Post-Selection-Free Mode-Locked Two-Photon State for High-Dimensional Hyperentanglement Generation

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Abstract: We report realization of high-dimensional hyperentanglement in frequency and polarization from a postselection-free mode-locked two-photon state. Quantum-interference dips and revivals are observed with 97.8% visibility and a Bell inequality is violated in polarization.

OCIS codes: (270.0270) Quantum optics, (270.5855) Quantum information processing

Recent developments of quantum communication technology are demanding that more information be encoded in an entangled photon pair. Such photon pairs can either be entangled simultaneously in different degrees of freedom, something known as hyperentanglement [1], or entangled in a high-dimensional space [2]. In particular, entangled two-photon state with comb-like spectrum has raised great interest in the form of high-dimensional frequency-bin entanglement, and is known for its surprisingly mode-locked behavior in two-photon interference experiments [3]. Previously, this mode-locked two-photon state (MLTS) was generated in a type-I phase-matched downconverter, which required postselection to separate the signal and idler, placing a theoretical upper limit of 50% on the visibility of two-photon interference.

Here we report the first telecommunication-wavelength MLTS that does not require postselection. Our experiment uses a type-II phase-matched periodically-poled $KTiOPO_4$ (PPKTP) waveguide together with a fiber Fabry-Perot cavity (FFPC). Furthermore, hyperentanglement is demonstrated with high-dimensional frequency-bin entanglement and polarization entanglement, with up to 10 quantum bits from a single photon pair. Because of the type-II phase matching, the signal and idler photons can be separated with 100% efficiency by means of a polarizing beam-splitter (PBS) such that MLTS, as first proposed theoretically in [4], can be generated experimentally for the first time. Quantum interference dips and revivals were observed with ~97.3% visibility in a Hong-Ou-Mandel (HOM)-type interferometer, providing evidence of the high-dimensional frequency bins in the spectral domain. Polarization entanglement was demonstrated by violation of Bell's inequality by up to 17.7 of standard deviations.

Figure 1 shows our experimental scheme. Entangled photon pairs were generated at frequency degeneracy by a spontaneous parametric downconverter (SPDC) built with a high-efficiency type-II phase-matched PPTKP waveguide that has been studied in detail [5]. 17 frequency bins can be filtered out using the FFPC within the SPDC bandwidth, which is equivalent to 4 quantum bits. A polarizing beam splitter was used to separate the orthogonally-polarized signal and idler photons. A half-wave plate and a quarter-wave plate were used in the upper arm to control the polarization of the signal photon, so that the two photons can be either co-polarized or orthogonally polarized at a 50/50 fiber coupler. Two fiber polarization controllers were used to ensure that the polarizations did not change after passing the fiber coupler. The coincidence measurement was performed with two InGaAs single photon detectors D_1 and D_2.

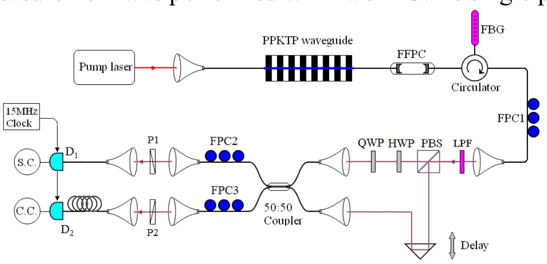

Fig. 1. Experimental scheme for generating the mode-locked two-photon state. FFPC: fiber Fabry-Perot cavity; FBG: fiber Bragg grating; FPC: fiber polarization controller; LPF: long-pass filter; PBS: polarizing beam splitter; P: polarizer; S.C.: singles counting C.C.: coincidence counting.

When the polarization of the signal photon was adjusted to be the same as the idler at the fiber coupler, the setup is ready for the two-photon interference measurement. Figure 2(a) shows the experimental results. We obtained coincidence-counting dips and revivals at the two outputs of the HOM interferometer. The visibility of the dips decreased exponentially due to the Lorentzian spectra of the single-frequency bins. Figure 2(b) zooms in on the dip at zero delay. Its maximum visibility was measured to be 85.7+/-0.5% without dark-count subtraction, and 97.3% after accounting for the 24.8s^{-1} dark-count rate.

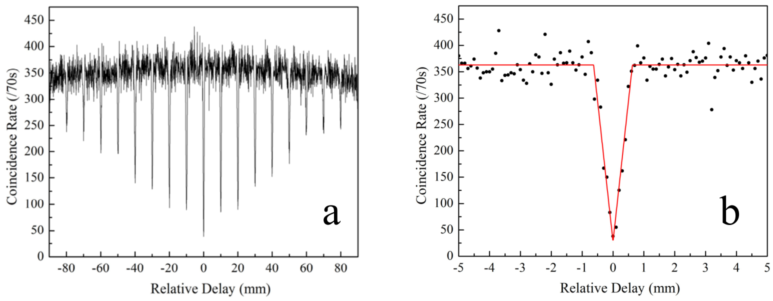

Fig. 2. (a) Coincidence-counting rate as a function of the relative delay between the two arms of the HOM interferometer. (b) Zoom-in on the coincidence rate around zero delay between the interferometer's two arms.

Next we rotated the half-wave plate by 45°, so that the signal and idler photons hit the 50/50 fiber coupler with orthogonal polarizations. We present a Bell-inequality test for the polarization entanglement when P1 was set at 45° and -90°, respectively. As shown in Fig. 3, both results are well fit by sinusoidal curves — with visibilities of 91.2+/-1.6% and 93.0+/-1.3% — that violate Bell inequality by 12.8 and 17.7 of standard deviations, respectively. This indicates that a high-quality high-dimensional hyperentangled state was generated.

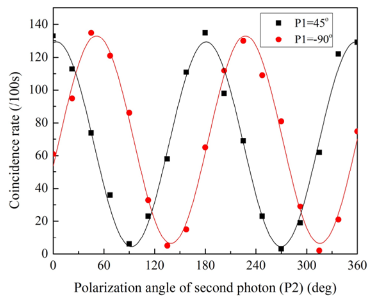

Fig. 3 Bell inequality test of the polarization entanglement with P1=45° (black line) and P1=-90° (red line).

In summary, we have generated a high-dimensional hyperentangled MLTS in frequency and polarization degrees of freedom from the type-II phase-matched SPDC in a PPKTP waveguide. A maximum of 97.8% visibility in a HOM interferometer was been obtained and Bell's inequality is violated by up 17.7 of standard deviations in the measurement. Such high-dimensional hyperentangled state encodes 5 quantum bits per photon (4 frequency bits and 1 polarization bit), allowing applications in dense quantum information processing and secure quantum key distribution channels.

We acknowledge discussions with J. Poekert, M. Itzler, and J. Liang. This work is supported by the DARPA InPho program under contract number W911NF-10-1-0416.

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