A Time-Bin Qubit Entangler based on Photon Switching

Hiroki Takesue
NTT Basic Research Laboratories, NTT Corporation, 3-1 Morinosato Wakamiya, Atsugi, 243-0198, Japan
e-mail: takesue.hiroki@lab.ntt.co.jp

Abstract: I present a simple scheme for entangling two independent time-bin qubits using quantum interference at a high-speed 2x2 optical switch. Non-classical two photon interference fringes were observed experimentally by using the proposed scheme.
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A time-bin qubit is a coherent superposition of single photon states in two or more different temporal modes [1]. Since this qubit possesses only a single polarization mode, it has been intensively used in quantum communication over optical fiber, where it is generally difficult to preserve the state of polarization because of its birefringence. In contrast, most photonic quantum information processing experiments have been undertaken using polarization qubits [2]. This is mainly because single and two-qubit gate operations are well established with polarization qubits, while they are largely unexplored with time-bin qubits. Although it is well known that a time-bin qubit can be converted into a polarization qubit using a simple linear optics circuit [3], such qubit conversion is accompanied by additional experimental errors and losses and is thus hard to implement in real systems. In this paper, I propose and demonstrate a simple scheme for implementing a two-qubit operation, namely an "entangling" operation to two independent time-bin qubits. The proposed scheme is useful for realizing various quantum gates such as controlled-Z gates and fusion gates for cluster state quantum computation [2] with time-bin qubits.

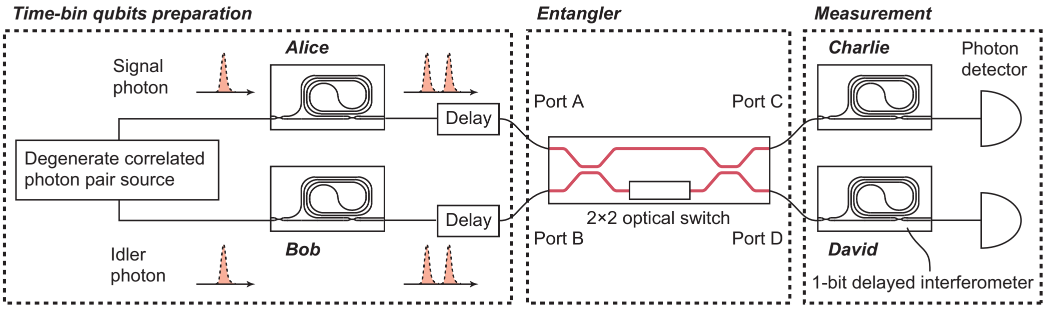

Fig. 1: Experimental setup.

Figure 1 shows the setup of the proposed scheme, which is based on two-photon quantum interference at an optical switch based on a Mach-Zehnder interferometer with 2 input and 2 output ports (2x2 optical switch). Alice and Bob prepare time-bin qubits whose states are given by $\frac{1}{\sqrt{2}}\left(a_A^\dagger(t_1)+e^{i\phi_A}a_A^\dagger(t_2)\right)|0\rangle$ and $\frac{1}{\sqrt{2}}\left(a_B^\dagger(t_1)+e^{i\phi_B}a_B^\dagger(t_2)\right)|0\rangle$, respectively. Here, $a_X^\dagger(t)$ denotes a creation operator for mode X (=A: Alice, B: Bob) and the temporal position t. t_1 and t_2 correspond to the temporal positions of the first and second temporal modes that compose the time-bin qubits. These photons are launched into the 2x2 optical switch. The evolution of the operators with the switch can be described as $a_A^\dagger(t_k)=a_C^\dagger(t_k)\cos(\theta(t_k)/2)-a_D^\dagger(t_k)\sin(\theta(t_k)/2)$ and $a_B^\dagger(t_k)=a_C^\dagger(t_k)\sin(\theta(t_k)/2)+a_D^\dagger(t_k)\cos(\theta(t_k)/2)$, where $\theta(t_k)$ denotes the phase difference between the two arms of the Mach-Zehnder interferometer at time t_k. For the entangling operation, I set $\theta(t_1)=\pi$ and $\theta(t_2)=0$. This means that the spatial modes of the launched photons are exchanged at the first time slot and unchanged at the second time slot. Note that this operation of temporal modes is equivalent to the operation of polarization modes using a polarization beam splitter. With this operation, and under the condition that the temporal and frequency distinguishability of the two time-bin qubits is eliminated, the state of the entire system is converted as follows.

$$\frac{1}{2}\left(a_A^\dagger(t_1)+e^{i\phi_A}a_A^\dagger(t_2)\right)\otimes\left(a_B^\dagger(t_1)+e^{i\phi_B}a_B^\dagger(t_2)\right)\Big|0\rangle=\frac{1}{2}\left(-a_D^\dagger(t_1)+e^{i\phi_A}a_C^\dagger(t_2)\right)\otimes\left(a_C^\dagger(t_1)+e^{i\phi_B}a_D^\dagger(t_2)\right)\Big|0\rangle$$
$$=\frac{1}{2}\left(-|1,0\rangle_C|1,0\rangle_D-e^{i\phi_B}|0\rangle_C|1,1\rangle_D+e^{i\phi_A}|1,1\rangle_C|0\rangle_D+e^{i(\phi_A+\phi_B)}|0,1\rangle_C|0,1\rangle_D\right)$$

Here, $|n,m\rangle_X$ denotes a state where there are n and m photons at the first and the second temporal modes, respectively, at a spatial mode X (=C, D). The photons output from ports C and D are received by Charlie and David, respectively. By measuring the coincidences between Charlie and David, we can post-select a time-bin entanglement whose state is given by $\frac{1}{\sqrt{2}}\left(-|1,0\rangle_C|1,0\rangle_D+e^{i(\phi_A+\phi_B)}|0,1\rangle_C|0,1\rangle_D\right)$.

The proposed scheme was implemented using the setup shown in Fig. 1. Pulsed degenerate correlated photon pairs with a wavelength of 1556 nm were generated at a clock frequency of 100 MHz using type-II spontaneous parametric downconversion in a periodically-poled potassium titanyl phosphate (PPKTP) waveguide. The average number of correlated photon pairs per pulse was set at 0.25. The generated signal and idler photons were sent to Alice and Bob, respectively, who prepared time-bin qubits, whose states were described in the previous paragraph, by launching the photons into 1-bit delayed interferometers based on silica waveguides [4]. Then, after adjusting the temporal positions of the photons so that the temporal distinguishability of the two qubits was erased, the photons were input into ports A and B of a 2x2 optical switch based on a lithium niobate waveguide, where the above time-bin switching operation took place. Here, the bandwidth and the extinction ratio of the switching were 10 GHz and 20 dB, respectively. The photons output from ports C and D were received by Charlie and David who were equipped with 1-bit delayed silica interferometers followed by single photon detectors based on InGaAs/InP avalanche photodiodes operated in a gated mode whose gate frequency was 100 MHz. When a time-bin qubit passes through a 1-bit delayed interferometer, we observe a photon detection possibly in three time slots at the interferometer output, and the interference effect is observed at the second slot [4,5]. Therefore, the detector gate positions were set at the second slot.

I measured the single count rate of Charlie's detector and the coincidences between the two detectors as a function of Charlie's interferometer phase. The result is shown in Fig. 2 (a). The crosses show the single count rate, which was almost independent of Charlie's interferometer phase, suggesting that each photon was in a mixed state. On the other hand, the coincidences showed clear sinusoidal modulations for two non-orthogonal measurement bases at David. The visibilities of the fringes were $52.8 \pm 12.9\%$ for David's interferometer phase 0 and $51.2 \pm 8.1\%$ for $\pi/2$. If we assume a Werner state, a visibility greater than 33% indicates the existence of entanglement [6]. Moreover, when the accidental coincidences were subtracted, the visibilities were $79.4 \pm 20.6\%$ (phase 0), and $84.4 \pm 12.6\%$ ($\pi/2$).Therefore, the obtained result suggests the successful generation of an entangled state using the proposed scheme. To confirm that the fringes were generated as a result of quantum interference, I undertook another coincidence counting experiment, where I changed the relative delay between two photons while setting Charlie's interferometer phase at 2π and π, with David's phase at 0. The result is shown in Fig. 2 (b). Clear bunching (Charlie's phase 2π) and anti-bunching (π) were observed only when the relative delay was set close to zero, which clearly indicates that Hong-Ou-Mandel two-photon interference [7] at the optical switch played a crucial role in the formation of entanglement.

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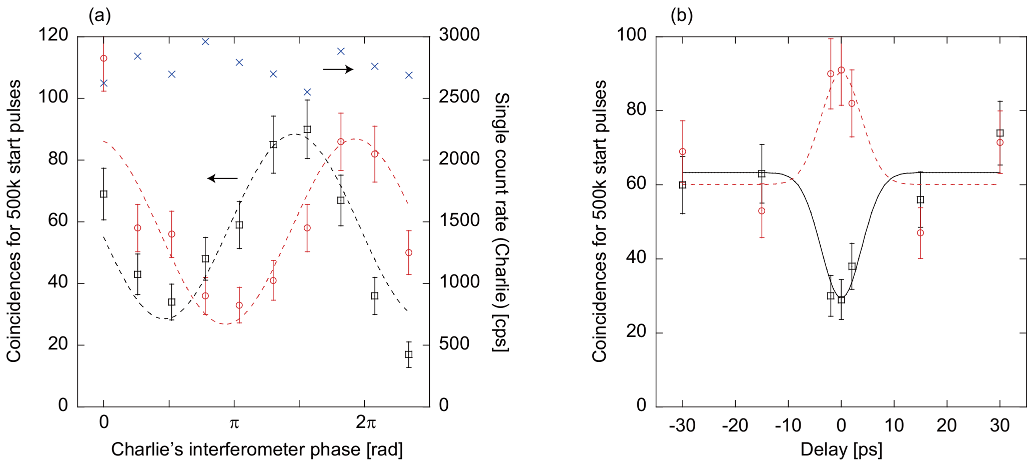

Fig. 2: The results of coincidence measurements. The coincidences were obtained for 500,000 detection events with the Charlie's detector. (a) The circles and squares show the coincidences as a function of Charlie's interferometer phase for David's interferometer phase of 0 and $\pi/2$, respectively. The crosses represent the single count rate of Charlie's detector. (b) Coincidences as a function of the relative delay time between photons from Alice and Bob. David's interferometer phase was set at 0, and Charlie's interferometer phase was set at π (squares) and 2π (circles).

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