al used two thin nonlinear crystals to prepare Bell state using non-collinear type-I SPDC. [11] In their scheme, these two crystals were arranged in cascade with their optical axes perpendicular to each other. By pumping with two orthogonally polarized pump beams, one can generated, for example, horizontal photons from the first crystal or vertical photons from the second crystals. With cw pump, these two down-conversions are mutually coherent and form an entangled state. Another kind of entangled state called “Time-Bin” entangled was discussed by Gisin’s group [12]. In cw pumped SPDC, there are readily available well-developed methods of preparing the polarization Bell state. For applications in quantum information field, cw pumped SPDC is not very useful, because the entangled photon pairs occur randomly with the coherence length of the pump laser. This huge time uncertainty makes it difficult to use in many applications, such as quantum teleportation, quantum swapping, the generation of multi-photon entangled state [13] and so on, because in these processes, the interaction between different photons generated from different sources are required. One way to solve this difficulty is using a femtosecond pulsed laser as a pump. Unfortunately, femtosecond pump pumped type-II SPDC shows very poor quantum correlation compared to cw case due to the very different behavior of two-photon wavepacket [14]. In order to get high visibility of quantum interference, usually, two ways are used: one is using very thin nonlinear crystal; another way is using a very narrow interference filter in front of detector. But even we use one of these two ways or both, we also can not achieve high interference visibility in principle [14], besides reduce the available flux of entangled photon pair significantly.

Recently, Kim et. al present a way for preparation of Bell state using femtosecond pulse pumped SPDC. [15, 16] In their scheme, an interferometric technique is used to remove the intrinsic distinguishability in femtosecond-pulse-pumped SPDC process. The two photon entangled state exhibits high-visibility quantum interference. The advantages of this method is: visibility is insensitive to the thick of crystals, also insensitive to the narrow-band filter. Usami et. al [17]used the same crystal geometry as Kwiat’s, but pumped by femtosecond pulse laser to produce entangled polarization photon pair. In order to restore the high entanglement, they used a narrow band interference filter in their experiment. Nambu et. al [18] used the same crystal but used pre-compensation method to get high entanglement. Bitton et. al [19] also present a scheme to produce the polarization-entangled photon pair pumped by femtosecond laser. The geometry of crystal is also similar to Kwiat’s geometry. The difference is two cascaded crystals are cut with type-II phase matching. Very recently, Kim and Grice [20] give a theoretical method to generate the pulsed polarization entangled
 photon pair via temporal and spectral engineering. In schemes [15, 16, 18, 19], a suitable optical delay should be included. If without this delay, no Bell state can be produced. In Ref. [17], a very narrow band interference filter is needed in order to get good quantum correlation.

In this paper, we present a novel way to produce pulsed polarization entangled photon pair using type-I phase matching SPDC process in a space cascaded two-crystal geometry, this polarization entangled photon pair exhibits high-visibility quantum inference for polarization experimentally. The main advantages of this scheme are as follows: we do not need to consider the suitable time compensation; In principle, visibility should be insensitive to the thickness of crystal, so we can use thicker crystal to increase the intensity of photon pair; The post-selection on spectrum by the narrow bandwidth filter is not needed. In the follows, we show our scheme in detail.

In our two-crystal geometry, two identical 5x2.5x1mm BBO crystals (produced by CASIX optronics Inc.) are used. They are oriented with their optical axes aligned in perpendicular plane, and stacked in vertical direction. Please refer to Fig. 1. These two crystals are cut collinearly in type-I phase matching, phase matching angle \( \Theta_m = 29.18^\circ \). If one beam with diameter \( a \) and 45 degree polarization pumps these two crystals, then for example, up crystal will produce horizontal polarization photon pair \(|HH\rangle\), and down crystal will produce vertical polarization photon pair \(|VV\rangle\). Obviously, these two processes are simultaneous, but are separable in space. If we make the spatial information about these two possible SPDC process indistinguishable, (In our experiment, we use the single mode fiber to realize it.) then these two possible downconversion processes are coherent. In our two-crystal geometry, we just consider the collinear process, so a postselection on amplitude is needed in order to get the polarization entangled state \(|HH\rangle + |VV\rangle\). (But postselection is not needed in principle, for example, we can use non-degenerated phase matching to solve it)

Observation of high-visibility quantum interference is a test of the degree of quantum entanglement. In quantum interference experiment for polarization, more than 86% visibility of two-photon quantum interference is obtained without narrow band filter and any time compensation. Consider the experimental setup shown in Fig. 2. A femtosecond laser from a mode-locked Ti: sapphire laser (coherent: Vitesse) is used to pump a 1mm BBO crystal cut with type-I phase matching to get frequency doubled radiation. The wavelength of femtosecond laser is 800nm, the pulse width is less than 100fs. Power of laser is about 870mw. Repetition rate is 80MHz. A prism, two dichroic mirrors which transmit 800nm light and reflect 400nm light, one 40nm interference filter with center wavelength 400nm and a polarizer are combined to cut remainder 800nm light. After pass a half waveplate, about 70mw 400nm laser with 45 degree polarization is used to pump our two-crystal SPDC source. We use another two dichroic mirrors and one prism to cut remainder 400nm light. After that, we couple photon pair to a 1m long single mode fiber (operation wavelength 800nm). The output of fiber is input to a 50/50 beamsplitter. At each output port of the beamsplitter, a detector package consisting of a Glan-Thompson analyzer A1 or A2 and a single-photon detector (PerkinElmer SPCM-AQR-14-FC) are placed. We do not use any narrow interference filter before detector, just place a bandpass filter (CVI company, LPF-750-1.00, transmit from 750nm) before the beamsplitter. The outputs of detectors are sent to coincidence circuit for coincidence counting. The coincidence circuit consists of a time-to-amplitude converter and single-channel analyzer (TAC/SCA) and a counter. The time window of coincidence counting is 2ns. The key of this experiment is how to make coincidence counting producing from two crystals equal. In experiment, we do it by adjusting the height of crystal. Then we fix the polarizer A2 in 45 degree, and rotate the polarizer A1 with each step 10 degree. From theory, we know, for the state \(|HH\rangle + |VV\rangle\), it should exhibit the polarization interference in coincidence counting rate if we do the two-photon interference experiment, and interference pattern should correspond to the expression: \( R_c \propto \cos^2(\Theta_1 + \Theta_2) \), where, \( \Theta \) and \( \Theta \) are angles of polarizer A1 and A2. Experimentally, we get the polarization interference pattern shown in Fig. 3. The visibility is more than 86% (including accidental coincidence counting). In principle, visibility should be 100%. The reason that it does not reach 100% , we think, it mainly is that the photon pairs from different crystals are not equal exactly. We can make them equal in principle, but it is difficult during the experiment. From the Fig. 3, we see that the first peak is lower than the second peak. We try experiment several times, this phenomena always exists, so we think that it may be caused by the small position shift of polarizer when it is rotated. During experiment, the single counting is almost unchanged. We measure that the fluctuation of single counting is less than 7%. This small change maybe due to expectedly high background light, for example, from BBO crystals. In our experiment, background count is almost equal to true single count from SPDC [21]. Such high background light mainly consists of two parts: one is from bad dark condition of our laboratory; another is from light reflected from many optical components, such as prisms, BBO crystals, mirrors etc. To make sure the state is really a polarization Bell state, we change the polarizer A2 to different angles and do the same experiments. Experimentally, interference patterns also shift the same angle as polarizer A2 shifts and almost same visibilities of quantum interference are observed, which means that the state we observed is truly a polarization entangled state.

One of main advantage of this scheme is that no any temporal compensation is needed. In our setup, two pumps arrive at crystal at the same time. In each crystal, the SPDC light is ordinary light, so no delay is introduced between two SPDC processes if two crystals have same length. The photon pair from up or down crystal leaves the crystal at the same time averagely, they are just sepa-
rable in space. So from temporal point, we do not need to do any compensation like in previous experiments [15–19] using optical delay or narrow band interference filter. Another advantage is that our scheme is insensitive to length of crystal. The wavepackets of photon pairs from up crystal and from down crystals are the same irrespective of crystal length. So, we can increase photon pair flux by using thicker crystal. The disadvantage of this scheme is that it need erase the space distinguishable information between two possible SPDC processes. In our experiment, we use the degenerate collinear phase-matching, so it need amplitude postselection to get the entangled state. But in principle, we can overcome this problem, for example, using collinear non-degenerate phase-matching.

The other three Bell states can be prepared by inserting the combination of a half waveplate and a π phase shifter. Using our scheme, non-maximally-entangled state, i.e., states of the form $|HH + eVV, \phi \rangle$, where $|\phi \rangle \neq 1$, may be produced, simply by adjusting the height of crystals or the angle of half waveplate. This kind of state has been shown useful in reducing the required detector efficiencies in loop-free tests of Bell’s inequalities [22]. Moreover, by our scheme, the arbitrary (partially) mixed state of type $\cos^2 \theta |HH\rangle + \sin^2 \theta |VV\rangle$ can be produced. We need only do no compensation in space (for mixed state) or partially compensate in space (for partially mixed state).

In summary. We present a novel scheme to produce Bell state using femtosecond pulse pump. We also show strong polarization correlation experimentally. One of main advantage is that no optical delay or narrow band interference filter for high quantum interference visibility. Besides, we can use thick crystal to get high intensity of photon pair. The disadvantage of this scheme is that the spatial compensation is needed.

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Fig. 1..
Fig. 2
