（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

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Research

I visited Prof. Wallraff's group (Quantum Device Lab) in ETH Zurich, Switzerland. Here, I worked on microwave-photon-generation experiments for quantum communication between superconducting qubits during the stay at ETH. Quantum communication between qubits can be implemented using an itinerant microwave photon on a transmission line. In this method, one emits a microwave photon from an interface at the transmitter device that includes a qubit, and absorbs the emitted photon at the receiver qubit device. In implementing this scheme, the two interfaces that pitch or catch the photon must have the same frequency. This requirement is difficult to satisfy because of the uncertainty in the fabrication process which causes deviations from the designed parameters. On top of it, the emitted photon needs to be shaped to ensure high fidelity communication.

To satisfy these two requirements, I have developed a new photon-generation method using only a fixed-frequency device and microwave drives. By detuning the drive that stimulates the photon emission, we have demonstrated that we can emit a shaped photon at various frequencies. This "off-resonant" driving scheme is good since we only need simple physical implementations. We have also shown in our paper that the variations in the frequencies can be effectively compensated for using our method. The flaw of this method is that we need to have a circulator, a microwave rectifier, between the devices to observe the photon and calibrate the system, since a circulator induces additional photon loss and makes the communication unidirectional.

On the other hand, conventional way of generating frequency-tunable shaped photons is to use a frequency-tunable element (such as SQUIDs) and shift the frequency of the interface by penetrating flux bias through the circuit. This method is based on an on-resonance driving between the quantum states to emit a photon. But the pitch and catch of the photon is prohibited when the variance of the frequencies cannot be compensated for the flux-bias tuning.

It becomes prominent especially when one tries to perform communication between multiple qubits (with multiple interfaces on each side). For that, they have developed a theory to emit a photon by off-resonantly driving the system, separately from our group. But contrary to expectations, the method had not been working well, and they were seeking the reason. In general, if the photon generation based on theory works well, we don't need any additional elements between the devices, which is good since we can avoid introducing photon loss and make the communication bidirectional.

Following the context above, what I was aiming for during the visit is to compare the photon generation methods. Through experiments and discussions, I have found that my method can only work under the adiabatic condition of the dynamics. This condition was guaranteed in my paper since the decay rate of the interface is huge. But the device I tested in ETH has much smaller decay rate and my method did not work well with short photon pulses where the adiabatic condition is no longer valid. On the other hand, the method developed in ETH worked well with an improved measurement code, and it turned out that the method can work without the adiabatic condition. However, the frequencies of the emitted photons are off from the target frequency by few MHz. The deviation becomes prominent when detuning of the drive becomes larger. When seeing the phase of the emitted photons, we observed that the phases are distorted systematically depending on the envelope of the target shape and the detuning. It has yet to be discovered where the distortion comes from, but this finding would be useful for implementing shaped-

photon generation with frequency tunability.

General experience

On the research side, since what I was doing in ETH is close to what I do in Tokyo, it was not so difficult to get used to the measurements. Nevertheless, each day presented new learning opportunities that I believe will enhance our research capabilities back in Tokyo. One of the things that I felt great was the style of meetings. They have a general meeting where one of the members will give a 30-min talk on their research. It will work well, especially when you are in a big research group and cannot track every single person's progress every week.

The international composition of the research group created an inherently English-speaking environment, as most members came from various non-English-speaking countries. This setting provided opportunities to discuss cultural differences and perspectives while reinforcing the importance of English communication skills in international research collaboration.

As to general life, it is quite safe in Switzerland. You can go out at night in Zurich. The city has good scenery around it, and it feels great living there. The people are also so great and kind that every time I was in trouble there appeared someone and they helped me a lot. However, the cost of living in Switzerland presents a significant challenge, with prices typically two to three times higher than those in Japan. This economic reality necessitated daily home cooking, which unexpectedly resulted in substantial improvement in my culinary skills. Regardless, I found the city awesome, and I want to visit it again in the future.

Conclusion

This research experience at ETH Zurich proved invaluable for my scientific development and international perspective. The collaborative work provided crucial insights into quantum communication methodologies and highlighted important technical considerations for future implementations.

I extend my sincere gratitude to Professor Wallraff and Professor Nakamura for facilitating this research visit, and to the FoPM (Frontiers of Physics and Materials) program for their generous financial support. I look forward to applying the knowledge and experience gained during this visit to advance our quantum communication research efforts and hope to maintain collaborative relationships with the ETH team in the future.



1 The building of the physics department in ETH Hönggerberg campus.