SIS photon detectors for THz observations beyond the gap energy

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***Abstract*— Interferometry is advantageous for high-resolution observations, but the sensitivity of heterodyne receivers is limited due to quantum noises especially above 1-THz. Photon Counting Terahertz Interferometry (PCTI), we proposed, uses direct detectors to measure intensity fluctuations which are caused by photon bunching for aperture synthesis, and it keeps high sensitivity in terahertz band. Photon counting detectors for PCTI needs low-noise and high-time resolution and developments of them are undergoing with antenna-coupled SIS photon detectors. PCTI's first observation is planned in the later 2020s from Antarctica where water vapor is sufficiently small that enables ground-based terahertz observations. This paper shows a concept and a design of 1.5 THz photon counting detectors to observe 205 µm [NII] emission.**

Keywords—Intensity interferometry, Superconducting detector, Terahertz observation

I. Introduction

Terahertz observation provides information on thermal radiation and atomic emission lines of celestial bodies and holds the key to elucidating the state of the early universe and the process of galaxy and star formation. However, in heterodyne interferometers, the sensitivity is limited by the quantum noise, and high-angular resolution observations above 1 THz have not yet become a reality (see Fig. 1). Therefore, a new technology is required for high-resolution observation methods in the Terahertz band.

We propose Photon Counting Terahertz Interferometry (PCTI) for high-resolution observations from space in the Terahertz band. PCTI measures photon bunching by high-time resolution to determine delay time and performs aperture synthesis. Since PCTI's system needs direct detectors, PCTI performs below the quantum limit of the heterodyne receiver in the high-frequency region. We developed photon counting detectors for PCTI in the 500 GHz band with Nb/Al/AlOx/Al/Nb SIS junctions with about 1 pA leakage current at below 0.8 K[2)]. As discussed below, the leakage current must be suppressed to measure photon bunching. Now we try to develop 1.5 THz photon counting detectors to demonstrate PCTI above 1 THz, which is our target.

PCTI's first test observations will take place in the late 2020s in Antarctica. Antarctic highlands have been found to have very good atmospheric transmission in the terahertz band compared to Chajnantor in Chile and Mauna Kea in Hawaii, due to the low water vapor content in the atmosphere[3)]. PCTI will use two telescopes with an aperture of 30 cm (Antarctic 30-cm Submm Telescope). The first telescope was developed by University of Tsukuba, which are equipped with a 500 GHz heterodyne receiver. The telescope will be sent to Antarctica in late 2023 in cooperation with National Institute of Polar Research. We will assemble the second 30-cm telescope to follow the first and it will arrive in Dome Fuji as early as 2027. Then, both telescopes will be equipped with 1.5 THz photon detectors for test observations. Candidate observational objects are Carinae nebula and 30Dor which have strong 205 μm [NII] emission lines.

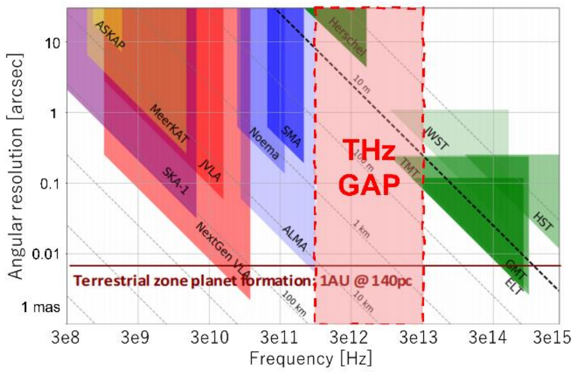

Fig.1 Observation target derived from Selina Robert et al., 2018[1)].

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II. Detector Concept

Our detectors must be low noise and fast response to measure photon bunching. Josephson junctions have fast response, but their leakage current will prevent identifying single photon. To suppress leakage current, our detectors use antenna coupled SIS junctions whose diameter is a few micrometers. We achieved a reduction in leakage currents of Nb/Al/AlOx/Al/Nb SIS junctions, and this study also uses the same structure.

A. SIS leakage current requirements

Thermal photons form photon bunching which is a signal for us by Bose-Einstein statistics which describe intensity fluctuation as eq. (1): P represents input power. If we observe from the Antarctica on summer, background intensity fluctuation could be estimated about 6×10^{-16} W/$\sqrt{\mathrm{Hz}}$ for temperature of $T_B = 50$ K, bandwidth of $\Delta\nu/\nu = 10\%$. On the other hand, Noise Equivalent Power (NEP) of SIS junctions is described as eq. (2). So, background limit of leakage current is estimated that must be below 3 nA, assuming $\eta \approx 0.3$.

$$\mathrm{NEP} = \sqrt{2P(h\nu + kT_B)}\ [\mathrm{W}/\sqrt{\mathrm{Hz}}] \quad (1)$$

$$\mathrm{NEP} = \frac{h\nu}{\eta}\sqrt{\frac{2I_{leak}}{e}}\ [\mathrm{W}/\sqrt{\mathrm{Hz}}] \quad (2)$$

B. Ground plane material

Our detectors consist of antenna coupled Nb/Al/AlOx/Al/Nb SIS junctions and detect photons by Cooper pair breaking. The double slot antenna is connected to the parallel connected twin junction (PCTJ) by the coplanar waveguide (CPW). PCTJ is a resonant circuit constructed by two SIS junctions. The CPW which is the same material used in the SIS junctions, causes transmission losses due to pair breaking. So, our detectors install an Al ground plane for the antenna and the CPW. Al is a superconductor at 0.8 K but behaves like a resistor for the 1.5 THz band, more than ten times higher frequency than superconducting gap energy.

C. Towards broadband observation

Previous work[4] achieved low leakage current with 0.3-kA/cm^2 critical current densities and 3 μm×3 μm square forms. Since these detectors are designed for the purpose of experiments in laboratory, so critical current density is relatively low and their bandwidth is limited. In this study, we try to expand the bandwidth keeping low leakage current by minimizing SIS junctions to 1 μm.

III. Detector Design

Fig.2 shows the design of 1.5 THz photon counting detectors. The double slot antenna and the PCTJ were tuned to 1.5 THz. These detectors use quartz wafers for lower stray capacitance. Impedance from antenna to PCTJ is matched to 100 Ω, where required critical current densities is about 1.3-kA/cm^2 for 1 μm circular junctions.

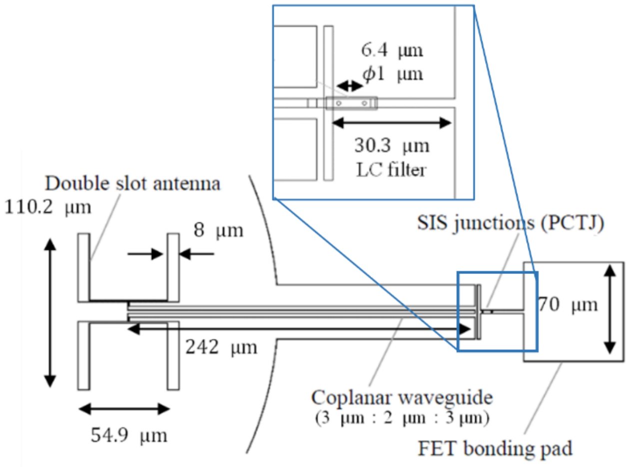

Fig.2 Design of 1.5 THz photon detector.

This study determined and fixed the ratio of antenna length to width referring to a previous paper[5] since this ratio affects directivity. Antenna parameters, length (and width) and slot line width were tuned by parametric analysis. Fig.3 is the calculation results of reflection coefficient of the antenna with final design parameters calculated by using FEKO, Altair. The reflection coefficient value is -38 dB at 1.5 THz. Fig. 4 shows the calculation results of 1.5 THz antenna beam pattern. This result is calculated by using HFSS, Ansys, by using the model whose antenna feed point is connected to wave port by CPW (see Fig.5). Calculation results of φ = 0 and 45 deg are slightly asymmetry due to CPW.

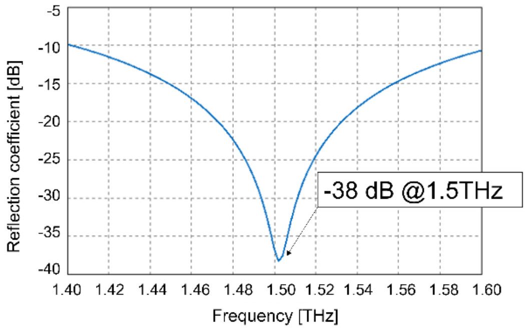

Fig.3 Calculation results of reflection coefficient of 1.5 THz double slot antenna.

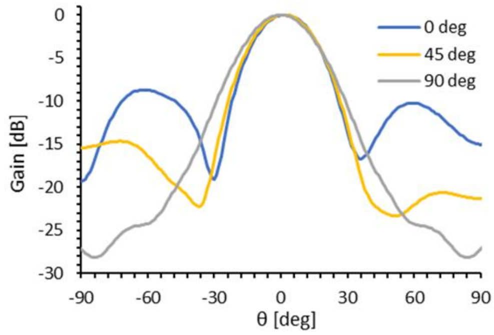

Fig.4 Calculation results of beam patterns for each azimuthal angle φ of 1.5 THz double slot antenna. The x-axis gives the polar angle θ.

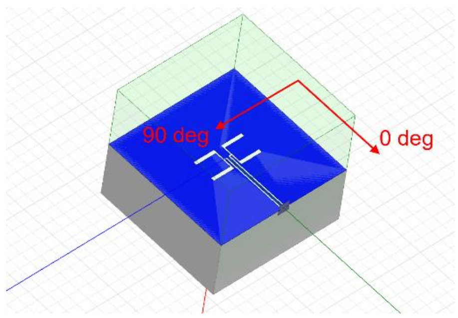

Fig.5 The double slot antenna model for calculating beam

Acknowledgments

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Reference

[1] Selina Robert, Murphy Eric, McKinnon Mark, et al. 2018, Proc. SPIE 10700. https://doi.org/10.1117/12.2312089

[2] Hajime Ezawa, Hiroshi Matsuo, Masahiro Ukibe, Go Fujii, and Shigetomo Shiki. 2019, Journal of Low Temperature Physics, 194:426–432. https://doi.org/10.1007/s10909-019-02149-y

[3] P.Tremblin, N.Schneider, V.Minier, G.Al.Durand, and J.Urban. 2012, Astronomy & Astrophysics, 548, A65. https://doi.org/10.1051/0004-6361/201220420

[4] Hajime Ezawa, Hiroshi Matsuo, Masahiro Ukibe, Go Fujii, and Shigetomo Shiki. 2020, Journal of Low Temperature Physics, 200, 226-232. https://doi.org/10.1007/s10909-020-02513-3

[5] Daniel F. Filipovic, Steven S. Gearhart, Gabriel M. Rebeiz. 1993, IEEE Transactions on Microwave Theory and Techniques, Vol. 41, No. 10. https://doi.org/10.1109/22.247919