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# Quality of polarization entanglement in spontaneous parametric down conversion

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**Abstract.** We experimentally demonstrated a high degree of polarization entanglement known as entanglement visibility through spontaneous parametric down conversion process pumped by a femtosecond laser. The entangled-photon pair was obtained using two type-I BBO crystal. The down-converted photons from these crystals demonstrates a high visibility of 98.7% ($\Theta 2 = 0^{o}$) and 90% ($\Theta 2 = 22.5^{o}$). These results are in agreement with the theory which expects high visibility from such arrangement.

## 1 Introduction

Entanglement, a counterintuitive phenomenon of quantum mechanics plays a crucial role in many interesting application in quantum mechanics such as in the development of quantum computation, quantum information, and quantum cryptography [1]. It is also the main point of the debate in foundation issues and interpretation of quantum mechanics since firstly pointed out by Einstein, Podolsky and Rosen in their renowned paper [2]. Entangled state of spin-1/2 particle has been utilized in Ekert's proposal [3] to realize quantum cryptographic protocol based on the notion of quantum non-locality (i.e. Bell theorem). Such cryptographic protocol was experimentally demonstrated for the first time using polarization-entangled photon [4]. Entanglement is also an efficient alternative source for single-particle quantum key distribution protocols (see for instance: [5]).
Furthermore, it has been proved that the protocol using entangled photon has the potential to extend the length of communication distance in the presence of realistic experimental imperfection [6]. These significant examples strongly highlight the importance of entangled photon generation. In today's technology, the most accessible and controllable source of entanglement comes from spontaneous parametric down conversion (SPDC) through stochastic process in the interaction between light and nonlinear optical materials [7]. It is necessary to mention here that the study on optimization of the process will contribute much to the development of unconditional secure communication.
Spontaneous parametric down conversion process in nonlinear optical materials is utilized in order to create one of four Bell states which are maximally entangled. The states can be mathematically written as follows:

$$\left|\Phi_{12}^{\pm}\right\rangle = \frac{1}{\sqrt{2}}\left(\left|H\right\rangle_1 \otimes \left|V\right\rangle_2 \pm \left|V\right\rangle_1 \otimes \left|H\right\rangle_2\right),$$

$$\left|\Psi_{12}^{\pm}\right\rangle = \frac{1}{\sqrt{2}}\left(\left|H\right\rangle_1 \otimes \left|H\right\rangle_2 \pm \left|H\right\rangle_1 \otimes \left|H\right\rangle_2\right)$$

where, $\left|H\right\rangle\left(\left|V\right\rangle\right)$ denotes Horizontal (Vertical) polarization of the photons. We use the notation $\otimes$, as a tensor product describing a composite system of two spatially separated photons.
In this letter, we report experimental results on the entanglement polarization from type-I phase matching down conversion processes by using femtosecond-pulse laser pumping. We shall demonstrate that highly entanglement polarization states with sufficiently large flux were obtained when an appropriate temporal compensation was given in the pump pulses. The resulted will be shown to be consistent with the theory of visibility which incorporates the coincidence rate as a function of the polarization analyzer angle.

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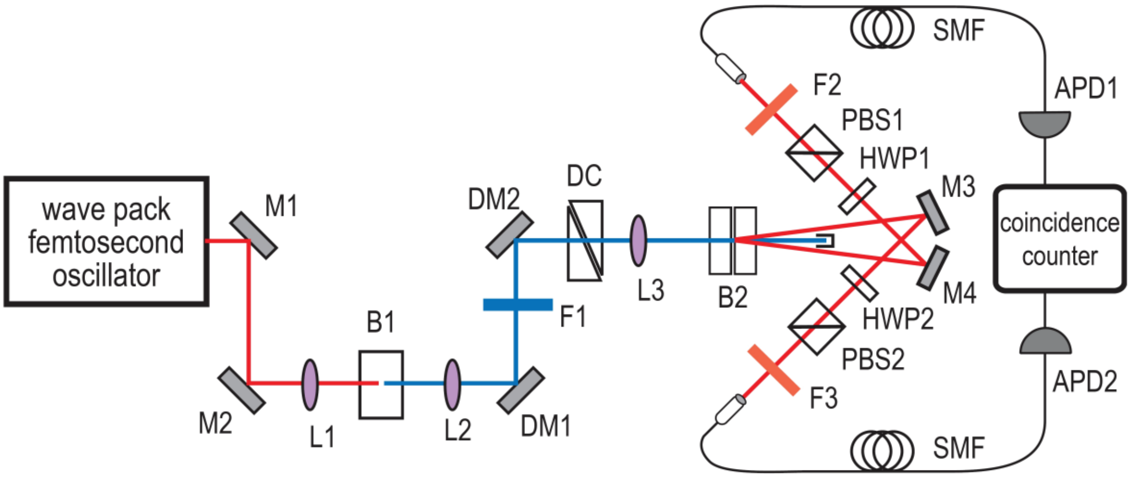



**Fig. 1.** Schematic of experimental setup used for generate polarization-entangled photon from spontaneous parametric down-conversion processes in the two type-I β-BBO (β− $BaB_2O_4$ - Beta Barium Borate) crystals. M, mirror; L, lens; B, β-Barium Borate crystal; F, color filter; DM, dichroic mirror; DC, delay compensator; HWP, half-wave plate; PBS, polarizing beam splitter; SMF, single mode fiber; APD, avalanche photo diode detector

## 2 Experimental setup

An experimental setup for generation of polarization entangles state, by spontaneous parametric down-conversion (SPDC) processes in a nonlinear crystal, is shown in Fig 1.
The configuration uses an active mode-locked femtosecond Sapphire oscillator emitting pulses of light at 794 nm. This radiation was frequency doubled by using 1 mm type-I β-BBO (β−BaB2O4 - Beta Barium Borate) crystal (B1), cut for collinear second harmonic generation (SHG) processes, to provided 200 fsec pulses (FWHM) at center-wavelength of 397 nm, with a repetition rate of 80 MHz and maximum power of ~300 mW. A pair of dichroic mirrors (M3 and M4) and a color glass filter (F1) were used to remove the residual fundamental wavelength coming from the femtosecond sapphire oscillator.

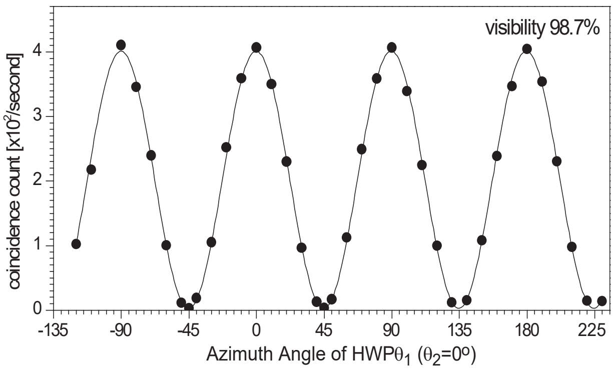
The cascaded type-I BBO crystal (B2) was placed at the waist position of the sequence femto second pulse collimated by lenses L2 and L3. Each crystal was designed in certain cut-angle to achieve phase matching condition for non-collinear frequency degenerate down conversion. The crystal are rotated with respect to other in such a way that horizontally polarized pump light generates pair of vertically polarized photon in the first crystal, and vertically polarized pump light generate pairs of horizontally polarized photon in the second crystal [7]. In order to generate a pair of polarized entangled photon we used pump beam polarized at 45° with respect to the crystal axis. By neglecting losses from passing through the first crystal, this polarized pump photon will be equally likely to down-convert in either crystal. Nevertheless, because of the combined effects of group velocity dispersion and birefringence in the two crystals, the space-time components of the two-photon state associated with the polarized states and are expected to be temporally displaced after the crystals. As a result, information about "which-polarization" the emitted photon pair has, as well as "which crystal" each pair originated from, may be available from the arrival time of the photon at the detector. On the other hand, the effective polarization entanglement requires the suppression of any distinguishing information in the other degrees of freedom that can provide potential information about the emitted pair have.

To eliminate this distinguishing space-time information, a polarization dependent optical delay line for the pump was inserted before the crystal, which is denoted as the delay compensator (DC) in Figure 1. The delay compensator was used as the pre-compensator for group velocity mismatch between ordinary and extraordinary rays in the BBO crystal, so that the state associated with $|HH\rangle$ created in the first crystal relative to the state associated with $|VV\rangle$ created in second crystal overlapped with them temporally. As the result, a two-photon Bell state $|VV\rangle+|HH\rangle,$ can be directly created.

To experimentally demonstrate the polarization entanglement of the collected photon pairs, their polarization correlations in two conjugate bases were measured. This was done by directing the down-converted light into adjustable polarization analyzers, each consisting of a polarizing beam-splitter cube (PBS) preceded by a rotatable half-wave plate (HWP). The residual violet light coming from the first BBO crystal was blocked using long-pass filters. After passing through the analyzers, the photons were coupled into single-mode fibers by using the aspheric coupling lenses with focal length of $f$ = 7.5 mm, the desired spectral bandwidth and the numerical aperture of the optical fiber, and then detected with passively quenched silicon avalanche photon diodes (Si-APDs). The detectors were linked to a time-to-amplitude converter for a record of coincidence counts. To keep the experimental setup compact, two mirrors (M3 and M4) were used to fold the paths of the fluorescence beams.

## 3 Results and Discussions

The experiments were carried out to confirm whether the polarized-entangled photon state $|\Psi^+\rangle$ was successfully prepared. The first measurement was performed by setting the azimuth angle of HWP in path-2 $\theta_2$ to be 0° and the HWP in path-1 rotated. During the second measurement, the azimuth angle of HWP in path-2 $\theta_2$ was set to 22.5°, with the azimuth angle of HWP in path- 1 rotated. This setup corresponds to the projection measurement onto $|L\rangle \otimes |\theta\rangle$ or $|R\rangle \otimes |\theta\rangle$ where $|L\rangle = (|H\rangle + i|V\rangle)/\sqrt{2}$ and $|R\rangle = (|H\rangle - i|V\rangle)/\sqrt{2}$, while $|\theta\rangle = cos\,\theta|H\rangle + i\,sin\,\theta|V\rangle$. Since the density matrix of the states approximately described by $\hat{\rho} = p|\psi^+\rangle\langle\psi^+| + q|\psi^-\rangle\langle\psi^-|$ where p and q are probabilities of finding our system in the state $|\psi^+\rangle$ and $|\psi^-\rangle$, respectively, the state should exhibit interference in coincidence rates for the two detector in proportion to $R_c(\theta_1,\theta_2) \propto \cos^2(\theta_1 - \theta_2)$.



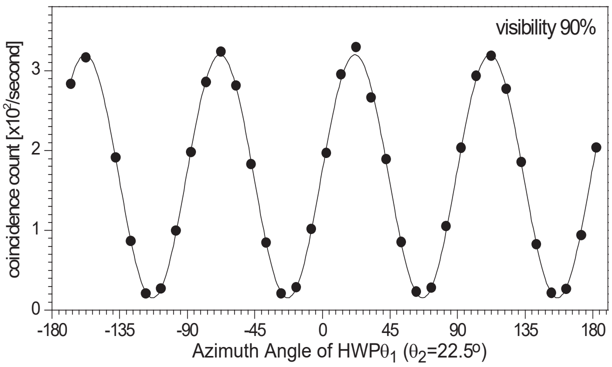




**Fig. 2:** Plot of coincidence rate as a function of idler polarization analyzer angle $\theta_1$. (a) Signal polarization analyzer was set at $\theta_2$ = 0°. The solid curve is a best fit, with visibility of V = 98.7%. (b) Coincidence rate for the signal at polarization analyzer at $\theta_2$ = 22.5°, with the visibility of 90%.

To evaluate the quality of a polarization entangled-photon state, we use the polarization visibility equation $V = (R_{cMax} - R_{cMin})/(R_{cMax} + R_{cMin})$, The equation states that one should observe high-visibility modulation in polarization correlation measurement for certain values of $\theta_1$ and $\theta_2$. The visibility was determined by a fit of the data with cosine-squared function of coincidence rates. Figure 2 shows the coincidence rate as a function of the HWM angle in path-2 and the evaluated visibility values.

The solid lines in Figure 2 are coincidence rates curve fitted to the measured data (dark circles). In this experiment, the values of visibility for the azimuth angles HWP in path-2, $\theta_2$ of 0° and 22.5° were 98.7% and 90%, respectively. Since the visibility of an observed interference pattern gives another convenient measure for the entanglement, this result clearly demonstrate that the high degree of polarization entanglement has been achieved in this experiment setup.

## 3 Summary

We have demonstrated a scheme to prepare pulse polarized-entangled photon pairs by femtosecond pulse-pumped SPDC in a cascade of two type-I crystals. The highly polarized entangled photon pairs were successfully obtained by using the pre-compensator optical component which appropriate to temporally delayed the orthogonal polarization components for the pump.

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