博士論文（要約）

Realization of universal resources for continuous-variable one-way quantum computation and demonstration of one-input one-output quantum operations multiplexed in time domain

（時間領域で多重化された連続量一方向量子計算における
ユニバーサルリソース及び1入出力量子操作の実現）

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Background

In recent years, we have seen impressive progress in the developments of the quantum computer. Among many possible candidates, continuous-variable (CV) quantum computing in the time domain based on one-way quantum computation (also known as measurement-based quantum computation (MBQC)) is one of the most promising in terms of scalability. In MBQC, instead of direct implementation of quantum operations on the input states, operations are implemented via local (single-qubit) measurements on a large-scale entangled quantum state called cluster state. The cluster states are considered as the platforms and measurements are considered as the programs in MBQC. Therefore, to realize large-scale universal MBQC, we need to realize cluster states with adequate size and structure and programmable measurement systems that allow us to do the measurements according to the desired operations.

Regarding the generations of the cluster states, time-domain multiplexing (TDM) method using CV optical systems is currently the most prominent. In the TDM method, localized wave packets are used as modes (CV analogue of qubits) and large-scale cluster states can be generated using only a few optical components. There have already been demonstrations of one-dimensional cluster states—universal resources for one-input one-output operations—up to 1,000,000 modes using TDM method. While this result signifies the strength of the TDM method regarding the scalability, this result by itself is insufficient to realize large-scale universal MBQC, and two main points need addressing. First, the structure of the cluster states. As we have already stated, the cluster states are the platform for MBQC which means that their structures determine what operations are possible. The structure of the previously generated one-dimensional cluster state allows only quantum operations on one input. Thus, we need to generate cluster states that can support universal multi-input multi-output operations. This type of cluster states is called *two-dimensional cluster state*. Second, the programmable measurement system. Although TDM one-dimensional cluster states have already been demonstrated in the previous works, basic operations using such cluster states have not been demonstrated. This is because the modes of the TDM cluster states are localized wave packet, meaning that the measurement bases need to be programmed and switched in the time domain. Without realization of such programmable system, even if large-scale cluster states can be generated using the TDM method, we cannot utilize them in actual quantum computations.

Summary of this work

In this work, there are two main results:

1. Theoretical proposal of a new setup to generate two-dimensional cluster states and their experimental realization

2. Development of the programmable homodyne measurement system and demonstration of basic quantum operations using TDM one-dimensional cluster states.

Regarding the generation of two-dimensional cluster states, although there exist previous theoretical proposals, we propose a new experimental system to improve the experimental feasibility. Then, we perform a theoretical analysis of the cluster states generated with this setup and also develop a methodology to use the generated states in actual quantum computation efficiently. Experimentally, by increasing the bandwidths of the squeezed light sources and the homodyne detectors and incorporating a new method to stabilize the system, we build the experimental system and generate two-dimensional cluster states with about 25,000 modes that can be used for 5-input 5-output MBQC. To the best of our knowledge, this is the first realization of two-dimensional cluster states among any physical system.

In the second result, we build a programmable homodyne measurement system. By incorporating this system into the generation system of the one-dimensional cluster states, we implement and verify various basic quantum operations. We first show that by selecting proper measurement bases, we can transform the quadrature of the input states according to the desired operations. Secondly, we show that even after the quantum operations, the nonclassicality based on quantum entanglement persists. Thirdly, we demonstrate that our system possesses the stability required to implement multi-step quantum operations. To demonstrate this, we sequentially implement quantum teleportation and observe up to 100-step quantum teleportation. Although the operations are noisy, we explicitly show that these noises are stemmed from the imperfections in the cluster states due to the finite squeezing, and there are no other noticeable sources of noises such as the instability of the experimental setup. Thus, by further improving the quality of the cluster states, we expect that our measurement system will allow at least 100 steps of quantum computation.

In conclusion, we have realized two-dimensional cluster states, which is universal resources for MBQC, and programmable homodyne measurement system and demonstrate quantum operations multiplexed in the time domain. Our results will serve as foundations for CV MBQC and provide a platform to unify various technologies in CV optical systems that have been developed modularly. Moreover, as the results in this work demonstrate a methodology to implement large-scale universal quantum computation efficiently, we believe that the developments of TDM MBQC will be accelerated more than ever and that this approach will become one of the leading approaches to realize a full-fledged quantum computer.