Chapter 1
Introduction

1.1 One-Way Quantum Computation

1.1.1 Quantum Computation

The historical origin of quantum mechanics was the *quantum hypothesis* proposed by Planck in 1900 [1]. From that time, considerable efforts have been devoted to the research of quantum mechanics. Since it predicted curious phenomena contradictory to classical mechanics, several researchers were skeptical about the new-coming theories. In order to show the incompleteness of quantum mechanics, several thought experiments were proposed. They included the paradox of nonlocal correlations proposed by Einstein et al. [2]. Afterward, it was experimentally demonstrated that such curious phenomena are observable in the real world. After long discussions on quantum mechanics, it is now accepted and hailed as one of the great scientific theories.

Recently, it was found that quantum mechanics can be applied to information processing. The birth of quantum information processing was the proposal of the quantum Turing machine by Deutsch in 1985 [3]. Although the superiority of quantum computation over classical computation had not initially been demonstrated, it was later proved that a quantum computer can solve some problems more efficiently than a classical computer [4–8]. A well-known example is the factoring of integers. Its discovery expedited research on quantum computers.

In the same way as the classical computation, the input of a quantum computer is classical information (Fig. 1.1). It is firstly encoded into a quantum state $|\psi_{in}\rangle$. A quantum computer has the ability to apply a unitary operator $\hat{U}$ onto the quantum state, leading to the output quantum state $|\psi_{out}\rangle = \hat{U}|\psi_{in}\rangle$. This quantum state manipulation is the key part of the quantum computation. The final answer of the quantum computation is also classical information, which will be read out by performing a measurement on the output quantum state.

The *superposition* of quantum states and quantum *entangled* states are characteristic traits of in quantum theory. Consider a two-level system labeled by $|0\rangle$ and $|1\rangle$, such as photon number states, or ground and excited states of an atom. An arbitrary one qubit state is represented by

R. Ukai, *Multi-Step Multi-Input One-Way Quantum Information Processing with Spatial and Temporal Modes of Light*, Springer Theses,
DOI 10.1007/978-4-431-55019-8_1

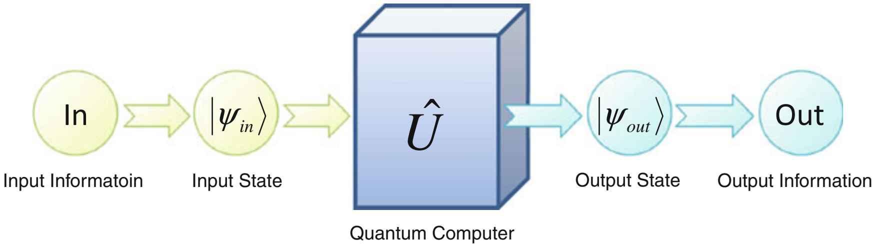

Fig. 1.1 Quantum computation

$$a|0\rangle + b|1\rangle. \tag{1.1}$$

This is called a superposition of $|0\rangle$ and $|1\rangle$. Different from a statistical mixture of two quantum states, it leads to quantum interference.

An entangled state (Sect. 3.7.1) refers to a quantum state which cannot be decomposed into two independent subsystems. The following is an example of entangled states in a two-qubit system:

$$\frac{|0\rangle_A|0\rangle_B + |1\rangle_A|1\rangle_B}{\sqrt{2}}. \tag{1.2}$$

This state cannot be represented by a tensor product of a state in the subsystem A and another state in the subsystem B. As mentioned above, entanglement was originally proposed by Einstein, Podolsky, and Rosen as a paradox which pointed out the apparent incompleteness of quantum mechanics. However, it was later demonstrated experimentally [9, 10], and it is now understood as a characteristic property of quantum mechanics. The quantum state proposed by Einstein, Podolsky, and Rosen is called the Einstein-Podolsky-Rosen state (*EPR state*). It is thought that the superiority of quantum computations originate from the parallelism of computation, based on superposition and entanglement [11].

1.1.2 Quantum Teleportation

Another application of quantum entanglement is *quantum teleportation* [12–21] (Sect. 4.1.1). It is a protocol with which one can transmit an unknown quantum state to a receiver at a distance (Fig. 1.2). The sender and the receiver are usually named “Alice” and “Bob”, respectively.

For this purpose, Alice and Bob share an EPR state in advance. The procedure of quantum teleportation is as follows. Firstly, Alice entangles the quantum state to be transmitted and half of the EPR state which belongs to Alice. Alice measures the two outcomes in an appropriate measurement basis. The measurement results are sent to Bob through classical channels. By performing correction operations on the other half of the EPR state, Bob can reconstruct the quantum state which was initially prepared by Alice.

Quantum teleportation has features in common with quantum computation, including that both handle entanglement, and require (some) quantum state transformations. Quantum teleportation can be considered as an identity operation on an input state, since the quantum state which Bob reconstructs is equivalent to that which was initially owned by Alice.

1.1.3 Application of Quantum Teleportation to Quantum Computation (Gate Teleportation, Offline Scheme)

Although quantum teleportation was initially proposed as a protocol to transmit a quantum state, it was later found that it can be applied to implement quantum computation. In quantum teleportation, an EPR state $|EPR\rangle$ is utilized as a resource for its protocol (Fig. 1.2). The first scheme of its application is to replace the resource state $|EPR\rangle$ with another state $\hat{D}|EPR\rangle$ [22, 23] (Fig. 1.3, Sect. 4.1.2).

By changing the resource state, Bob reconstructs $\hat{D}|\psi\rangle$, which is a unitary transformed version of the initial state $|\psi\rangle$. The unitary operator $\hat{D}$ is determined by the resource state $\hat{D}|EPR\rangle$. This scheme is called a *gate teleportation* since the unitary operator $\hat{D}$, which was initially applied to the resource state, becomes applied to the input state through the quantum teleportation. In addition, it is also called an *offline scheme* of quantum computation. This is because the unitary operator $\hat{D}$ can be considered to be applied to the offline resource state $|EPR\rangle$, leading to the revised resource state $\hat{D}|EPR\rangle$. During the online computation, it is applied to the input state through the quantum teleportation.

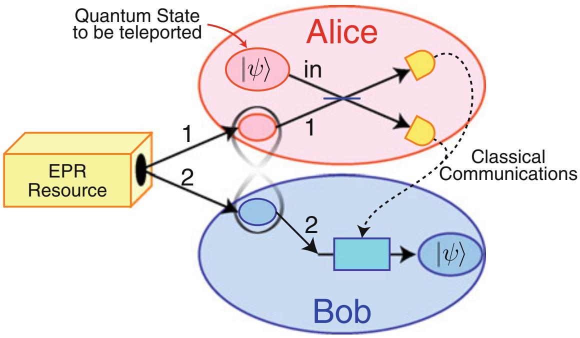

Fig. 1.2 Quantum teleportation

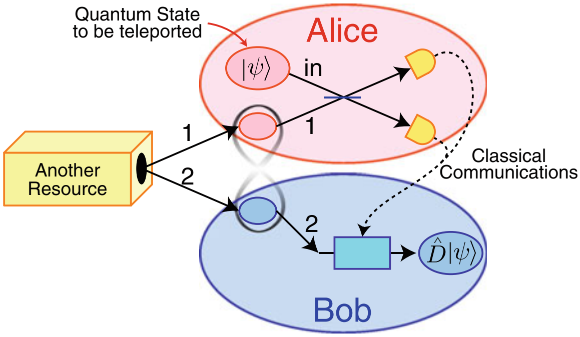

Fig. 1.3 Gate teleportation, offline scheme

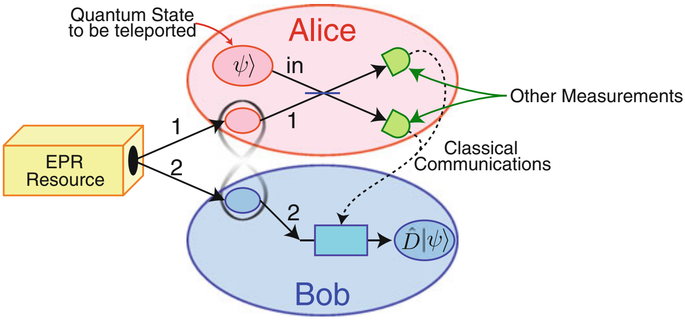

Fig. 1.4 One-way quantum computation

1.1.4 Application of Quantum Teleportation to Quantum Computation (One-Way Quantum Computation)

Another application of quantum teleportation to quantum computation was later proposed. It is called *one-way quantum computation* [24–29] (Sect. 4.2 and Chap. 5), which is the main topic of this thesis. In one-way quantum computation, we change the measurements from the quantum teleportation (Fig. 1.4).

Since the quantum state is projected to another basis, the state after the measurements is dependent on the measurement basis. Therefore, the state which Bob reconstructs becomes $\hat{D}|\psi\rangle$, where $\hat{D}$ is determined by the basis of the measurements Alice has performed. One-way quantum computation is a model of quantum computation where operations are controlled by measurement bases. It is also called the *cluster model* of quantum computation, or *cluster computation*, since a multi-partite entangled state, called the *cluster state*, is used as a resource for quantum computation.

1.1.5 Circuit Model and Cluster Model

Quantum computation is usually studied by using the *circuit model* [11, 30], where computation is described by the order of unitary gates onto the initial states. The circuit model is a universal model of quantum computation: an arbitrary quantum computation can be described in this model.

The cluster model is an alternative to the standard circuit model. In this model, the actual process of computation is focused on: operations are achieved by a succession of measurements on an entangled state. In the example of Fig. 1.4, a bipartite entangled state (EPR state) is utilized as a resource for the computation. Since the number of measurements is equivalent to the number of resource modes, two measurements are involved. In addition, it is also equivalent to the degrees of freedom (DOF) of unitary transformations since each measurement provides a DOF. Therefore, Fig. 1.4 has the ability to perform unitary transformations with two DOF.[1] In this manner, the DOF of unitary operations achieved by one-way quantum computation is determined by the number of resource modes. By using a larger-scale resource state, we can perform unitary operations with more DOF.

The procedure of cluster-model quantum computation is summarized by the following:

- Prepare a multi-partite entangled state (cluster state, Sect. 5.1), which will be used as a resource for quantum computation.
- Couple an input state with the cluster state (Sect. 5.3).
- Perform reshaping of the cluster state based on the operation to be achieved (Sect. 5.4).
- Perform unitary operations through measurements (Sect. 5.5).
- Read out the unmeasured modes, which give us the solution of the computation.

A sufficiently large cluster state can be used as a universal resource for one-way quantum computation, that is, an arbitrary computation is achieved by using the same cluster state. Once a requested unitary operation is determined, the cluster state is transformed so that it can be efficiently implemented through the one-way quantum computation. The operation determines the set of measurement bases. By choosing an appropriate set of measurement bases, we can implement an arbitrary unitary transformation. Since operations can be switched by adjusting measurement bases using the same resource cluster state, one-way quantum computation can be considered as a *software-based* quantum computation. Note that the resource cluster state is consumed irreversibly during the computation. This is the reason why it is

[1] To be precise, Fig. 1.4 shows the teleportation-based input coupling scheme (Sect. 5.3.3), where both measurements are homodyne measurements. A homodyne measurement has one DOF: the relative phase θ between the signal beam and the local oscillator beam. Thus, Fig. 1.4 has two DOF. In general, we can implement a transformation with multiple DOF using an elementary one-mode one-way gate (Sect. 4.2.3) by choosing a complicated measurement. However, we usually assume that we construct a large-scale quantum computation by concatenating several kinds of elementary gates with limited DOF. Therefore, the total DOF of operations still increase as well by concatenating elementary gates.

called the *one-way* scheme. However, the transformation of the input state to the output state is unitary, thus reversible.

1.1.6 Continuous-Variables and Universality

1.1.6.1 Continuous-Variable Quantum Computation

We have so far used two-level systems with $|0\rangle$ and $|1\rangle$ in order to show several examples. However, quantum computation is also discussed by using more high-dimensional systems, including continuous-variable (CV) systems where computational bases are continuously varying quantum states, such as eigenstates of momentum operators $|p = s\rangle$ (Sect. 3.1).

In recent experimental demonstrations of quantum computations using quantum states of light (Chap. 2), not only discrete-variable (DV) systems but also CV systems are utilized. We use optical CV systems in this thesis. The main merit of optical CV systems is that entangled states can be generated deterministically (success probability is equal to 100 %), and thus operations can also be implemented deterministically. It is stark contrast to optical DV systems where entangled states are generated probabilistically and experiments are verified via postselections.

We mention here that there also exists a drawback in optical CV systems: ideal computational basis states such as $|p = s\rangle$ require an infinite amount of energy. It is different from the DV systems where computational basis states are physical states. Since we cannot employ such unphysical states in actual experiments, they are approximated by other physical states. For example, the zero eigenstate of the momentum operator $|p = 0\rangle$ is approximated by a p-squeezed vacuum state (Sect. 2.2.3). Approximations of these states lead to unavoidable errors in CV quantum computations.[2]

1.1.6.2 Universality

It is known that an arbitrary digital classical computation can be achieved by cascading NAND gates in an appropriate order. In a similar manner, an arbitrary CV quantum computation can be achieved by cascading the following elementary gates in an appropriate order (Sect. 3.6):

- Gate which can perform an arbitrary one-mode Gaussian operation.
- Gate which can perform a two-mode Gaussian operation.
- Gate which can perform a one-mode non-Gaussian operation.

[2] Since both optical DV and CV systems have merits and demerits of their own, a hybrid scheme is also being studied [31], where DV gates are implemented using optical CV setups. It is thought that the imperfections of quantum states may be compensated by limiting the dimension of computational bases.

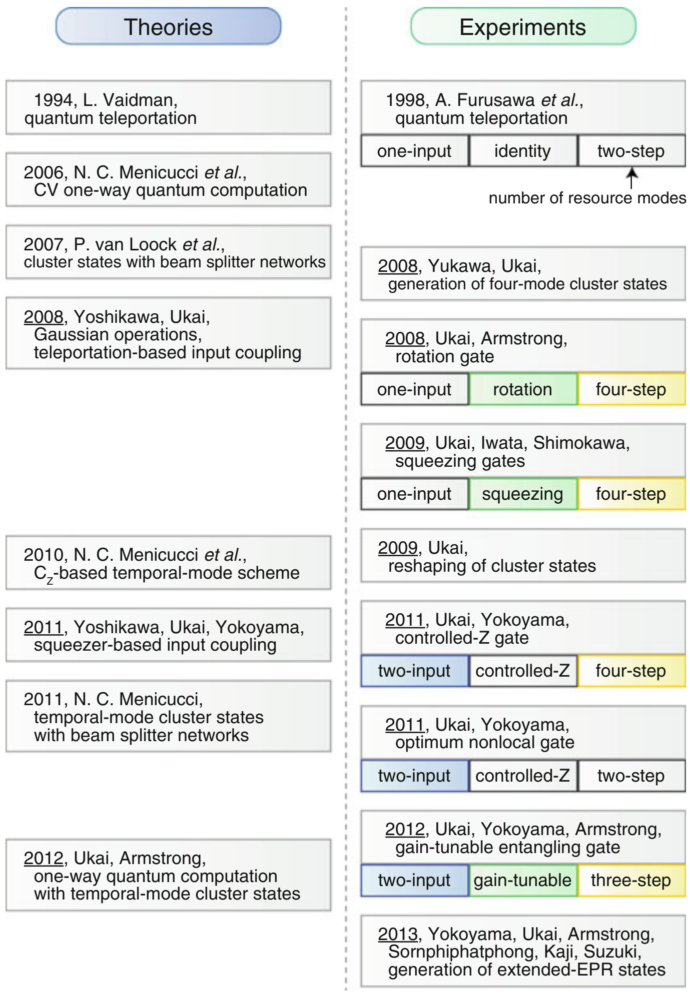

Fig. 1.5 History of CV one-way quantum computation. Works in our laboratory are shown with *underlines*

Here, Gaussian operations correspond to unitary transformations with inhomogeneous quadratic polynomial Hamiltonians in the canonical operators (Sect. 3.4.3). Similar to the classical computation, multi-step operations should also become possible because a total quantum computation is achieved by cascading these elementary gates.

1.2 History of One-Way Quantum Computation and This Thesis

1.2.1 History of One-Way Quantum Computation

Figure 1.5 shows a brief history of CV one-way quantum computation and the status of this thesis. In this figure, we include CV quantum teleportation as well since it has a connection with CV one-way quantum computation (Sect. 1.1).

Although quantum teleportation was originally proposed in the DV systems [12], it was later extended to the CV systems [13, 15]. An experimental realization of CV quantum teleportation was first reported in 1998 [17].

Since quantum teleportation is a protocol to transmit a one-mode quantum state without applying any unitary transformations, we can consider it as an identity operation on a one-mode state. Note that a two-mode entangled state called EPR state is utilized as a resource for quantum teleportation. Since we equate the number of resource modes with the number of operations in one-way quantum computation, we can consider that a quantum teleportation is a two-step operation.

Similar to quantum teleportation, one-way quantum computation was first defined in the DV systems [24, 32]. Several years after the original proposal, DV one-way quantum computation experiments were also reported [33, 34].

The CV cluster state was introduced in 2006 [26] by extending the DV counterpart. Shortly after, one-way quantum computation was proposed by Menicucci [27]. They were basic theories of CV cluster states and one-way quantum computations where controlled-Z gates are utilized as entangling gates for the generation of a cluster state and the coupling of an input state with the cluster state[3] (Sects. 5.2.1 and 5.3.2). However, they were not desirable theories especially for experimentalists because a controlled-Z gate required a large-scale experimental setup [36, 37], and thus it was not realistic to prepare multiple controlled-Z gates for generations of cluster states and demonstrations of one-way quantum computations.

One of these problems was solved by van Loock et al. [35] (Sect. 5.2.2). They showed that, compared to the original proposal that an ideal cluster state is generated by entangling eigenstates of momentum operators by using controlled-Z gates, an approximation of the ideal cluster state can be generated by combining squeezed vacuum states by using beam splitters. In the limit of infinite squeezing, it becomes identical to the ideal cluster state. It made it easier to generate cluster states, leading to several experimental reports including four-mode cluster state generations [38, 39] and eight-mode cluster state generations [40]. In addition, an experimental demonstration of cluster state reshaping (Sect. 5.4) was also reported [41].

As for the coupling of an input state with a cluster state, we found that a quantum teleportation can be applied for this purpose, where a beam splitter, not a controlled-Z gate, plays the role of input coupling [42] (Sect. 5.3.3). Together with the cluster

[3] In Ref. [26], it was already mentioned that special shapes of cluster states can be generated by using beam splitter networks. However, its generalization was given in Ref. [35].

state generation with beam splitter networks, it became possible to implement one-way quantum computations without using controlled-Z gates. Afterward, we found that not only quantum teleportation but also a squeezing operation can be applied to input coupling in one-way quantum computations as well (Sect. 5.3.4).

We then move onto implementations of one-way quantum computations. In the original paper of CV one-way quantum computations [27], it was already given how the operation is determined by a specific measurement basis. However, conversely, it was an open question how the set of measurement bases should be chosen for a specific operation using a multi-partite cluster state. An example of multi-step one-way quantum computation was first given in Ref. [29]: approximate *squeezing operations*, which are members of one-mode Gaussian operations, are achieved by using four-mode cluster states with homodyne measurements. Note that the operation was inevitably an approximate version of the ideal squeezing operation even though the resource cluster state was an ideal state. This is because the sets of measurement bases were not optimum for the squeezing operations.

In 2009, we reported several general answers for choices of measurement bases [42] (Sect. 5.5). One main result was that arbitrary one-mode Gaussian operations, including squeezing operations, can be achieved by using a four-mode linear cluster state with homodyne measurements. Different from the earlier proposal [29], we have shown the set of measurement bases with which we can achieve an ideal one-mode Gaussian operation when we can utilize an ideal cluster state as a resource. We have also proved that several one-mode Gaussian operations cannot be implemented by using a three-mode linear cluster state as a resource, thus the four-mode linear cluster state is the minimum resource which satisfies the universality of one-mode Gaussian operations. In addition, we have also proposed the set of measurement bases for arbitrary multi-mode Gaussian operations though it was not the optimal choice of measurement bases.

By combining the methodology of one-mode Gaussian operations with the teleportation-based input coupling scheme [42], we have experimentally demonstrated several one-mode Gaussian operations (rotation and squeezing operations) using four-mode linear cluster states as resources. Although we have demonstrated only several members of one-mode Gaussian operations, the experimental setup had the ability to implement an arbitrary one-mode Gaussian operation.

As a next step for universal one-way quantum computation, demonstrations of multi-mode Gaussian operations were highly anticipated. Its first trial was reported in Ref. [43]. Although they tried to demonstrate a two-mode gate which had an ability to entangle two separable states, they could not observe entanglement at the output. The main reason was that the level of entanglement present in the cluster state was not sufficient. Entanglement at the output is the key criterion of the entangling gate, thus the operation was not successful.

1.2.2 *This Thesis*

1.2.2.1 Spatial-Mode Experiments

In this thesis, we show the first successful demonstration of a two-mode operation (controlled-Z gate) in one-way quantum computation (Chap. 7), which has already been reported in Ref. [44] as well. Though it was a similar experiment to the previous report [43], we have successfully observed entanglement at the output, which was sufficient to show the nonclassical nature of the gate.

By combining with the demonstrations of one-mode Gaussian operations, we now have all the tools to implement an arbitrary multi-mode Gaussian operation in a framework of one-way quantum computation.

Including the controlled-Z gate experiment, three experimental demonstrations of one-way quantum computations on two-mode input states are reported in this thesis [44]. They have a common property that they are demonstrations of two-input quantum gates which have the ability to entangle two independent quantum states. In addition, each mode of the quantum states is distinguished from the others by its spatial location (spatial modes).

The inherent features of each experiment are summarized as follows.

Controlled-Z Gate Experiment

This is an experiment of a two-mode Gaussian operation using a four-mode linear cluster state as a resource. The operation which is implemented is the *unity-gain* controlled-Z gate [27]: it does not impart an additional squeezing operation on each quantum mode. It can be considered as an experimental demonstration of gate teleportations [22, 23] on a two-mode system, because it is nothing but the circuit which is acquired by exchanging the order of the controlled-Z gate in the circuit where a controlled-Z gate is applied to the outcomes of two quantum teleportations.

Optimum Nonlocal Gate Experiment

This is an experiment of a two-mode Gaussian operation using a two-mode cluster state as a resource. The *nonlocal* controlled-Z gate (with additional squeezing operations) is implemented using the minimum resource: a bipartite entangled state shared in advance, and a classical channel in each direction (two channels in total) [45]. Here, a *nonlocal* gate refers to a quantum gate whose target two modes are located at a distance from each other [36, 45–49].

Gain-Tunable Entangling Gate Experiment

This is an experiment of two-mode Gaussian operations using a three-mode cluster state as a resource. In contrast to the other two experiments where operations are fixed, we can control the on-off switching as well as the gain of the entangling interaction by changing the measurement basis [42]. It shows the property of one-way quantum computations where operations are controlled by measurement bases onto cluster states.

Temporal-Mode Theories

In this thesis, one-way quantum computation using *temporal-mode* cluster states is also studied [50, 51]. It will lead to the experimental generation of ultra-large entangled states and experimental demonstrations of many-step one-way quantum computations.

Similar to classical computations where an arbitrary computation is achieved by concatenating NAND gates, an arbitrary CV quantum computation can be achieved by concatenating several basic quantum gates. For that purpose, many-step operations should be implemented. Nonetheless, the current schemes for one-way quantum computation experiments lack extensibility. This is because each mode of cluster states is encoded *spatially*, thus the experimental setup becomes larger in proportion to the number of operations. Although it is proposed that one can encode each mode in a different frequency using a frequency comb [52, 53], it would not be easy to implement one-way quantum computations using the frequency-mode cluster states.

Recently, one-way quantum computation using *temporal modes* was proposed [50, 51]. In this scheme, each mode is encoded in a different time, instead of its spatial location. It enables us to implement many-step one-way quantum computations without enlarging our experimental setup.

In Ref. [51], the schematic for the generation of temporal-mode cluster states was proposed, with which one can generate cluster states of an arbitrary size by using a limited and fixed optical setup (Sect. 10.1.3). It was a giant step toward the realization of many-step one-way quantum computation.

However, since the cluster states to be generated had complex structures, it was not known how all resource modes can be utilized for computation. It was proposed that quantum computation can be achieved by using a half or a quarter of the generated cluster states after eliminating the other modes. Although it was sufficient to show superiority of the temporal-mode scheme theoretically, it was expected that a strategy for implementing one-way quantum computations without disposing cluster modes would be discovered (Sect. 10.1.4).

In this thesis, we propose a solution to this problem. We show that computation using a temporal-mode cluster state is equivalent to a repetition of quantum teleportations (Sect. 10.3.3). Since we can implement one-mode Gaussian operations with two DOF by controlling the measurement basis in a quantum teleportation (Sect. 5.3.3), we can utilize all modes of the temporal-mode cluster state in one-way quantum computations without eliminating any of them. In addition, we show that non-Gaussian operations and multi-mode Gaussian operations are also achieved without eliminating resource modes (Sects. 10.5 and 10.6) by considering repetitions of a one-way quantum computation circuit with the three-mode linear cluster state, and the quantum computation circuit of the controlled-Z gate experiment (Chap. 7). It is expected that these findings will lead to the development of both theories and experiments over temporal-mode one-way quantum computation.

1.3 Structure of This Thesis

In Chap. 2, we briefly review quantum optics. In Chap. 3, we describe CV quantum states and quantum state manipulations.

Theories of one-way quantum computation is described in Chaps. 4 and 5. In the former section, we will introduce one-way quantum computation by comparing it with the offline scheme. The details of one-way quantum computation are discussed in the latter section.

Through Chaps. 6–9, we show experiments of one-way quantum computations. Chapter 6 describes the generation of cluster states which are used in the following three demonstrations of quantum gates. In Chap. 7, we show the theory, experimental setup, and results of the controlled-Z gate experiment using a four-mode linear cluster state as a resource. In Chap. 8, we show the optimum nonlocal gate experiment using a two-mode cluster state. In Chap. 9, we show the gain-tunable entangling gate using a three-mode cluster state as a resource.

Before concluding this thesis, we show theories of one-way quantum computation using temporal-mode cluster states in Chap. 10.

References

1. Planck, M.: Ueber das Gesetz der Energieverteilung im Normalspectrum. Annalen der Physik **309**, 553 (1901)
2. Einstein, A., Podolsky, B., Rosen, N.: Can quantum-mechanical description of physical reality be considered complete? Phys. Rev. **47**, 777 (1935)
3. Deutsch, D.: Proc. Roy. Soc. London, Ser. A **400**, 96 (1985)
4. Shor, P.W.: In: Proceedings, 35th Annual Symposium on Foundations of Computer Science. IEEE Press, Los Alamitos, CA (1994)
5. Shor, P.W.: Polynomial-time algorithms for prime factorization and discrete logorithms on a quantum computer. SIAM J. Computing **26**, 1484 (1997)
6. Grover, L.K.: Quantum mechanics helps in searching for a needle in a Haystack. Phys. Rev. Lett. **79**, 325 (1997)
7. S. J. Lomonaco, Jr., and L. H. Kauffman, Quantum Hidden Subgroup Problems: A Mathematical Perspective, e-print arXiv:0201095 [quant-ph]
8. Lomonaco, S.J. Jr., Kauffman, L.H.: A Continuous Variable Shor Algorithm, e-print arXiv:0210141 [quant-ph]

9. Aspect, A., Grangier, P., Roger, G.: Experimental tests of realistic local theories via Bell's theorem. Phys. Rev. Lett. **47**, 460 (1981)
10. Aspect, A., Dalibard, J., Roger, G.: Experimental test of Bell's inequalities using time-varying analyzers. Phys. Rev. Lett. **49**, 1804 (1982)
11. Nielsen, M.A., Chuang, I.L.: Quantum Computation and Quantum Information. Cambridge University Press, Cambridge (2000)
12. Bennett, C.H., Brassard, G., Crépeau, C., Jozsa, R., Peres, A., Wootters, W.K.: Teleporting an unknown quantum state via dual classical and Einstein-Podolsky-Rosen channels. Phys. Rev. Lett **70**, 1895 (1993)
13. Vaidman, L.: Teleportation of quantum states. Phys. Rev. A **49**, 1473 (1994)
14. Bouwmeester, D., Pan, J.-W., Mattle, K., Eibl, M., Weinfurter, H., Zeilinger, A.: Experimental quantum teleportation. Nature **390**, 575 (1997)
15. Braunstein, S.L., Kimble, H.J.: Teleportation of continuous quantum variables. Phys. Rev. Lett. **80**, 869 (1998)
16. Boschi, D., Branca, S., De Martini, F., Hardy, L., Popescu, S.: Experimental realization of teleporting an unknown pure quantum state via dual classical and Einstein-Podolsky-Rosen channels. Phys. Rev. Lett. **80**, 1121 (1998)
17. Furusawa, A., Sørensen, J.L., Braunshtein, S.L., Fuchs, C.A., Kimble, H.J., Polzik, E.S.: Unconditional quantum teleportation. Science **282**, 706 (1998)
18. Takei, N., Yonezawa, H., Aoki, T., Furusawa, A.: High-fidelity teleportation beyond the no-cloning limit and entanglement swapping for continuous variables. Phys. Rev. Lett. **94**, 220502 (2005)
19. Yonezawa, H., Furusawa, A., van Loock, P.: Sequential quantum teleportation of optical coherent states. Phys. Rev. A **76**, 032305 (2007)
20. Yonezawa, H., Braunstein, S.L., Furusawa, A.: Experimental demonstration of quantum teleportation of broadband squeezing. Phys. Rev. Lett. **99**, 110503 (2007)
21. Yukawa, M., Benichi, H., Furusawa, A.: High-fidelity continuous-variable quantum teleportation toward multistep quantum operations. Phys. Rev. A **77**, 022314 (2008)
22. Gottesman, D., Chuang, I.L.: Demonstrating the viability of universal quantum computation using teleportation and single-qubit operations. Nature **402**, 390 (1999)
23. Bartlett, S.D., Munro, W.J.: Quantum teleportation of optical quantum gates. Phys. Rev. Lett. **90**, 117901 (2003)
24. Raussendorf, R., Briegel, H.J.: A one-way quantum computer. Phys. Rev. Lett. **86**, 5188 (2001)
25. Gottesman, D., Kitaev, A., Preskill3, J.: Encoding a qubit in an oscillator. Phys. Rev. A **64**, 012310 (2001)
26. Zhang, J., Braunstein, S.L.: Continuous-variable Gaussian analog of cluster states. Phys. Rev. A **73**, 032318 (2006)
27. Menicucci, N.C., van Loock, P., Gu, M., Weedbrook, C., Ralph, T.C., Nielsen, M.A.: Universal quantum computation with continuous-variable cluster states. Phys. Rev. Lett. **97**, 110501 (2006)
28. Nielsen, M.A.: Cluster-state quantum computation. Rep. Math. Phys. **57**, 147 (2006)
29. van Loock, P.: Examples of Gaussian cluster computation. J. Opt. Soc. Am. B **24**, 340 (2007)
30. Braunstein, S.L., Pati, A.K.: Quantum information theory with continuous variables. Kluwer, Dordrecht (2003)
31. Furusawa, A., van Loock, P.: Quantum teleportation and entanglement. Wiley -VCH (2011)
32. Briegel, H.J., Raussendorf, R.: Persistent entanglement in arrays of interacting particles. Phys. Rev. Lett. **86**, 910 (2001)
33. Walther, P., Resch, K.J., Rudolph, T., Schenck, E., Weinfurter, H., Vedral, V., Aspelmeyer, M., Zeilinger, A.: Experimental one-way quantum computing. Nature **434**, 169 (2005)
34. Prevedel, R., Walther, P., Tiefenbacher, F., Böhi, P., Kaltenbaek, R., Jennewein, T., Zeilinger, A.: High-speed linear optics quantum computing using active feed-forward. Nature **445**, 65 (2007)
35. van Loock, Peter, Weedbrook, Christian, Mile, Gu: Building Gaussian cluster states by linear optics. Phys. Rev. A **76**, 032321 (2007)

36. Filip, R., Marek, P., Andersen, U.L.: Measurement-induced continuous-variable quantum interactions. Phys. Rev. A **71**, 042308 (2005)
37. Yoshikawa, J., Miwa, Y., Huck, A., Andersen, U.L., van Loock, P., Furusawa, A.: Demonstration of a quantum nondemolition sum gate. Phys. Rev. Lett. **101**, 250501 (2008)
38. Su, X., Tan, A., Jia, X., Zhang, J., Xie, C., Peng, K.: Experimental preparation of quadripartite cluster and Greenberger-Horne-Zeilinger entangled states for continuous variables. Phys. Rev. Lett. **98**, 070502 (2007)
39. Yukawa, M., Ukai, R., van Loock, P., Furusawa, A.: Experimental generation of four-mode continuous-variable cluster states. Phys. Rev. A **78**, 012301 (2008)
40. Su, X., Zhao, Y., Hao, S., Jia, X., Xie, C., Peng, K.: Experimental preparation of eight-partite linear and two-diamond shape cluster states for photonic qumodes, arXiv:1205.0590 [quant-ph]
41. Miwa, Y., Ukai, R., Yoshikawa, J., Filip, R., van Loock, P., Furusawa, A.: Demonstration of cluster-state shaping and quantum erasure for continuous variables. Phys. Rev. A **82**, 032305 (2010)
42. Ukai, R., Yoshikawa, J., Iwata, N., van Loock, P., Furusawa, A.: Universal linear Bogoliubov transformations through one-way quantum computation. Phys. Rev. A **81**, 032315 (2010)
43. Wang, Y., Su, X., Shen, H., Tan, A., Xie, C., Peng, K.: Toward demonstrating controlled-X operation based on continuous-variable four-partite cluster states and quantum teleporters. Phys. Rev. A **81**, 022311 (2010)
44. Ukai, R., Yokoyama, S., Yoshikawa, J., van Loock, P., Furusawa, A.: Demonstration of a controlled-phase gate for continuous-variable one-way quantum computation. Phys. Rev. Lett. **107**, 250501 (2011)
45. Eisert, J., Jacobs, K., Papadopoulos, P., Plenio, B.: Optimal local implementation of nonlocal quantum gates. Phys. Rev. A **62**, 052317 (2000)
46. Huang, Y.-F., Ren, X.-F., Zhang, Y.-S., Duan, L.-M., Guo, G.-C.: Experimental teleportation of a quantum controlled-NOT gate. Phys. Rev. Lett. **93**, 240501 (2004)
47. Gao, W.-B., Goebel, A.M., Lu, C.-Y., Dai, H.-N., Wagenknecht, C., Zhang, Q., Zhao, B., Peng, C.-Z., Chen, Z.-B., Chen, Y.-A., Pan, J.-W.: Teleportation-based realization of an optical quantum two-qubit entangling gate. In: Proceedings of the National Academy of Sciences of the United States of America vol. 107, p. 20869 (2010)
48. Gottesman, D.: The Heisenberg representation of quantum computers. In: Corney, S.P., Delbourgo, R., Jarvis, P.D. (eds.) Group22: Proceedings of the XXII International Colloquium on Group Theoretical Methods in Physics, pp. 32–43. International Press, Cambridge, MA (1999), e-print arXiv:9807006 [quant-ph]
49. Zhou, X., Leung, D.W., Chuang, I.L.: Methodology for quantum logic gate construction. Phys. Rev. A **62**, 052316 (2000)
50. Menicucci, N.C., Ma, X., Ralph, T.C.: Arbitrarily large continuous-variable cluster states from a single quantum nondemolition gate. Phys. Rev. Lett. **104**, 250503 (2010)
51. Nicolas, C.: Menicucci, temporal-mode continuous-variable cluster states using linear optics. Phys. Rev. A **83**, 062314 (2011)
52. Menicucci, N.C., Flammia, S.T., Zaidi, H., Pfister, O.: Ultracompact generation of continuous-variable cluster states. Phys. Rev. A **76**, 010302(R) (2007)
53. Zaidi, H., Menicucci, N.C., Flammia, S.T., Bloomer, R., Pysher, M., Pfister, O.: Entangling the optical frequency comb: simultaneous generation of multiple 2×2 and 2×3 continuous-variable cluster states in a single optical parametric oscillator. Laser Phys. **18**, 659 (2008)

Springer

http://www.springer.com/978-4-431-55018-1

Multi-Step Multi-Input One-Way Quantum Information Processing with Spatial and Temporal Modes of Light
Ukai, R.
2015, XIX, 351 p. 215 illus., 100 illus. in color., Hardcover
ISBN: 978-4-431-55018-1