Quantum interference between weak coherent light and SPDC photon pairs for three-photon time-bin entangled state generation

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A photon is an important information carrier in quantum communication. As we know, polarization qubits have been widely used because it can be easily operated with optical components, but its quantum state is perturbed due to the polarization mode dispersion in long distance optical fiber transmission. A time-bin state is a coherent superposition of two temporal mode $|t_1\rangle$ and $|t_2\rangle$ states. It had been used in many optical fiber-based quantum communication because of its robustness against polarization disturbance in optical fibers.

For the three-photon time-bin entangled state generation, we prepared time-bin single photon source by a weak coherent light of $\frac{1}{\sqrt{2}}(|t_1\rangle + |t_2\rangle)_{A'}$ and time-bin entanglement by spontaneous parametric down-conversion (SPDC) process of $\frac{1}{\sqrt{2}}(|t_1,t_1\rangle + |t_2,t_2\rangle)_{B'C}$. In order to manipulate different temporal modes of time-bin qubits, we used a high speed two-input, two-output (2x2) optical switch. The 2x2 optical switch operation can be expressed as $a_{A'}^{\dagger}(t_k) = a_A^{\dagger}(t_k)cos\left(\frac{\theta(t_k)}{2}\right) - a_B^{\dagger}(t_k)sin\left(\frac{\theta(t_k)}{2}\right)$ and $a_{B'}^{\dagger}(t_k) = a_A^{\dagger}(t_k)sin\left(\frac{\theta(t_k)}{2}\right) + a_B^{\dagger}(t_k)cos\left(\frac{\theta(t_k)}{2}\right)$, where $\theta(t_k)$ denotes the phase set by the optical switch at time t_k, $k \in \{1, 2\}$ and index A' (A) and B' (B) are the input (output) ports of 2x2 switch, respectively [1]. It had been used to demonstrate the entanglement generation and quantum logic gates for time-bin qubits by modulating the 2x2 optical switch as a time-dependent beam splitter (TDBS) [1] and partially TDBS [2]. Based on these previous researches, we propose the three-photon time-bin entanglement generation scheme using a TDBS, and set it to $\theta(t_1) = 0$ and $\theta(t_2) = \pi$, as shown in Fig. 1 (a). By operating the TDBS to the input states, we can generate three-photon time-bin entanglement of $\frac{1}{\sqrt{2}}(|t_1,t_1,t_1\rangle - |t_2,t_2,t_2\rangle)_{ABC}$ in the output ports after the post-selection measurement on three-fold coincidences.

As a preliminary experiment, we performed quantum interference between the independent light sources by setting the switch as a half beam splitter ($\theta(t_k) = \frac{\pi}{2}$) for both temporal modes without placing 1-ns delay Mach-Zehnder interferometers (MZI) in front of the SSPDs. We measured three-fold coincidences (Coin.) while changing the delay time between two photons using the optical delay line (DL). The visibility of the HOM-dip interference [3] was 0.78 ± 0.001 (Fig. 1. (b)).

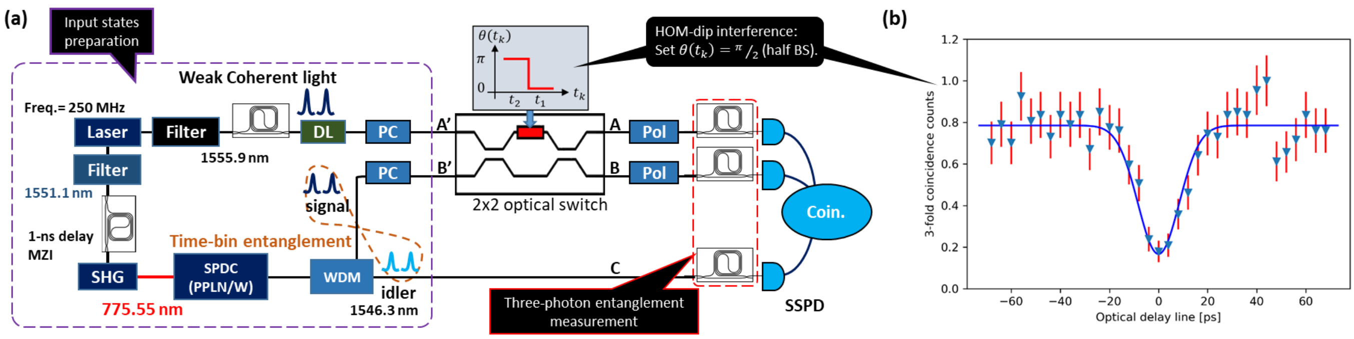

Figure 1. (a) Experimental setup for three-photon time-bin entanglement generation and measurement. SHG: second harmonic generation, PC: polarization controller, Pol: polarizer, PPLN/W: periodically poled lithium-niobate waveguide, SSPD: superconducting single-photon detector. (b) HOM-dip interference by setting a 2x2 switch as a half BS.

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[3] C. K. Hong, Z. Y. Ou, and L. Mandel, Phys. Rev. Lett. 59, 2044 (1987).