Goal6 Realization of a fault-tolerant universal quantum computer that will revolutionize economy, industry, and security by 2050.

Development of Quantum Interfaces for Building Quantum Computer Networks

Here begins our new MIRAI
MOONSHOT
RESEARCH & DEVELOPMENT PROGRAM

R&D Theme

Diamond Quantum Memory

Progress until FY2022

1. Outline of the project

We are developing quantum interfaces that connect superconducting quantum computers with optical fiber quantum communications to realize a distributed quantum computer system (Fig. 1). The core of this project is the quantum memory and optomechanical crystals, and integrated development from the diamond growth and nanofabrication to 3D mounting will be carried out. In this R&D theme, we have achieved the following outcome.

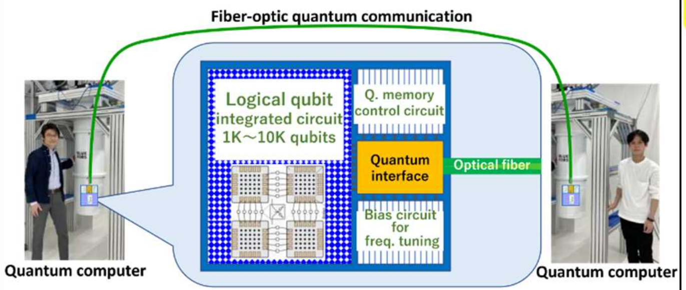

Fig. 1. Distributed quantum computer system.

2. Outcome so far

Subject 1: Diamond Quantum Memory

- Quantum entanglement light source development

Using nitrogen vacancy (NV) centers in diamond (Fig. 2), we have achieved quantum entanglement generation between photons and electrons with a fidelity of 98%.

- Fault-tolerant universal quantum gate operation for quantum memory

We have achieved fault-tolerant universal quantum gate manipulation with a fidelity of 99.97% by performing geometric quantum manipulations on the electron spins in the NV center.

- Complete Bell measurement in quantum memory

We have achieved a complete Bell measurement between two carbon nuclear spins with a fidelity of 90%.

- Laser irradiation color center generation

Toward the formation of deterministic quantum memory in nanostructures, we have succeeded in generating GR1 defects, which are the nuclei of NV centers, by irradiating intense ultrashort laser pulses.

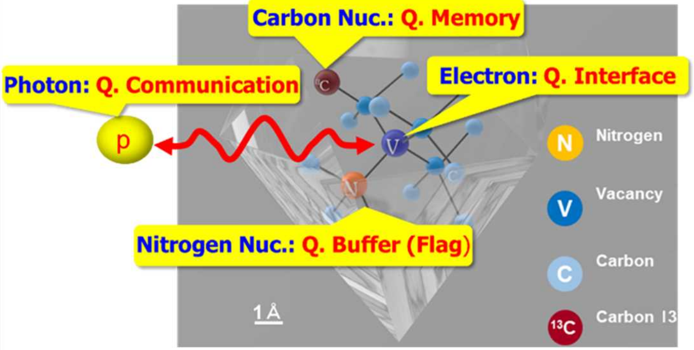

Fig. 2. Quantum system in the diamond NV center.

Subject 2: Diamond Quantum Structures

- Fabrication of diamond nanostructures

We have developed submicron patterning technology using an electron beam lithography system to fabricate nanostructures such as diamond optomechanical cavities and micro comb-shaped electrodes (IDTs).

- Fabrication of diamond piezo structures

A surface acoustic wave (SAW) device was fabricated by forming IDT electrodes on an aluminum nitride (AlN)/diamond multilayer film (Fig.3) and successfully generated sound waves (acoustic waves) at ~5 GHz.

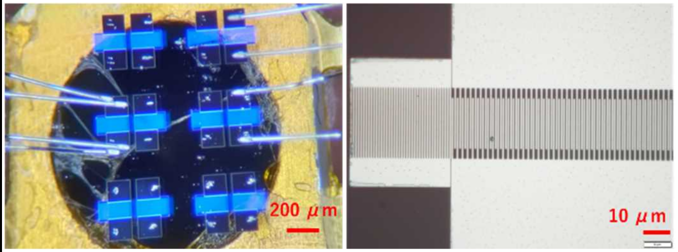

Fig. 3. (Left) 2-port diamond SAW device, (Right) enlarged view of electrode in 1-port device.

Subject 3: Diamond Quantum Crystals

- Diamond high-purity crystal growth

We have performed high-purity diamond crystal growth and impurity control to stabilize the charge state of NV centers and reduce their spectral diffusion.

Subject 4: Diamond Color Centers

- Development of ion beam for variety of color centers

In addition to the mainstream NV and SiV centers, we developed beams to create GeV, SnV, and Pb centers. We successfully developed an L-arginine beam to place carbon near the NV center (Fig. 4).

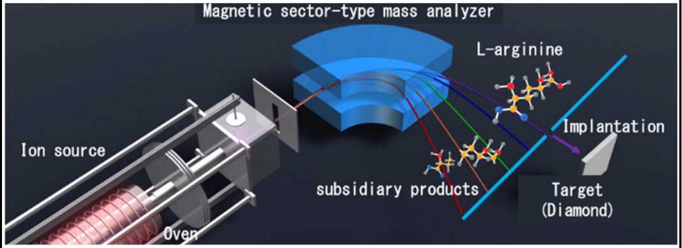

Fig. 4. L-arginine ion implantation into diamonds.

3. Future plans

We will form the quantum memory in a diamond optomechanical cavity and couple it with a piezoelectric microwave cavity.

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Japan Science and Technology Agency

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R&D Theme

Optomechanical Cavity

Progress until FY2022

1. Outline of the project

Although there are many candidates for quantum computers, the potential of diamond is second to none in other physical systems (Fig. 1). In this project, we aim to develop a superconducting optical quantum interface, in which superconducting microwave photons and optical photons are quantum-connected by diamond (Fig. 2), to realize a large-scale distributed superconducting quantum computer system. In this R&D theme, we will develop optomechanical cavities that will be the building blocks of the interface. We have achieved the following outcome.

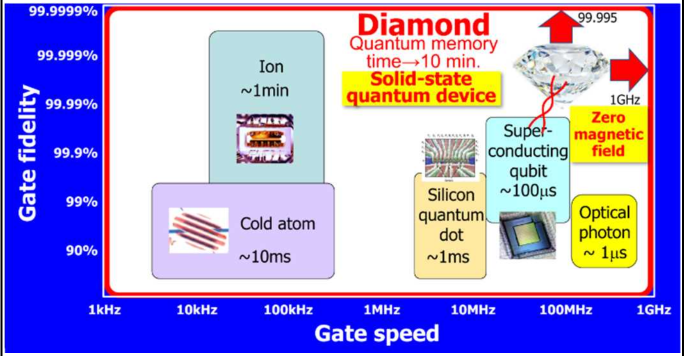

Fig. 1. Candidate physical systems that constitute a quantum computer and comparison of their performance.

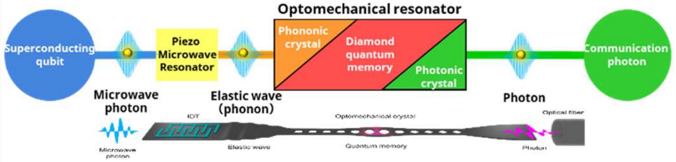

Fig. 2. Role of optomechanical cavity in quantum IF.

2. Outcome so far

Subject 1: Photonic Crystal Optical Cavity

・In a photonic crystal cavity consisting of diamond and aluminum nitride (AlN) stacked structures, we have found a structure in which the Purcell factor, which is an indication of the intensity of the emission increase from the diamond color center, greatly exceeds the initially set target value (over 100).

・ We developed fabrication technology for diamond optomechanical cavities and succeeded in realizing an air-bridged diamond photonic crystal nanobeam cavity structure (Fig. 3). We also conducted basic studies for integration.

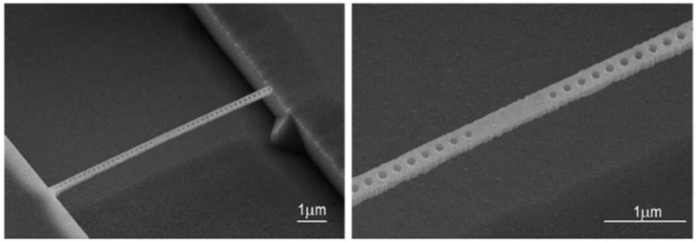

Fig. 3. SEM photograph of the structure of a diamond air-bridge photonic crystal nanobeam cavity.

Subject 2: Photonic Crystal Optical Cavity Mounting

・The goal was to design a coupling structure from the optical fiber to the optomechanical cavity (Fig. 4) with a loss of 10 dB or less. Specifically, a silicon nitride (SiN) waveguide was assumed for the fiber coupler and optical wiring, and tapered coupling was employed for the piezoelectric AlN and diamond laminated waveguide. In addition, we aimed for critical coupling from the waveguide to the optomechanical cavity by apodizing the end of the cavity. As a result, the total loss from the fiber to the cavity was estimated to be 1.49 dB.

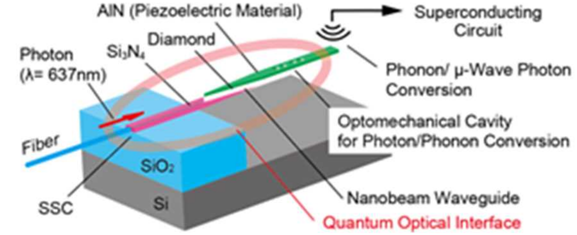

Fig. 4. Optical interface configuration.

Subject 3: Phononic Crystal Sound Cavity

・We have designed a diamond optomechanical cavity that strongly and simultaneously confines phonons and photons in a narrow region and couples quantum memory dramatically and strongly. The cavity performance far exceeded the target value. We also evaluated the conversion efficiency of microwave-to-communication wavelength photons via quantum memory (Fig. 5).

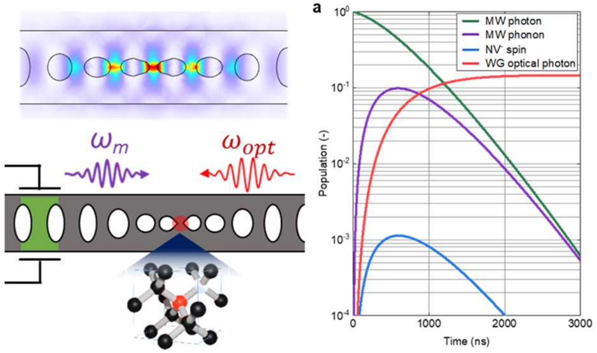

Fig. 5. Simulation of microwave-to-communication wavelength photon conversion.

3. Future plans

We will realize the diamond optomechanical cavity and integrate them with the quantum memory and the piezoelectric microwave cavity.

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R&D Theme

Piezoelectric Microwave Cavity

Progress until FY2022

1. Outline of the project

This project aims to develop a quantum interface that connects superconducting qubits with photons for communication to realize a large-scale distributed superconducting quantum computer. In this R&D theme, we will develop a piezoelectric microwave resonator that will be a component of the system (Fig. 1). In this R&D theme, we have achieved the following outcome.

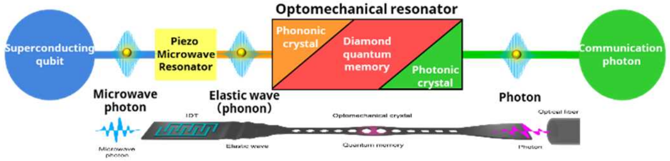

Fig. 1. Role of piezoelectric microwave cavity in quantum IF.

2. Outcome so far

Subject 1: Piezoelectric Microwave Cavity

- Material search and structural design of piezoelectric microwave cavity

In order to convert microwave photons into phonons with a wavelength of ~1 mm, which is equivalent to telecommunication photons with a wavelength 5 orders of magnitude shorter, we fabricated a diamond surface acoustic wave (SAW) device by forming a piezoelectric material, aluminum nitride (AlN), on diamond (Fig. 2).

- Conversion from microwaves to phonons

We have succeeded in quantum manipulation of NV-centered quantum memory by generating phonons from 5 GHz microwaves (Fig. 2a).

- Quantum manipulation of NV-centric quantum memory by microwaves

We have succeeded in quantum manipulation of NV-centric quantum memory by the electric field of microwaves (Fig. 2b). We have also fabricated a microwave resonator with a Q-value of 8,000.

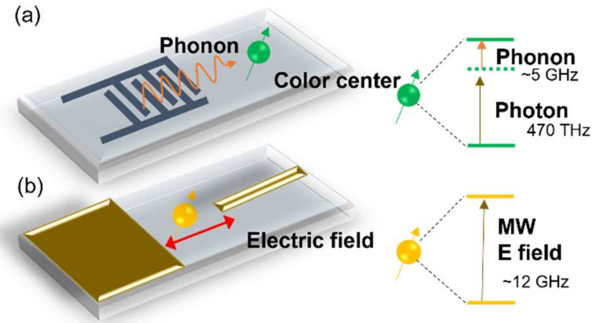

Fig. 2. Overview of quantum memory control by (a) phonon and (b) electric field.

Subject 2: Quantum-Controlled Electronic Integrated Circuits

・To achieve fast and high-fidelity quantum control of quantum circuits at cryogenic temperatures, we have developed a superconducting microwave pulse generator capable of generating microwaves of arbitrary amplitude (Fig. 3). A single flux quantum (SFQ) circuit is used to generate a 100 GHz density-modulated SFQ pulse train, and a superconducting filter is used to generate a 5 GHz microwave pulse.

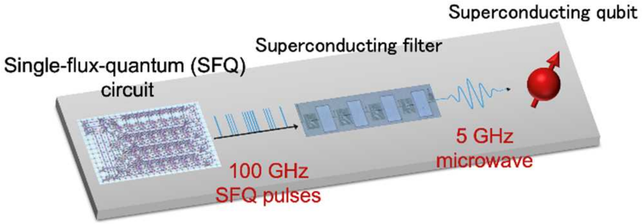

Fig. 3. 5GHz microwave pulse transmitter with 4K operation using superconducting circuits.

Subject 3: Theoretical study of quantum interface

・We theoretically investigated the quantum media conversion from a superconducting-atom qubit to a microwave-photon qubit. We proposed a method to demonstrate the SWAP gate between an atom qubit and a frequency-encoded photon qubit using a weak classical microwave pulse at the single photon level, and confirmed the bidirectional quantum state transfer. The fidelity of the atom-to-photon (photon-to-atom) state transfer reached 0.829 (0.801) (Fig. 4).

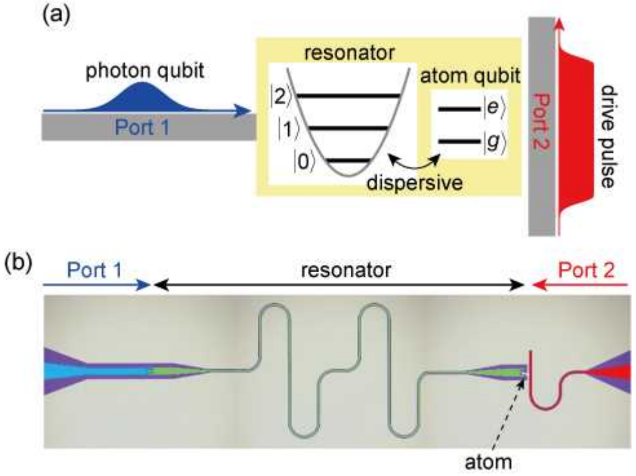

Fig. 4. The SWAP gate between a superconducting-atom qubit and a microwave-photon qubit. (a) conceptual view, (b) micrograph of the device.

3. Future plans

We will improve the performance of piezoelectric microwave cavities and integrate them with optomechanical cavities with quantum memory.