

6. Research and development on photon number counters with high detection efficiency and high counting rate made of Titanium superconductors

Progress until FY2024

1. Outline of the project

In this research, we aim to develop a photon number resolving detector with superconducting Transition Edge Sensors (TES). In the first term of a research period, we aim to produce photon number resolving detectors with the world's highest performance that combines high speed and high efficiency by making full use of the titanium/gold superconducting bi-layer materials and optical absorption cavities made of dielectric multilayer films. Compared to the iridium-based superconductors that have been used in this project so far, titanium-based superconductors have a higher superconducting transition temperature, so we can expect faster signal response characteristics. In addition, the optical cavity using dielectric multilayer film is a technology, which is realized for the first time in the world by our AIST group, is essential for extremely lossless photon detection in a telecommunication wavelength band. Furthermore, a national standard traceable evaluation system will be established for important performance of quantum optical sensors, such as detection efficiency. This will accelerate the development of an error-tolerant general-purpose optical quantum computer based on reliable performance standards that guarantee international equivalence.

2. Outcome so far

(a) Design and creation of a highly efficient and fast TES

To build a TES with the above performance, we designed an optical cavity suitable to obtain high detection efficiency. For the design technology, we followed the optical cavity design technology using dielectric multilayer films that we have used in the past, while for the creation, to obtain more reliable optical absorption characteristics, we aimed to construct an optical cavity using a dielectric multilayer film with ideal stoichiometry. We also use a new method, such as ion beam sputtering, for the film fabrication method.

Therefore, we started by creating a single layer of optical films of Ta_2O_5 and SiO_2 , derived the complex refractive index by multi-angle spectroscopic ellipsometry, and optimized the optical cavity based on this information. **Figure 1(a)** shows a schematic diagram of the optical cavity (left) and the multilayer film structure for the TES to obtain maximum absorption at a wavelength of 1550 nm. A total of 16 layers are stacked on the back of the TES, including a gold (Au) reflective mirror. In addition, three anti-reflective layers are placed on the front of the TES. Each dielectric multilayer film (green and brown) has a thickness of about 200 nm to 300 nm. Simulation confirmed that this resulted in a light absorption characteristic of approximately 99.7%. **Figure 1 (b)** shows a micrograph of the TES we created.

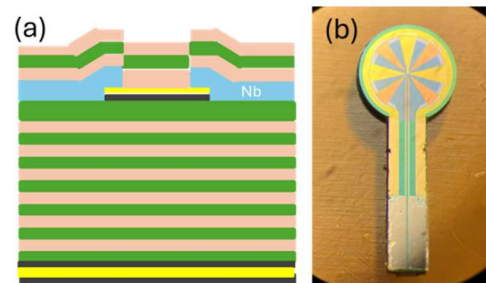


Figure 1 (a) Concept of an optical cavity with di-electric films for high detection efficiency. We use 16-layers in total. (b) A Photo for a fabricated TES device.

(b) Evaluation of high-efficiency, high-speed TES

The photon number discrimination performance of the developed TES was evaluated. **Figure 2 (a)** shows the response signal waveform when coherent light with an average photon number of 3 photons/pulse (wavelength 1.5 μm) was irradiated onto the TES. With the incidence of photons, we succeeded in acquiring high-speed signal waveforms that decay with a rise time constant of about 40 ns and a fall time constant of about 50 ns. This time constant of 50 ns is the fastest time in the world, comparable to that

of SSPD. **Figure 2 (b)** also shows the photon number spectrum constructed from the pulse height value. Clear state discrimination is possible according to the number of detected photons n . When the quantum state is a pulsed light, the number of events that can be processed within a unit time depends heavily on the speed of this fall time, so this high speed is an important achievement toward generating GKP states with a high generation rate. In addition, the detection efficiency of the element alone was confirmed to be over 98 % by an evaluation system traceable to national standards, which is comparable to the world's highest record.

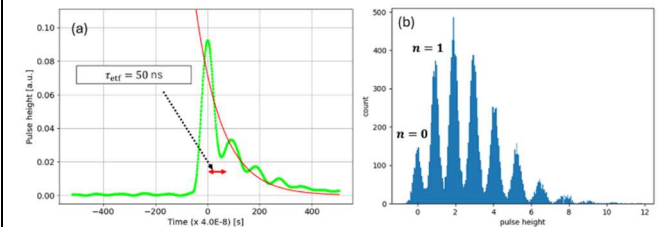


Figure 2 (a) Signal response of the TES, (b) Photon number distribution for a coherent pulsed laser source.

3. Future plans

This achievement has made it possible to realize the resources required for a highly efficient photon number discriminator to generate non-Gaussian states. In the future, in cooperation with the University of Tokyo group, we will proceed to the experiments such as generating GKP quantum states by extracting the number of photons from the squeezed state. We will also work to construct a photon number discrimination device with even higher efficiency and speed.