（別紙様式２）

フォトンサイエンス国際卓越大学院プログラム（XPS）
光科学特別実習　報告書

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研究課題名	オンライン国際会議 Workshop on Enabling Technology and Algorithms for Quantum Computing における招待講演
日程	西暦 2021 年 4 月 13 日　～　西暦 2021 年 4 月 14 日

Since April 2020, collaborators and I had been working on developing and demonstrating an efficient scheme for estimating the quantum many-body state of an entangled string of microwave photons. In February 2021, I was invited to talk about this result at an international workshop called the Workshop on Enabling Technology and Algorithms for Quantum Computing. This is an online workshop hosted by the Wallenberg Centre for Quantum Technology, a Swedish research program at Chalmers University of Technology which aims to develop a quantum computer based on superconducting qubits.

Website of the workshop:
https://www.chalmers.se/en/centres/wacqt/calendar/Pages/ws%20enabling%20technology.aspx

There were 24 invited talks, mostly on experimental results using a superconducting qubit and some on theoretical results. There were also two keynote talks given by senior researchers. The invited talks were all given by young researchers, including graduate students around my age and post-doctoral researchers. I was familiar with many of the works because they were presented one month ago at the largest conference of this field, APS March Meeting. However, because this workshop was much smaller and each speaker had more time (15 minutes talk + 5 minutes questions), I was able to understand the talks much better and ask questions. My talk also got great questions which had not been asked when I presented this result at the March Meeting. One of the questions was about the computational cost of one part of our estimation algorithm, and that question motivated us to look further into the efficiency of the algorithm and include the analysis in our paper.

Another great thing about the format of this workshop was that it was recorded and made public on YouTube. This is good because some of the talks were scheduled past midnight in our time zone and others at inconvenient times in the United States. I could also listen again to the talks I found interesting but didn't have enough time to understand everything on the slides. The recording of my own talk may come in handy in case I want to give someone a quick overview of my project by sending them the YouTube link.

Recording of my talk on YouTube: https://www.youtube.com/watch?v=TW4P8gmCnR0&t=5760s

Other than the purpose of sharing the latest results among the researchers, this workshop had another purpose of helping young researchers in considering where to do their post-doctoral research. At the beginning of the workshop, the host talked about the projects and the research environment at the Wallenberg Centre for Quantum Technology and advertised that they are actively hiring. It is always great to know that there are open positions in our research field. Many of the invited speakers were from the institutions which I was considering applying for a post-doctoral position, so it was great that I got to know what kind of projects the young researchers there are working on. These people will become my colleagues if I get accepted for the position there, so it was motivating for me to participate in a workshop with them.

Summary of my talk:

Generating a many-qubit entanglement is the essential first step in measurement-based quantum computation and error-corrected quantum communication. A class of highly entangled states called cluster states is remarkable for its universality as a computational resource and the existence of efficient generation schemes using time-domain multiplexing. Recent works in the optical [1–3] and microwave [4] domains demonstrated these schemes by sequentially emitting a string of entangled photons into a waveguide.

However, the efficiency of the generation does not necessarily guarantee that the resulting quantum state can be efficiently measured and evaluated. In fact, reconstructing the many-qubit density matrix by conventional quantum state tomography becomes exponentially difficult as the number of qubits increases. Because of this difficulty, only an inseparability criterion was evaluated in the previous works with continuous-variable entanglement [2, 3]. Others took an alternative approach of reconstructing a single emission cycle as a quantum operation [1, 4], but this requires a complete characterization of the emitter and assumes that the emission process is always identical.

Here, we propose and experimentally demonstrate an efficient scheme for reconstructing the density matrix of a sequentially emitted string of entangled photons. We take advantage of the fact that the time-domain multiplexing can only generate entanglement which is "local" in time, in the sense that the many-qubit density matrix is a matrix product operator [5] which can be reconstructed from local correlation measurements [6]. Using this scheme, we reconstruct the density matrix of a 35-qubit one-dimensional cluster state of microwave photons generated using a superconducting qubit and a resonator.

[1] I. Schwartz *et al.*, Science **354**, 434–437 (2016).
[2] M. Larsen *et al.*, Science **366**, 369–372 (2019).
[3] W. Asavanant *et al.*, Science **366**, 373–376 (2019).
[4] J.-C. Besse *et al.*, Nat. Commun. **11**, 4877 (2020).
[5] C. Schön *et al.*, Phys. Rev. Lett. **95**, 110503 (2005).
[6] T. Baumgratz *et al.*, Phys. Rev. Lett. **111**, 020401 (2013).

Screenshot of the recording on YouTube: