Non-Gaussian Quantum State Generation for Optical Quantum Computers

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Abstract *Optical quantum computers, which use traveling waves of light, are highly compatible with optical telecommunication technology and are capable of large-scale and high-speed computations. We have established a fundamental technology for generating Gottesman-Kitaev-Preskill qubits, which are non-Gaussian states and essential for realizing fault-tolerant quantum computers.*

Introduction

Continuous-variable optical quantum information processing (CVQIP), where quantum information is encoded in the quadrature phase amplitude of a traveling wave of light, is a promising candidate for ultra-fast fault-tolerant quantum computers[1],[2]. By leveraging the traveling wave nature, it becomes possible to generate resource states, known as cluster states. The cluster state consists of squeezed light sources, asymmetric interferometers, and homodyne detectors, as shown in Fig. 1. Various quantum calculations can be performed by switching the measurement phases of the homodyne detectors by changing local oscillators' phase, so this part is called "processor". To date, large-scale time-domain multiplexed cluster states have been successfully generated, and fundamental quantum operations have been performed using these states[3]–[6]. This is a significant advantage over standing-wave systems that multiplex qubits spatially. Moreover, optical quantum computation is compatible with high-speed, large-capacity optical communication technology that supports 5G/B5G and 6G, paving the way for ultrafast quantum computation[7].

However, the above processors alone are not fault-tolerant, that is, logical qubits with some redundancy must be embedded in the optical wave packet. In the case of encoding a quantum state into a two-level system, as in the widely studied superconducting qubits, a large number of qubits must be prepared, and by entangling them, to construct a logical qubit. In contrast, in the case of CVQIP, it is possible to encode a logical qubit in a single optical wave packet. The necessary state for this is a non-Gaussian quantum state and can be introduced to the processor as shown in Fig. 1, where "ancilla light source" generates non-Gaussian states[8]. There are several candidates for the logical qubit. The most promising of which is Gottesman-Kitaev-Preskill (GKP) qubit[9],[10]: the wavefunction of the GKP qubit is comb-like structure with a spacing of $2\sqrt{\pi}$, and the position of the comb shifts when an error occurs. This shift can be detected by error syndrome measurement based on a homodyne detector. Also, error correction can be performed by feed-forward operation. The larger the number of combs and the narrower the comb width, the higher the error correction capability[11].

Since the generation of non-Gaussian quantum states such as GKP qubits requires strong nonlinearity, this has so far only been realized in standing-wave systems such as cavity quantum electrodynamics[12]. To realize fault-tolerant quantum computers, it is necessary not only to generate these states but also to extract and use them in traveling-wave systems where large-scale quantum computing platforms are realized. If GKP qubits is created in optical systems, it would be a quantum leap forward and cause a paradigm shift in the research of fault-tolerant quantum computers.

Here we present two of our recent studies on optical GKP qubit generation. One is an experiment in which we generated an approximate state of a three-peaked GKP qubit from non-Gaussian states with two peaks[13],[14], which are relatively easy to generate. The second is a non-Gaussian state generation and verification technique using an ultrashort pulse light source and a photon-number resolving detector (PNRD), which are essential for better GKP qubit generation[15]. By combining these two technologies, GKP qubits can be generated in the optical domain in prin-

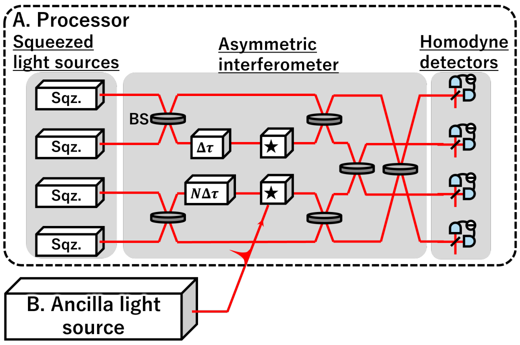

Fig. 1: Optical quantum computer

ciple. In other words, a fault-tolerant optical quantum computer can be realized.

Approximate GKP qubit generation

We first present a GKP qubit generation experiment in an optical system as shown in Fig. 2[14]. Several methods of generating optical GKP qubit have been proposed[13],[16]–[18], and we focus on one of them here. Two Schrödinger cat states (Cat 1 and Cat 2) are generated by a photon-subtraction method (not shown)[19]. A squeezed light is bifurcated by a beam splitter to generate quantum entanglement, and one output of the beam splitter is detected by a photon detector. When the photon detector clicks, a non-Gaussain state appears in the other output of the beam splitter. The Schrödinger cat state is a quantum superposition of coherent states that are out of phase by $180°$, and have two peaks in the wavefunction as shown in Fig. 2. These two peaks can be regarded as a live cat and a dead cat. Two Schrödinger cat states are prepared and interfered with by another beam splitter (BS). A homodyne measurement is made at one of the outputs of the BS, and when the measured value is within a certain range, the other output splits the two peaks into three, producing a GKP qubit as shown in Fig. 2. By repeating this operation, the number of peaks is increased, and a GKP qubit with high fault tolerance can be generated. We should note that since this method is conditioned by homodyne measurement, GKP qubits are not generated with 100% probability. However, by performing appropriate feed-forward operations based on the results of the homodyne measurement, a GKP qubit can be generated deterministically[13].

Non-Gaussian state generation in ultrashort optical wave packet by PNRD

Next, we have established a non-Gaussian quantum state generation and measurement technique using a pulsed light source and a photon-number resolving detector (PNRD). Since the first experiment is a proof-of-principle, two Schrödinger cat states were generated by continuous-wave (CW) light and single-photon detectors, which are relatively easy to generate non-Gaussian quantum states. The larger the amplitude of the input Schrodinger's cat state (i.e., the farther apart the two peaks) are, the more efficient the generation of GKP qubits can be. This can be achieved by using PNRDs instead of single-photon detectors[20]. It has been difficult to measure photon numbers in the telecommunication wavelength where photon energy is low. In recent years, superconducting sensors have been remarkably developed, and PNRDs with high detection efficiency and low dark counts have been developed[21],[22].

However, PNRDs are not very compatible with CW experiments unless special measures are taken[23]. In addition, to perform high-speed quantum calculations, it will be necessary to generate states in ultrashort wave packets on the order of picoseconds. The main challenge in pulsed light experiments is the verification of the generated state by homodyne measurements. In a pulsed homodyne measurement, the temporal waveform of the local oscillator light must be matched with the waveform of the non-Gaussian state, which cannot be directly measured. Several experiments using pulsed light have been performed, but the results are typically worse than those using CW, and loss correction is often applied to compensate for experimental imperfections. We have solved these problems and established a non-Gaussian quantum state generation and verification technique. Three photons are subtracted from picosecond pulsed squeezed light by a superconducting transition-edge sensor. We succeeded in obtaining the negative value of the Wigner function, a non-classical property, without any loss correction[15].

Conclusion

The first experiment is a proof-of-principle demonstration of generating GKP qubits from two-Schrödinger cat states. And the second experiment is a demonstration of the technology that elevates the first one from verification of principle to practical application. The combination of these results enables us to realize GKP qubits with a high error correction threshold (specifically, GKP qubits with a large number of peaks) even in

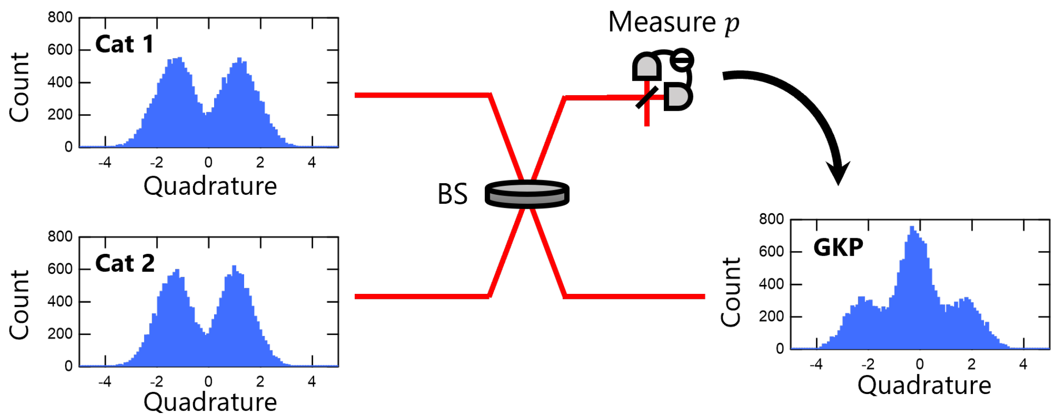

Fig. 2: Result of GKP state generation. Histograms show homodyne measurement on x quadrature. Two Schrödinger cat states (Cat 1 and Cat 2) have two peaks. The number of peaks has increased to three due to conditioning by the results of homodyne measurements after the interferometer.

optical systems. Since pulsed lasers and optical frequency combs with repetition rates well above GHz already exist[24], they can be used for processors with clock frequencies above GHz. Furthermore, it has been proposed to use a single processor as if it were many processors by using frequency multiplexing technology[7]. The last piece of the puzzle in optical quantum information processing, non-Gaussian quantum states, especially GKP qubits, can now be generated and utilized. This is a significant achievement toward realizing fault-tolerant optical quantum computation in the traveling wave system.

Acknowledgements

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