URSI GASS 2023, Sapporo, Japan, 19 – 26 August 2023

Developments toward the Terahertz Photon Counting System

Hajime Ezawa* (1,2), Hiroshi Matsuo(1,2), Go Fujii(3), Shigetomo Shiki(3), Ayako Niwa(4),
Norio Okada(1), Mitsuhiro Fukushima(1)
(1) National Astronomical Observatory of Japan; e-mail: h.ezawa@nao.ac.jp
(2) The Graduate University for Advanced Studies, SOKENDAI, Tokyo, Japan
(3) National Institute of Advanced Industrial Science and Technology, Ibaraki, Japan
(4) University of Tsukuba, Ibaraki, Japan

Fast photon counting detectors at terahertz frequencies may have various applications for observational astronomy and astrophysics. Photon counting detectors will realize high sensitivity observations by resolving each photon arrival. They may be applied to high-precision measurements by evaluating the photon statistics, to study the physical emission conditions of the sources. Applications may also include intensity interferometry to realize terahertz observation with high angular resolution and sensitivity. The presentation will discuss the recent developments for the detector system to realize fast photon counting at terahertz frequencies, especially for laboratory experiments.

Fast and low noise detection is the key to realize the photon counting capability. SIS junction is a good candidate for this purpose, where the photon-assisted tunneling process may operate as fast as 1 GHz. For terahertz frequencies, the noise equivalent power (NEP) at the order of 10^{-17} W/$\sqrt{\text{Hz}}$ is required. Recently we have developed an antenna coupled detector with SIS junctions of Nb/Al/AlOx/Al/Nb. The junction is 3 μm×3 μm in size with the critical current density of J_c = 200-300 A/cm^2, which exhibited a low leakage current of 2 pA at the cryogenic temperature of $T \leq 0.8$ K [1]. The SIS junctions form parallel-connected twin junctions (PCTJ) and are connected to a twin-slot antenna with a coplanar waveguide, which are designed for 500 GHz. The detector was processed at the CRAVITY facility [2] at National Institute of Advanced Industrial Science and Technology (AIST). Studies to improve the detector performances are in progress; so far a detector with center frequency of 530 GHz has been realized [1]. The bandwidth of the detector is limited to accommodate laboratory experiments where the background photons dominate.

The cryogenic system to support the low leakage SIS detector as well as its first stage cryogenic readout circuit, is also developed. The system is designed to realize a cryogenic environment at 0.8 K with a sufficient cooling power of ≥ 200 μW, which is operated with a set of ^{4}He sorption fridges. We have developed a compact ^{4}He sorption fridge [3,4] which dissipates relatively small heat to the condensation temperature stage. The cryogenic system is built in a cryostat cooled with a pulse-tube cooler to 3-4 K, which serves the condensation temperature to the sorption fridge. A prototype cooling system has been configured for evaluation, where the sorption fridge could hold the cryogenic temperature at 0.8 K for approximately 2 hours, following the fridge-cycling of 80 minutes. Two of these sorption fridges are mounted on the cryostat to alter their operation for continuous cooling, which has been realized by optimizing the parameters of fridge-cycling.

The design and performance of the detector and cryogenics will be discussed in the presentation. Studies for cryogenic readout circuits, and possible future applications such as space intensity interferometry are also ongoing, which will be discussed in other submissions.

References

[1] H. Ezawa et al., "Optical Performance of SIS Photon Detectors at Terahertz Frequencies", *J. Low Temp. Phys.* **200**, August 2020, pp. 226-232, doi:10.1007/s10909-020-02513-3.
[2] M. Ukibe et al., "Soft X-ray Detection Performance of Superconducting Tunnel Junction Arrays with Asymmetric Tunnel Junction Layer Structure", *Jpn. J. Appl. Phys.* **51**, December 2011, 010115 (5pp), doi:10.1143/JJAP.51.010115.
[3] H. Matsuo et al., "Compact 0.8 K Helium-4 Sorption Cooler", presented at LTD-17, Kurume, Japan, July 17-21, 2017, PD-8.
[4] A. Niwa, M.S. thesis, University of Tsukuba, Ibaraki, Japan, 2022. (in Japanese)