Automated Quantum State Tomography of Four Bell States Generated by Compact SPDC Source

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Abstract: The high fidelity of the four maximally entangled two-photon states, generated by a compact type-I SPDC source, is verified using automated quantum state tomography system.

1. Introduction

The evolution of quantum technology systems is steadily approaching the expectations of its ambitious industry market. Generation and measurement of Bell states are crucial in most quantum protocols and algorithms. Despite the advances in the generation and measurement of entangled photon pairs, time-lasting experimental procedures are always required to generate and measure high fidelity output. In this manuscript, we introduce a comprehensive, compact, and automated system for generation and running quantum state tomography measurements. The photon pairs are produced using noncollinear spontaneous parametric down conversion (SPDC) in two type-I β-BBO crystals pumped by a single-wavelength diode laser. The generated state can be one of the Bell states $|\phi^{\pm}\rangle$ based on the tilting angle of a quarter wave plate acting on the diagonally polarized pump beam. These states are transformed to the other two Bell states $|\psi^{\pm}\rangle$ by rotating a half-wave plate in one of the two arms of the entangled pair. Quantum state tomography and visibility measurements are done using a home developed automation system, which demonstrates a high fidelity output with visibility ~ 90%.

2. SPDC Setup and Automated system

Type-I SPDC produces frequency-entangled and momentum-entangled pairs of photons with the same polarization, which is orthogonal (at small emission angles) to the polarization of the pump beam. To achieve polarization entanglement, two identical type-I crystals are set back-to-back such that their optic axes lie in the horizontal and vertical planes. The two-crystal set is pumped by a beam polarized at 45°.

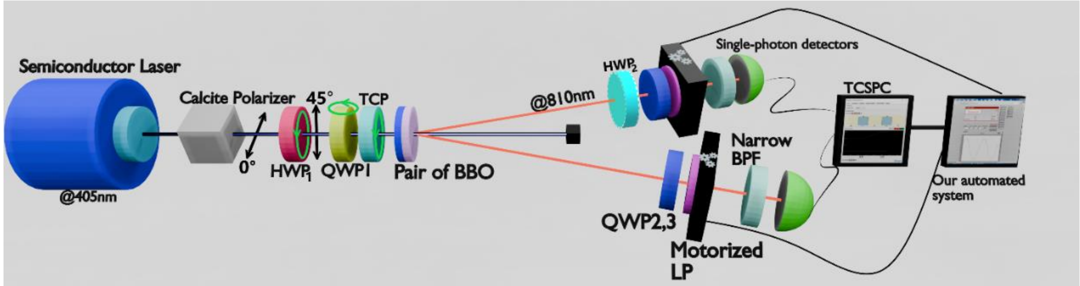


Figure 1 SPDC single photon source setup. The output of the SPDC process is 3° from the pump beam.

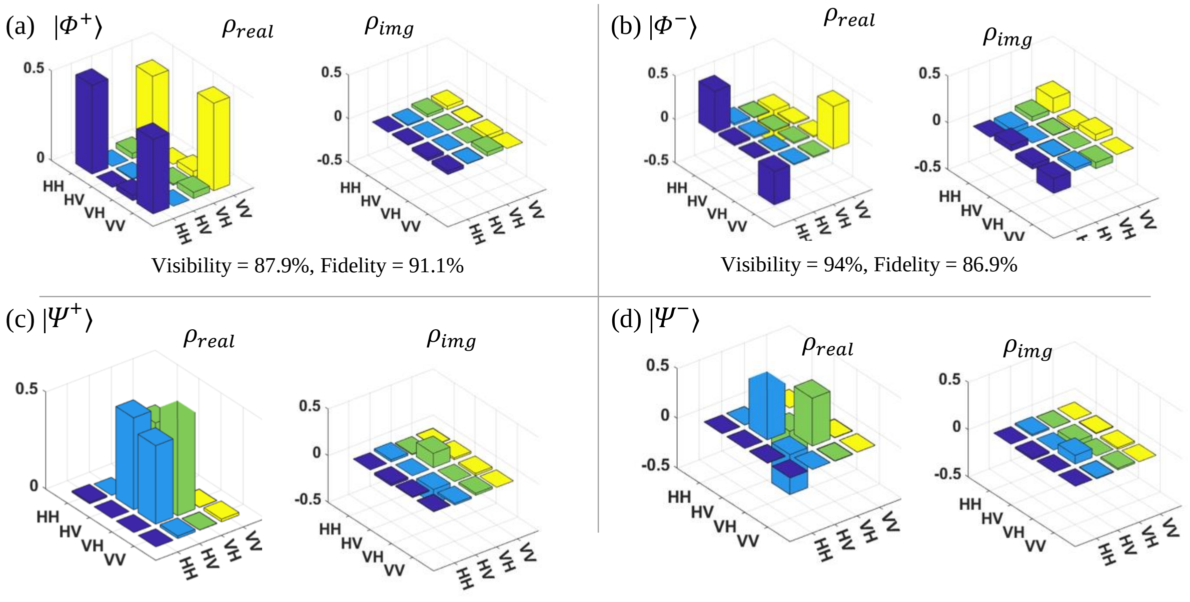
As in Fig. 1, a 405-nm semiconductor laser is used to pump the two crystals. A calcite polarizer is utilized to elevate the extinction ratio of the pump beam. A half-wave plate (HWP1) followed by a tiltable quarter waveplate (QWP1), respectively, prepares the 45° linear polarization state of the pump beam and then tunes its relative phase. By pumping the two SPDC crystals, polarization entangled photon pairs are created, which ideally have the state $(|H_1H_2\rangle + \exp(i\phi)\ |V_1V_2\rangle)/\sqrt{2}$. However, due to birefringence, there is always a time delay between the HH and the VV components, reducing the purity of the state and diminishing the degree of entanglement. To compensate for this delay difference, a quartz time-compensation plate (TCP) is inserted on the path of the pump beam. The output photons are emitted at 3° from the pump beam, forming a SPDC scattering cone of 6° opening angle. The four Bell states $|\phi^{\pm}\rangle$ and $|\psi^{\pm}\rangle$ can be produced by tilting QWP1 (to adjust the phase ϕ to 0 or π) and by rotating HWP2 to 0° or 45°.

A LabVIEW-based automation system is configured to perform quantum state tomographic measurements and visibility measurements of the four produced Bell states. The automated system alternates between 16 different rotation settings of QWP2, QWP3, and two linear polarizers (LP) to project the output state on different measurements bases according to [3]. Each reading is taken in 16 seconds: 10 seconds to ensure the stabilization of the coincidences, 5 seconds to take the readings with exposure time of 1 second and average them, and 1 second to rotate the stages. The whole process takes less than 5 minutes. The rotation stage (Thorlabs K10CR1/M) has a resolution of 0.03 degrees (smallest increment that can be applied) with an accuracy of 60 microrad when backlash correction is applied. The speed used in the experiment is 10 degrees/sec which is the maximum speed.

3. Results

Fig. 2 shows the results of the automated quantum state tomographic measurements for the four Bell states settings. The calculations on the collected tomographic data including maximum likelihood estimation were performed according to [3] and were verified with the tomography interface in [4]. The fidelity of the produced states was calculated as in Fig. 2.

In the visibility measurements, the automation system calculates the mean and the standard deviation based on 10 coincidence counts for every measurement setting. The system controls the rotation angle of one of the linear polarizers with step 5°, while the other polarizer is at 45°. It then counts the coincidence events, store the readings, calculate the visibility, and plot the visibility fringes (not included here). Throughout the experiments, multimode detection is used without applying spatial compensation, which justifies the measured visibility and fidelity. Using single-mode detection or applying suitable spatial phase compensation [5,6] is expected to show better visibility.



Visibility = 87.9%, Fidelity = 91.1%

Visibility = 94%, Fidelity = 86.9%

Visibility = 86.9%, Fidelity = 89.5%

Visibility = 86.3%, Fidelity = 89.9%

Figure 2 Quantum state tomographic measurements of the four produced Bell states performed by the automation system.

3. References

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