R&D Theme

# Atom networking technology

## Progress until FY2022

### 1. Outline of the project

In this research and development (R&D) theme, we will develop a quantum interface for networking atom-based quantum computers consisting of neutral atoms as qubits processing quantum information and the necessary photon detection technology. The goal of this R&D theme will establish the elemental technology of quantum networking for scaling up various quantum computers, including atom-based quantum computers, and the realization of a fault-tolerant universal quantum computer, which is the final target of Moonshot Goal 6.

To achieve this goal, we are working on creating quantum entanglement among atoms and photons on a large scale as a challenging theme. Beyond the realization of one-to-one qubit connections demonstrated already, we are working on an attempt at multiplexing technologies for atoms, optical circuits, and photon detectors. These developed elemental technologies useful in other R&D themes and projects will be actively provided and contribute to the final target of Moonshot Goal 6.

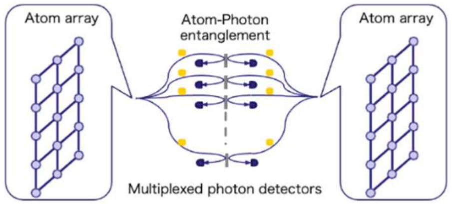



Fig. 1: Concept of a networked atom quantum computer

### 2. Outcomes so far

(1) Demonstration of Rb atom array and construction of photon detection system and Proposal of Bell state distillation between logical qubits.

(2) Proposal and demonstration of "Optical frequency tweezers" for multiplexed network connections and Proposal of a photonic quantum computer with time-frequency modes.

(3) Superconducting nanowire photon detector (SNSPD) device development for 710 nm, 780 nm, and 850 nm wavelength bands, achieving a detection efficiency of more than 70% and a dark count rate of less than one count per second in each wavelength band. Six patent applications have been made.

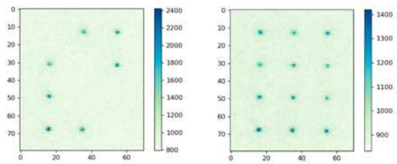


Fig. 2: CCD image of demonstrated atomic array.
Left: Single shot
Right: Integrated

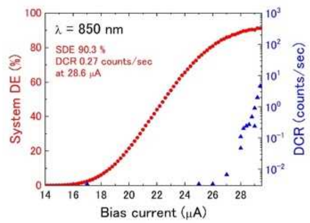



Fig. 3: Detection efficiency and dark count characteristics of SNSPD in 850 nm band.

(4) Refrigerator system development with 12 channels of SNSPD for cooling below 2.3 K. 32 channel SNSPD refrigerator system has been successfully demonstrated.

Fig. 4: 32-ch SNSPD refrigerator system exhibited at G7.
We have developed an SNSPD refrigeration system with 32 SNSPD packages that can be cooled to a temperature of 2.12 K. It has optical signal input, drive circuits, and signal readout ports.

### 3. Future plans

Our research achievements so far include elemental technologies for quantum processors of atom arrays and a proposal of quantum protocols, demonstration of the working principle of routing photons from multiplexed photon sources, expansion of the wavelength of SNSPD and performance enhancement, and demonstration of a refrigerator system capable of multiplexing SNSPDs to the scale of 32 channels (world competitive scale). In the future, we aim to demonstrate quantum networking using these technologies.


国立研究開発法人 科学技術振興機構 JST Japan Science and Technology Agency

R&D Theme

# Photon networking technology

## Progress until FY2022

### 1. Outline of the project

Compared to other physical quantum systems, photons have high coherence, can maintain their quantum nature at room temperature, and can be transported over long distance in optical fibers. Arbitrary one-qubit gates can be operated with high fidelities by using linear optics. Furthermore, large number of qubits can be created by way of time-division multiplexing. The mainstream of quantum computing with photons is the linear optical quantum computing (LOQC), which utilizes photon generation via parametric down conversion and quantum gates based on the detection of photons by single-photon detectors. In particular, measurement-based quantum computation, where quantum computation is carried out by simple measurements on photonic qubits in a cluster state (Fig. 1).

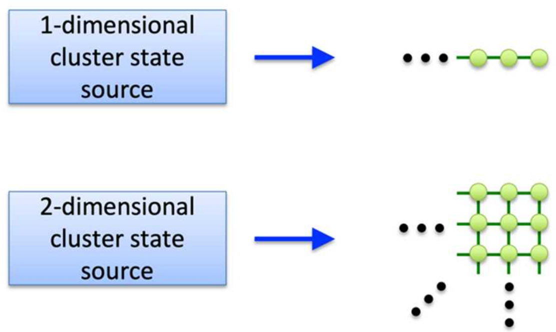



Fig. 1: Photonic cluster state source

However, since generation of photons and creation of their cluster states are probabilistic process, LOQC requires enormous number of resources.

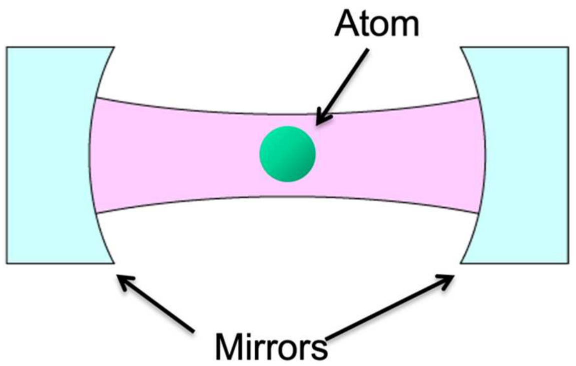



Fig. 2: Cavity QED system

Cavity quantum electrodynamics (QED) systems (Fig. 2) provide a scheme for deterministic generation of single photons and photonic cluster states. In this project, we aim to develop photon networking technologies. Specifically, we develop technologies to realize such sources of quantum light by using nanofiber cavity QED systems.

### 2. Outcomes so far

We have set up a nanofiber cavity QED system suitable for photon networking technology (Fig.3). By using L-type three-level structure of D2 line of Cesium atoms, we have developed elementary technologies for deterministic generation of single photons with vacuum-stimulated Raman adiabatic passage (vSTIRAP). We have also developed elementary technologies for the standard Duan-Lukin-Cirac-Zoller quantum repeater scheme.

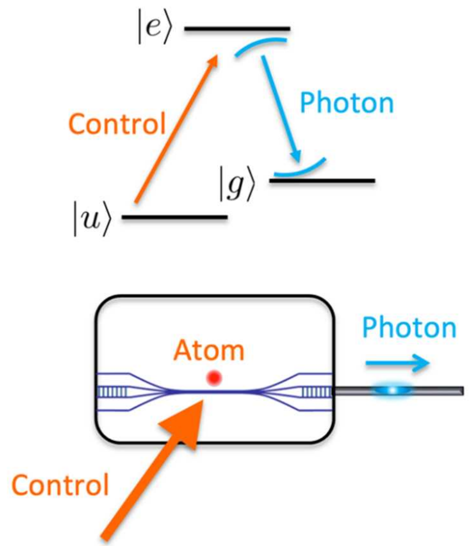



Fig. 3: Single-photon generation with nanofiber cQED

### 3. Future plans

We will continue to develop photon networking technology based on nanofiber cavity QED systems, particularly the technologies for generating photonic qubit array and photonic cluster states.

R&D Theme

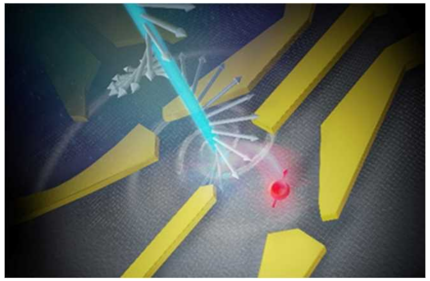
# Semiconductor networking technology

## Progress until FY2022

### 1. Outline of the project

We will develop the technologies of quantum interface between photons and silicon qubits based on spin of electrons or holes in semiconductor quantum dots (QD) and intermediate distance coupling between silicon qubits for constructing networks of semiconductor quantum computers. We also develop the connection of semiconductor qubits to large-scale optical networks. By accomplishing these research subjects, we will establish the semiconductor networking technologies for fault-tolerant quantum computers, which is the goal of Moonshot project.

Toward this goal, the detailed research subjects that we focus are the intermediate distance coupling between silicon qubits networking silicon NISQ quantum computers, Ge hole QDs as a quantum interface for telecom photons and a creation of an entanglement between remote spin qubits from an entangled photon pair.



Schematic of quantum interface for quantum state conversion from a single photon to a single electron spin in a spin qubit.

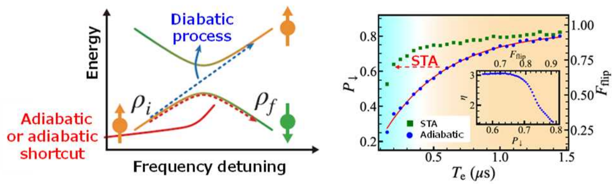
### 2. Outcomes so far

① **Adiabatic shortcut for a semiconductor spin qubit**

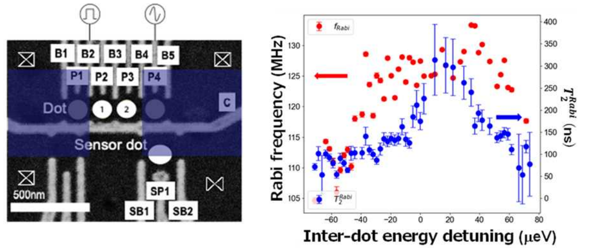
As an intermediate distance coupling technology, adiabatic quantum state transfer (AQT) transfers a quantum state from one end to the other by adiabatically controlling the exchange interactions at both ends in a spin chain formed in a one-dimensional QD array. However, a longer operation time is needed for a longer spin chain to prevent the diabatic error process. The adiabatic shortcut is generally known as a speed-up method. We demonstrated the accelerated adiabatic passage for single electron spin in a semiconductor qubit, for the first time, by adding a counter diabatic term. This would offer a way to speed up the AQT in the future.

② **Ultrafast and high-fidelity spin manipulation using interdot tunneling in a double QD**

While the single spin manipulation is conventionally performed in a single QD, we can speed up the spin manipulation by utilizing interdot tunneling in a double QD. Moreover, the Rabi decay time can be also maximized at the fastest spin manipulation condition and the fidelity for single spin control exceeds 99% which is the highest value reported in GaAs spin qubits. This result would be useful for a strong coupling of spin qubits with a superconducting resonator for the intermediate coupling between silicon qubits and photon-silicon qubit quantum interface.




(Left) Schematic of adiabatic shortcut. The spin state always follows the ground state and flips. (Right) Dependence of the spin-flip probability on the operation time. Compared to the adiabatic transition (blue circles), the adiabatic shortcut (green squares) achives a higher-sipin-flip probability at a shorter operation time. The inset shows the speed-up factor η.




(Left) Electron micrograph of GaAs multiple quantum dots. Double quantum dots between micromagnets (blue squares). (Right) Rabi frequency (red circles) and Rabi relaxation time (blue circles) as a function of inter-dot energy detuning of double quantum dots. High-speed operation above 100 MHz and long Rabi decay time near zero detuning are realized.

### 3. Future plans

Utilizing the results obtained, we will develop the intermediate coupling between Si qubits and photon quantum interface. Moreover, we will establish the photon-spin quantum interface based on Ge QD operating at telecom wavelength and introduce entangled photon pairs for networking.

R&D Theme

# Superconducting networking technology

## Progress until FY2022

### 1. Outline of the project

In this project, we will develop a "quantum transducer" towards networked superconducting quantum computers. We will mainly focus on a quantum transducer that converts microwave photons, the quantum information inside superconducting quantum computers, to optical photons at millikelvin temperature. As the medium for the quantum transduction, we will exploit the microwave and optical transitions of silicon-vacancy (SiV) centers in a diamond crystal.

The challenges are implementing an optical cavity including a bulk diamond crystal, stabilizing an optical cavity at millikelvin temperature, and combining microwave and optical cavities. To this end, we designed a custom dilution refrigerator that can mitigate vibrations with an equipped active-damping system.

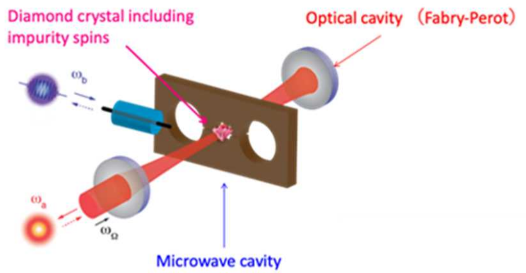



Figure 1 Schematic of the quantum transducer developed in this project.

### 2. Outcomes so far

1. Stabilizing an optical cavity at a millikelvin temperature in the custom dilution refrigerator was achieved.
2. An optical cavity that includes a bulk diamond crystal with an anti-reflection coat on one side and a high-reflection coat on another side was realized.
3. Microwave-optical combo cavity device was designed, fabricated, and tested at low temperatures.
4. A numerical simulation for the quantum transducer was performed.

Regarding 1, we could stabilize an optical cavity in a cryogen-free dilution refrigerator, where the pulse tube's cold-head induces vibrations, making optical cavity stabilization very challenging (Figure 2). Regarding 2, we managed to stabilize an optical cavity, even including a bulk diamond crystal. This manifests that the quantum transducer developed in this project is technically possible. Regarding 3, it is the transducer device. A diamond crystal must be placed in microwave and optical cavity modes. To this end, we designed and tested a combo-cavity (Figure 3). Regarding 4, we developed a theory of the microwave-optical photon conversion and simulated the conversion efficiency.

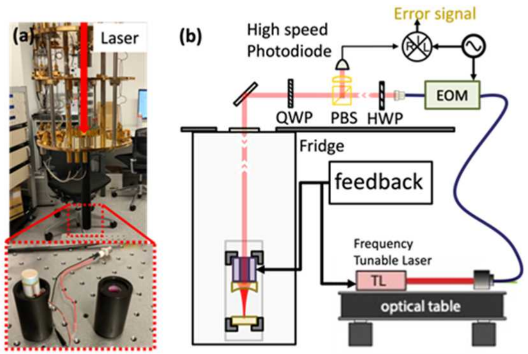



Figure 2 Stabilizing an optical cavity in a dilution refrigerator. (a) Photographs of the custom dilution refrigerator (top) and the cavity (bottom). (b) Schematic of the setup.

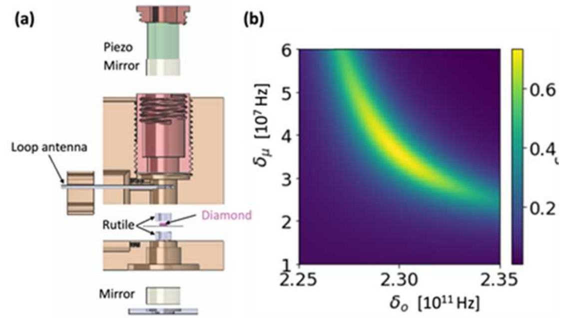



Figure 3 (a) CAD rendering of the combo-cavity device. (b) An example of numerical simulation. The conversion efficiency is plotted versus microwave and optical frequency detunings.

### 3. Future plans

Using the developed transducer device, we will first convert classical weak microwave or optical signals to demonstrate the proof-of-concept of the quantum transduction. We will then convert non-classical quantum microwave photons prepared by a superconducting qubit to optical photons. We will collaborate with the "Development of Integration Technologies for Superconducting Quantum Circuits" team for these objectives.



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