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

Development of large-scale fault-tolerant universal optical quantum computers

Here begins our new MIRAI
MOONSHOT
RESEARCH & DEVELOPMENT PROGRAM

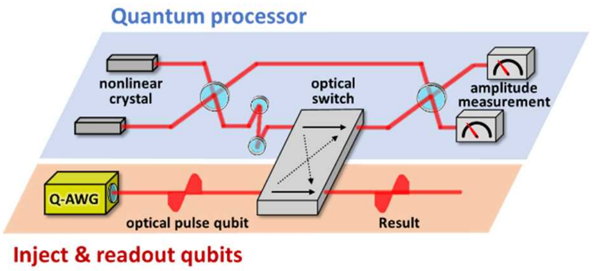
R&D Theme

Research and development on time-domain multiplexed general-purpose optical quantum computer

Progress until FY2022

1. Outline of the project

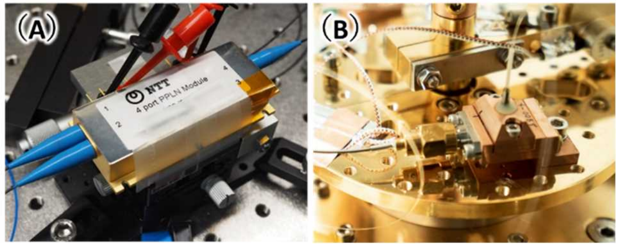
Research is progressing in various physical systems towards the implementation of practical quantum computers. In most systems, a major challenge lies in the requirement of highly complex quantum processors necessary for practical quantum computing. On the other hand, optical system can perform practical quantum computing with compact quantum processors. As such quantum processors have already been demonstrated, the main focus of developments is the generation of optical qubits. As an optical qubit source, we proposed the Quantum Arbitrary Waveform Generator (Q-AWG). The Q-AWG is a versatile quantum light source that can output arbitrary quantum states of light with arbitrary pulse waveforms. Due to its high versatility, the Q-AWG can serve as the core light source for practical optical quantum computers, and it has the potential to solve various challenges that arise during the path to the implementation of practical quantum computers. The Q-AWG is truly an "ultimate quantum light source," and its realization would greatly accelerate the development of optical quantum computers.



An optical quantum computer consisting of a quantum processor and a Q-AWG.

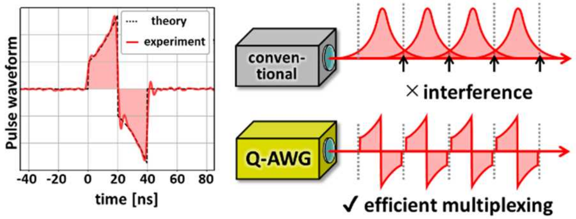
2. Outcome so far

In FY 2022, we developed a method to precisely control the pulse waveform of quantum light according to objectives, thus establishing the fundamental technology for the Q-AWG. By using this method, we generated qubits with specialized pulse waveforms required for the operation of optical quantum processors. It had been challenging to achieve arbitrary pulse waveforms and control them while minimizing the loss of quantum light. To address these issues, we developed a novel method to indirectly control the pulse waveform through highly broadband quantum entangled light. The generation of broadband quantum entangled light utilized the optical parametric amplification module developed in FY 2021. Additionally, superconducting nanowire single-photon detectors were employed to ensure the strong non-classicality of the generated qubits. These devices are closely related to optical communication technology, highlighting the significant acceleration of quantum technology through interdisciplinary fusion in FY 2022.



(A) optical parametric amplification module
(B) superconducting nanowire single-photon detector

The qubits generated by this method possess a special pulse waveform known as a balanced time-bin waveform. This waveform is required for the operation of optical quantum processors, but its realization was unknown prior to this method. With this achievement, it has become possible to input qubits into quantum processors, opening up prospects for demonstrations of optical quantum computing. Furthermore, the balanced time-bin waveform has a distinctive shape that does not have tails on both ends. This enables the qubits to be spaced more closely together than with conventional methods, allowing for the input of a large number of qubits into quantum processors. By fully utilizing the potential of the currently used optical parametric amplification module, it is possible to input up to one billion qubits. This number overwhelms other physical systems where scalability is a challenge, making it a game-changer towards the implementation of practical quantum computers.



Balanced time-bin waveform necessary for the quantum processors and efficient multiplexing of qubits.

3. Future plans

We will integrate the Q-AWG and quantum processors to advance the actual use of optical quantum computers, including implementation of real machines and cloud migration. At the same time, we will improve the Q-AWG for generating fault-tolerant qubits. Through these two strategies, we will steadily approach the realization of large-scale, fault-tolerant, and universal quantum computers. Furthermore, by actively leveraging the excellent technological platform of optical communication, as demonstrated in this research, we expect that the technological developments mentioned above will advance at an unprecedented pace.

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Development of Large-scale Fault-tolerant Universal Optical Quantum Computers

R&D Theme

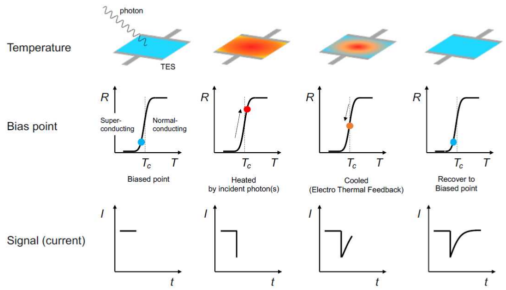
Research and development on superconducting photon number discriminator

Progress until FY2022

1. Outline of the project

Quantum entanglement is generated by squeezed light and a beam splitter, and GKP qubits are generated by detecting a predetermined number of photons. The GKP qubit appears at the moment when a predetermined number of photons is detected. We are developing a high-speed photon number resolving detector for GHz clock optical quantum computers. A superconducting transition edge sensor (TES) in the communication wavelength band can resolve the number of photons. TES is operated at the superconducting transition edge, by setting a proper operation temperature.

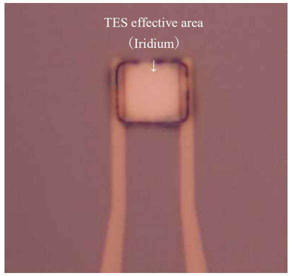
Transition Edge Sensor (TES)

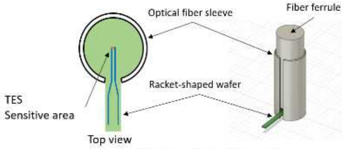


The temperature rise triggered by the absorption of near-infrared incident photons is read out as a current drop which corresponds to an absorbed energy. In order to realize high-speed TES operation, we will fabricate a device that minimizes the size of the sensor so that the temperature rise can propagate immediately over the entire sensor and the current change occurs instantaneously. The sensor size is to be minimized, thus the corresponding heat capacity is minimized, which contributes to the higher temperature rise. Therefore, higher S/N ratio, faster signal, and better identification of the number of photons are expected.

2. Outcome so far

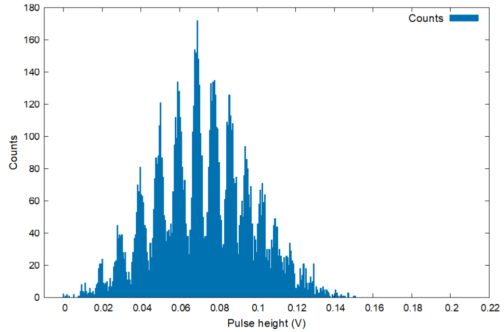
The lower left figure shows a photograph of the fabricated 8 μm square TES. The TES is made on a silicon substrate, processed to have an outer shape that matches the size of the optical component, and is self-aligned so that it can be aligned with the optical fiber. It was confirmed that the fabricated TES showed a rise time of 16.2 ns and a corresponding bandwidth of ~20 MHz.





Schematic of self-alignment

The TES shows a current change whose magnitude is proportional to the absorbed energy of incident photons. When we operate TES with monoenergetic photons, discrete energies are deposited on the sensor according to the number of photons. Therefore, an absorbed energy histogram shows peaks corresponding to the number of incident photons. The measured histogram below shows that the number of near-infrared photons can be identified and resolved with our fabricated device.



3. Future plans

According to our simulation calculation for tiny TES, the rise time of signal is estimated to be less than 300 ps, therefore, a signal bandwidth of GHz is expected. Further miniaturization of the device is planned. Precise structure is considered by employing Focused Ion Beam (FIB), which enables arbitrarily fine structures in the sensor design such as the use of array structures to satisfy the effective area requirement. Furthermore, the replacement of the superconducting quantum interference device (SQUID) is planned since the bandwidth of the SQUID is limited.

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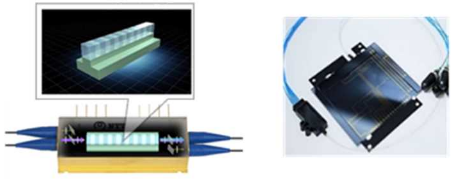
R&D Theme

R&D of waveguide optical parametric amplifiers and optical quantum waveguide circuits

Progress until FY2022

1. Outline of the project

This R&D theme is on quantum teleportation on a chip. This chip technology will contribute to Goal 6 and the goal of this project, which are to achieve a large-scale fault-tolerant universal optical quantum computer as an elemental technology that provides high-quality quantum states and quantum information processing. In this theme, we will apply waveguide-type periodically poled lithium niobate (PPLN) and planar lightwave circuit (PLC) technologies, which were developed for optical communications, to quantum information processing (Fig. 1). With these technologies, we aim to achieve teleportation with 10-dB squeeze light and 8.3 fidelity.

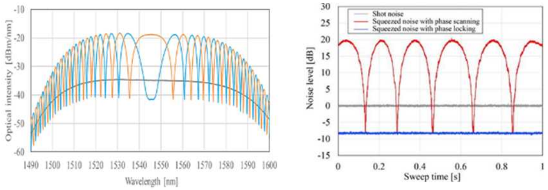


(a)Waveguide-type PPLN (b)Planar lightwave circuit

Fig.1 Device technologies for optical quantum computing

2. Outcome so far

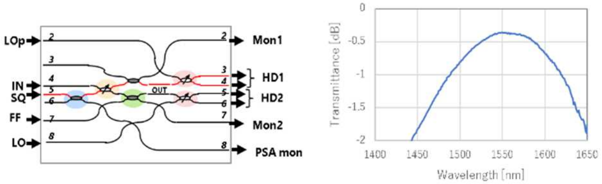
(1) By squeezing with only a PPLN waveguide with reduced loss, the world's first 10-THz bandwidth was achieved without the resonator structure causing band limitation, and the squeezing level exceeded 8 dB (Fig. 2).



(a) Squeezing band width over 6.3dB at 12 THz on both sides of the band (b) Noise characteristics with squeezing levels of 8dB

Fig 2. Quantum noise intensity of squeezed light of waveguide -type PPLN squeezer

(2) Using a PLC-type universal squeezer circuit that can be scaled up to a quantum teleportation circuit, we have thoroughly reduced the loss and confirmed that it can be kept to around 0.5 dB (Fig. 3).



(a) Universal squeezer PLC (b) Transmittance of path(Red line of(a))

Fig. 3 Universal squeezer by PLC and its transmittance

(3) In quadrature phase amplitude detection, which is the basis of projection measurements, we demonstrated for the first time quantum measurements in the 43-GHz band using a PPLN-waveguide phase-sensitive amplifier as a pre-amplifier, rather than a bandwidth-limiting, late-stage electrical amplifier (Fig. 4).

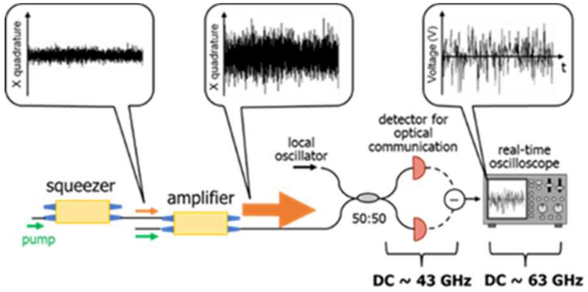


Fig. 4 Quadrature phase amplitude measurement system with waveguide-type PPLN phase sensitive pre-amplifier

3. Future plans

We aim to further develop the device technology to achieve the target characteristics. From the viewpoint of demonstrating quantum computing as quickly as possible, we will combine waveguide-type PPLN modules with spatial optics and optical fiber systems and collaborate with other R&D themes in the project to demonstrate optical quantum computing.

References

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