（別紙様式５）

変革を駆動する先端物理・数学プログラム（FoPM）

国外連携機関長期研修　報告書

氏　　名	長吉博成
所属部局	工学系研究科　　物理工学専攻
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In this program, I spent four weeks at Leopold-Franzens-Universität Innsbruck under the supervision of Professor Hans J. Briegel. Innsbruck is a city located in the western part of Austria that has long been playing a central role in the Tyrol region both politically and culturally. Since Innsbruck is situated in the middle of high mountains, it is also known as an ideal place to enjoy winter sports such as skiing and snowboarding. In the center of the city, one can enjoy the historical atmosphere of stone architecture that was built back in the Middle Ages. The university boasts a long history of more than 300 years and hosts excellent students and researchers from all over the European countries, with whom I enjoyed fruitful discussions.

Currently, I am engaged in research on applications of optical quantum computers. Although quantum technologies have been developing very rapidly, they have yet to achieve the goal of so-called fault-tolerant quantum computation mainly due to large decoherence and lack of scalability and controllability. The main target of our group, the optical quantum computer, has numerous advantages such as deterministic entanglement generation, high scalability enabled by time-domain multiplexing, high bandwidth that enables ultrafast computation, and compatibility with quantum communication. On the other hand, it is also known that with current technologies it is hard to implement nonlinear optical interactions, and thus certain quantum operations are inaccessible, which is the bottleneck for universal quantum computation with optical systems. Nevertheless, recent research has found numerous approaches to utilize such quantum devices for practical tasks, but it is still unknown whether they can ultimately surpass conventional computers. To fully exploit the potential of current quantum devices, it is necessary to design a hardware-friendly quantum algorithm while guaranteeing its performance.

Quantum machine learning (QML) is a class of quantum algorithms that is expected to exhibit quantum enhancement with near-term quantum computers. In QML protocols, the quantum devices are employed as a parametrized black box to sample a random variable from a probability distribution that is hard to compute, and whose parameters are optimized with the aid of classical computers. After the training processes, the quantum circuit will yield certain input-output relations from which one can extract information. The quantum circuit called ansatz is carefully designed so that it performs desired quantum information processing to the information that is encoded in the circuit. The research group of Prof. Briegel has presented papers on the application of QML to measurement-based quantum computation (MBQC), which constitutes the foundation of optical quantum computing schemes that we are focused on. For this reason, I expected that my visit here would open a new perspective in finding a practical application for the upcoming optical quantum devices.

During my stay, I had insightful discussions as I had wished. I would like to express my gratitude to those who were involved in our project. Among them, two of the collaborators, Isaac Smith David and Hendrik Poulsen Nautrup, have keenly participated in the discussions and exchanged ideas with me almost every day.

They are experienced researchers who mainly work on qubit computing, a paradigm of quantum computing that employs a two-dimensional quantum system, whereas I have been majoring in what is called continuous-variable (CV) computing. Given these conditions, we started by identifying the key techniques that are employed in previous research and attempted to generalize their methodologies to the photonic systems.

Although the qubit approach has been vigorously investigated in analogy with the classical computer theory and the discrete mathematics, when dealing with the optical computers it is more convenient to consider an infinite system of photons where quantum states are represented as continuous wave functions. This approach, namely CV computing, can encode the continuous information to the quantum system without digitalizing and thus analogical to analog computing in terms of information theory, which is also the main framework for continuous systems such as electronic circuits and classical optics. However, it is not straightforward to find the correspondence between continuous and discrete systems as they exhibit significant differences in their natures, and the computation theoretic aspects of CV computing have scarcely been elucidated.

After many discussions, we have come up with an idea to construct a CV circuit that is relatively easy to implement on real devices yet exhibits certain performance for classical tasks of machine learning. This was enabled by combining both CV and qubit protocols adequately. More specifically, we imported a technique that is often used in qubit QML to a framework of CV-QML ansatz, which was originally invented by mimicking classical neural network structures to the quantum systems. I hope that our methodology will enable the first demonstration of a practical application of optical quantum computers. I would also like to thank again to the collaborators since this result would not have been achieved without their profound insights.