Development of 1.5 THz photon detectors for terahertz intensity interferometry

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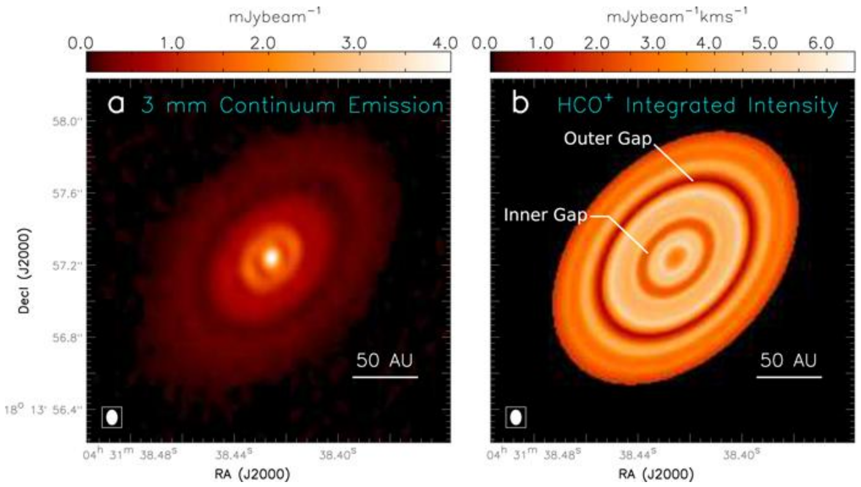
Research background
– Lack of high angular resolution instruments above 1 THz

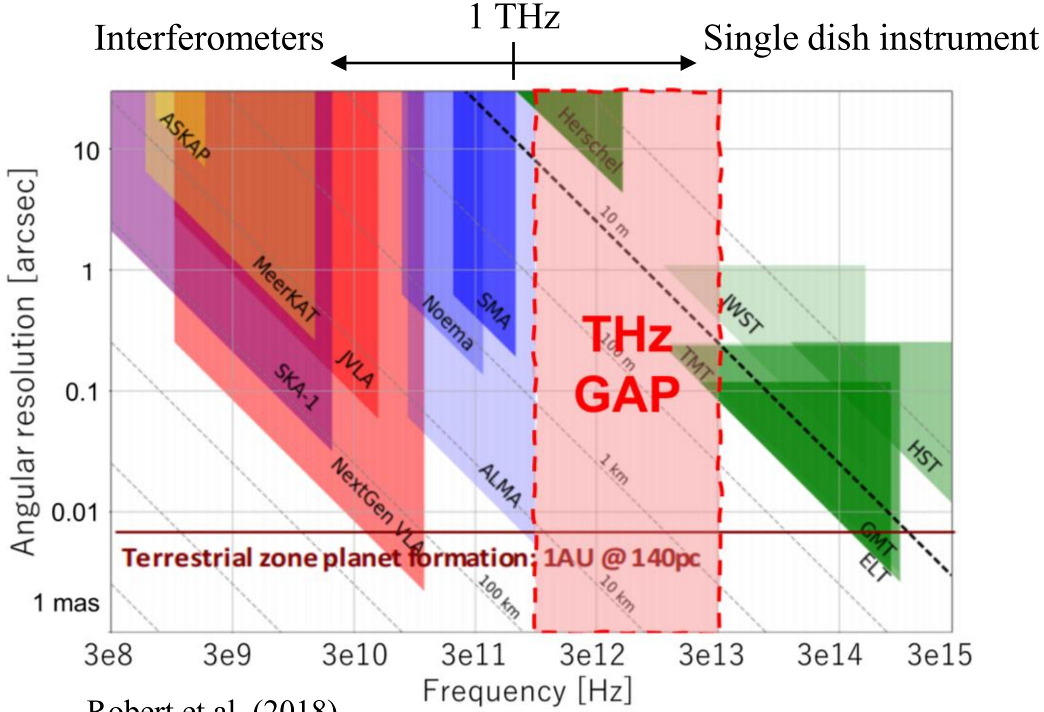
The Observation targets for high angular resolution instruments

- Protoplanetary disks
- High-z galaxies
- Black holes in nearby galaxies …etc.



Yen et al. (2016)

Interferometers achieved high angular resolution observations at radio and terahertz regions, **except 1-30 THz region**.



Robert et al. (2018)

We propose **Terahertz Intensity Interferometry (TII)** for the use of a space telescope.

Research background
– Synthesis imaging by Terahertz Intensity Interferometry

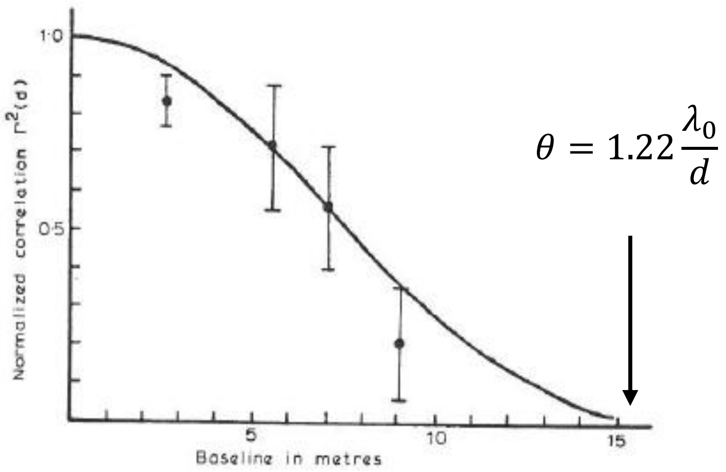
☐ Terahertz Intensity Interferometry (TII)

✓ Synthesis imaging

✓ Observable in space in the background noise limit

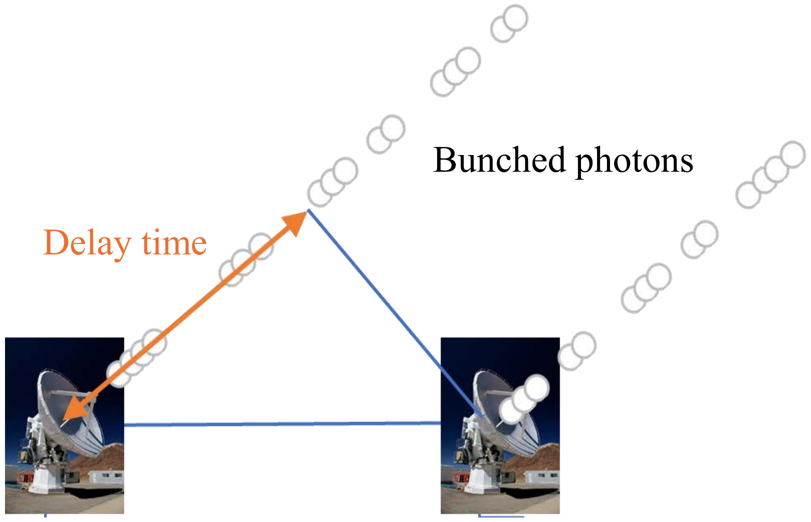
→ **Fast photon detectors (time resolution~1 ns) is required.**

Intensity correlation



Hanbury Brown and Twiss. (1958b)

Phase information



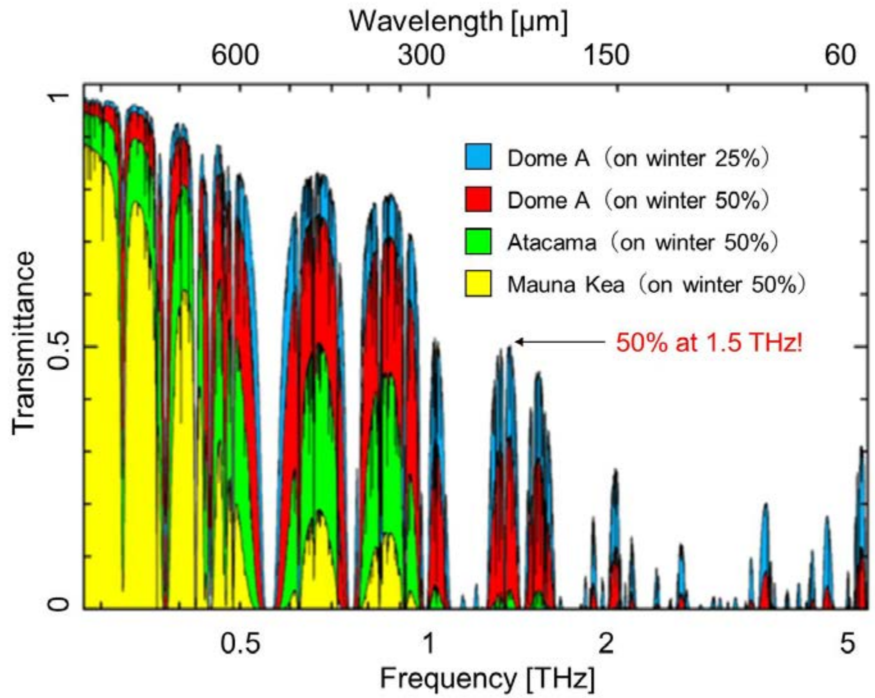
Research purpose
– 1.5 THz photon detectors for Antarctic experiments

The Antarctic terahertz window has high transmittance, compared to other sites.

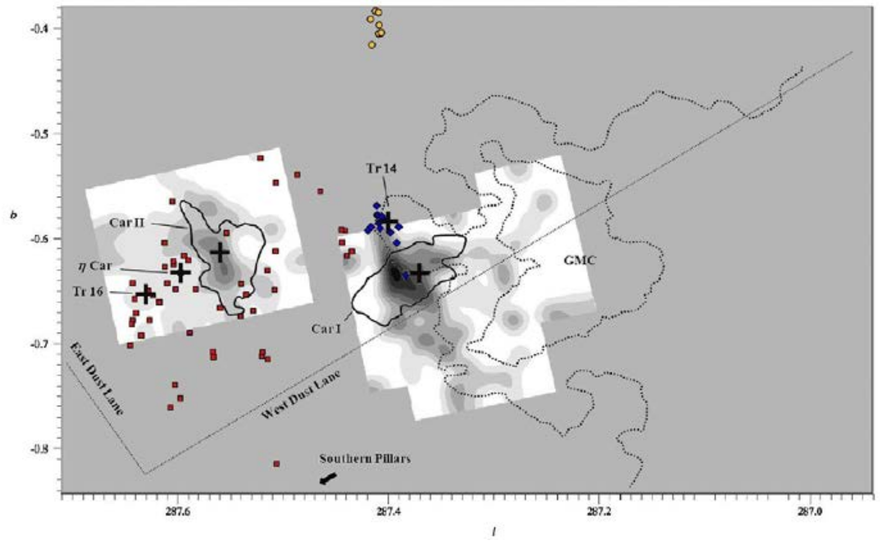
→ We develop the 1.5 THz photon detectors for the Antarctic TII experiments (with two 30-cm telescopes).

205 μm [NII] emission line is observed SPIFI on AST/RO, which has less angular resolution of 54″.

→ ~10 m baseline interferometry exceeds the angular resolution of previous studies.



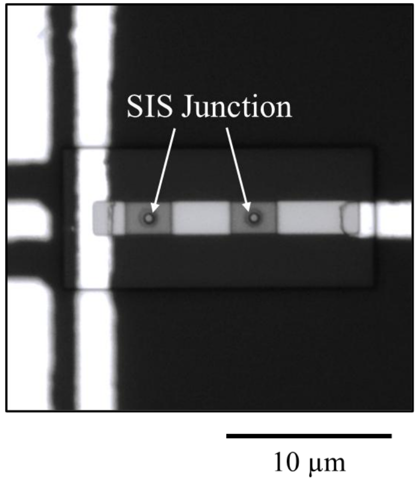
Yang et al., 2010



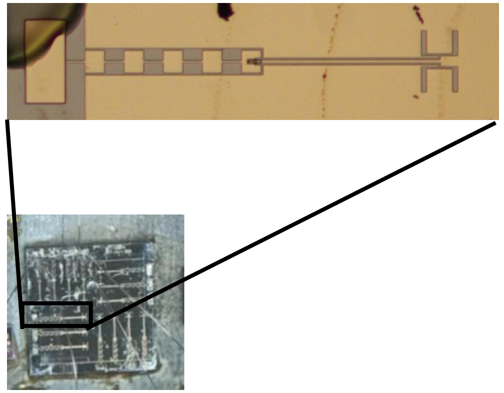
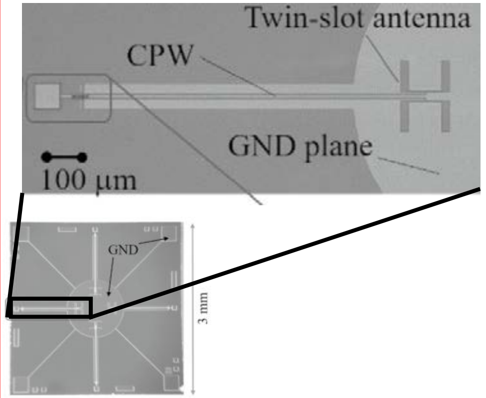
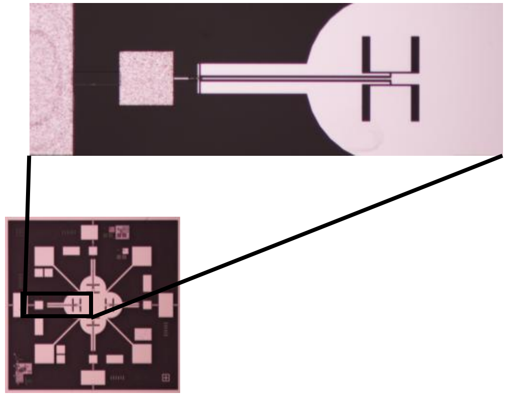
Observed by SPIFI with 205 μm [NII]

Oberst et al., 2011

Research background
– Our developments of SIS photon detectors for TII



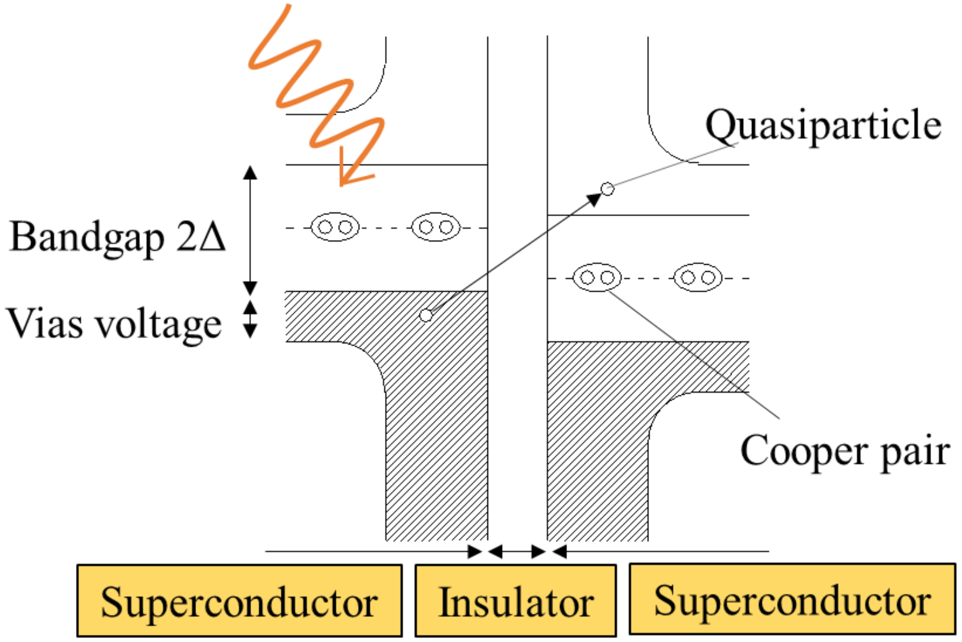
- ☐ Photon detectors with SIS (Superconductor-Insulator-Superconductor) junctions
  - SIS is a Josephson junction with superconducting materials.
  - SIS junctions can be work with fast photon detection process.
  - Nb/Al-AlOx/Al/Nb junctions which form resonance circuit to achieve required center frequency.

660 GHz (Ezawa+2019, Ezawa+2020)	530 GHz (Ezawa+2024)	1.5 THz (Niwa+2024)
		

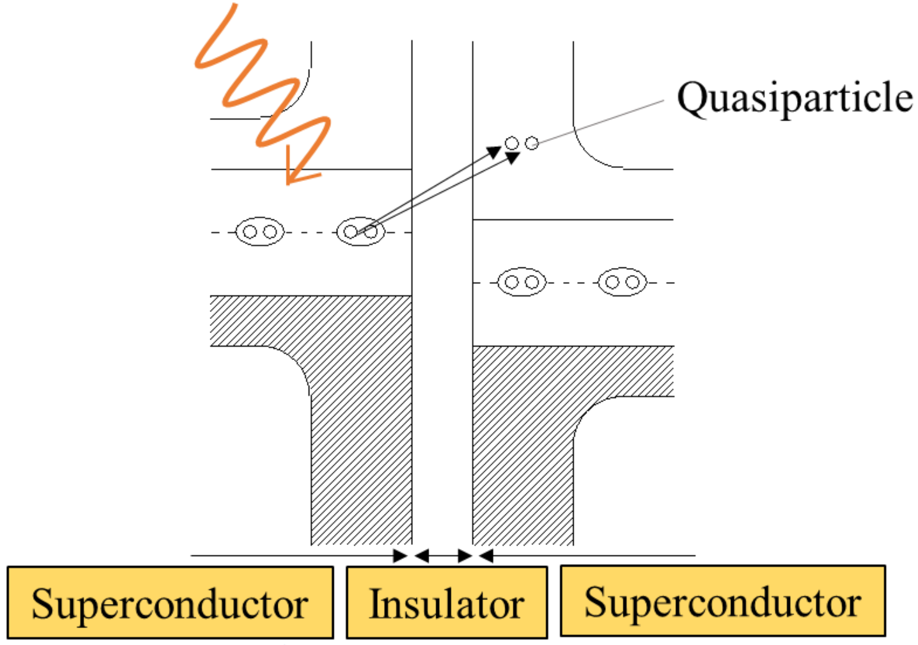
The design of 1.5 THz photon detectors

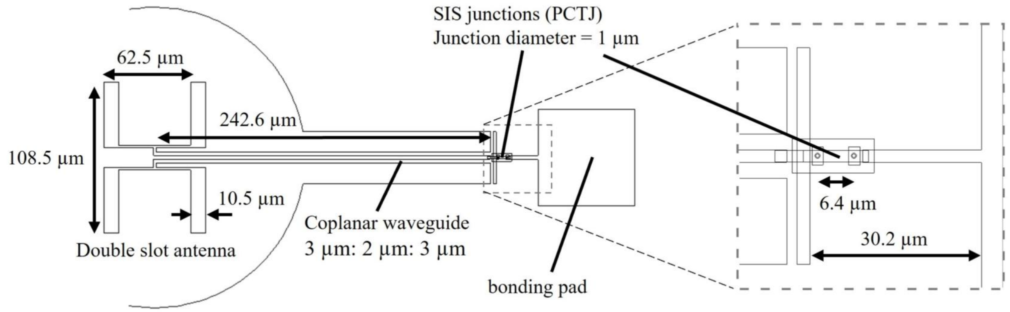
– Detection principle of antenna-coupled SIS for 1.5 THz photon

$2\Delta > h\nu$, Photon assisted tunneling



$2\Delta < h\nu$, Cooper pair breaking





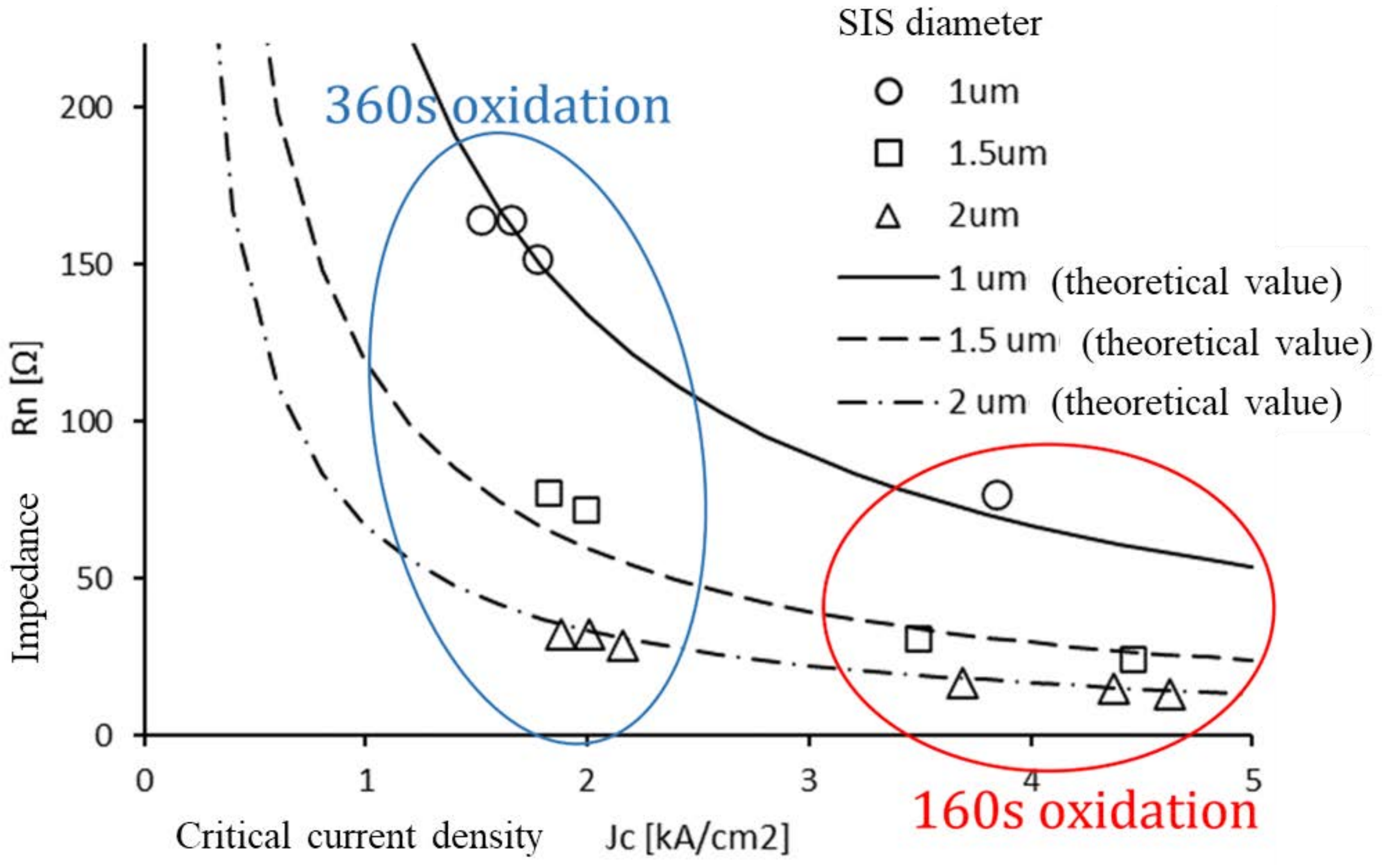
1.5 THz detectors

One photon→Two quasiparticle

The design of 1.5 THz photon detectors
– Determination of SIS junction size

Leakage current of SIS oxidation film must be below 2 pA to identify single photon.

Smaller junction achieves extending bandwidth and low leakage current.



Measured at 4 K.

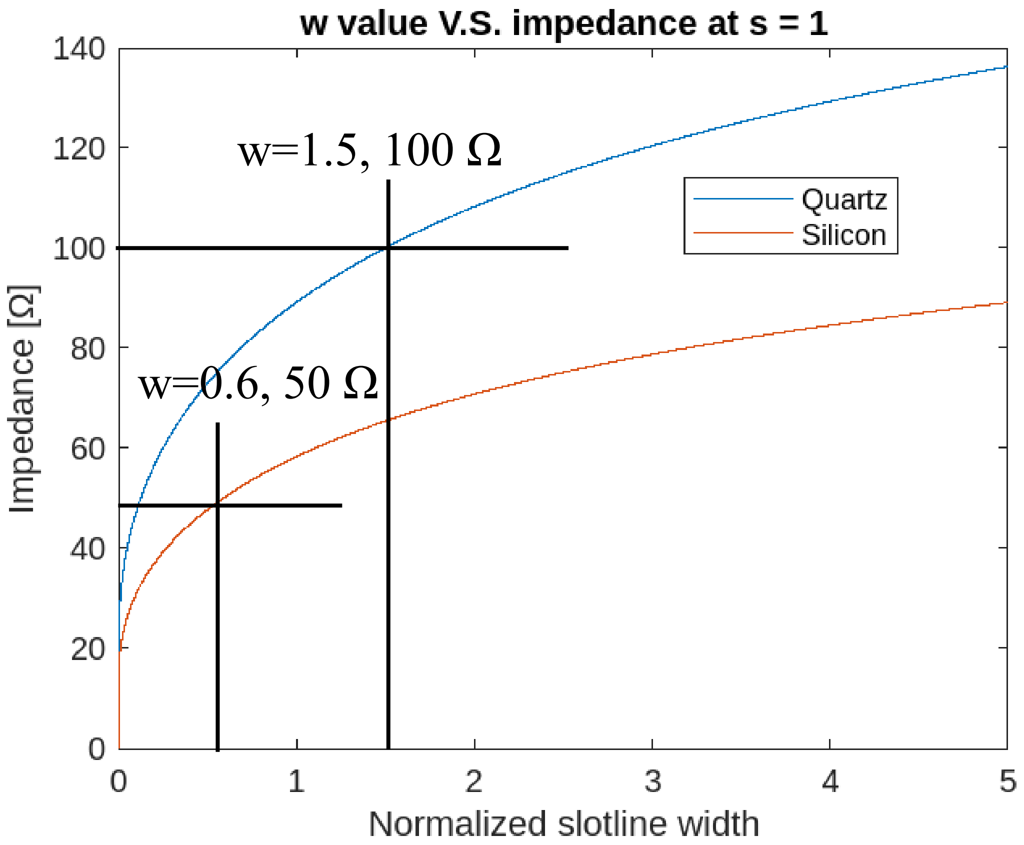
The design of 1.5 THz photon detectors

– Impedance tunings about CPW on Quartz wafer

Antenna, CPW, and SIS require impedance matching.

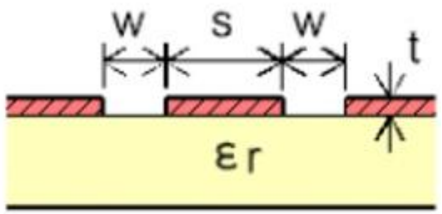
The fabrication facilities require a minimum slot line width to be wider than 1 μm.

→Impedance of the CPW with the quartz substrate ε_r = 4.456 calculated in MATLAB (Mathworks).



Cross section of CPW

W: Slot line width



Quartz substrate

The design of 1.5 THz photon detectors

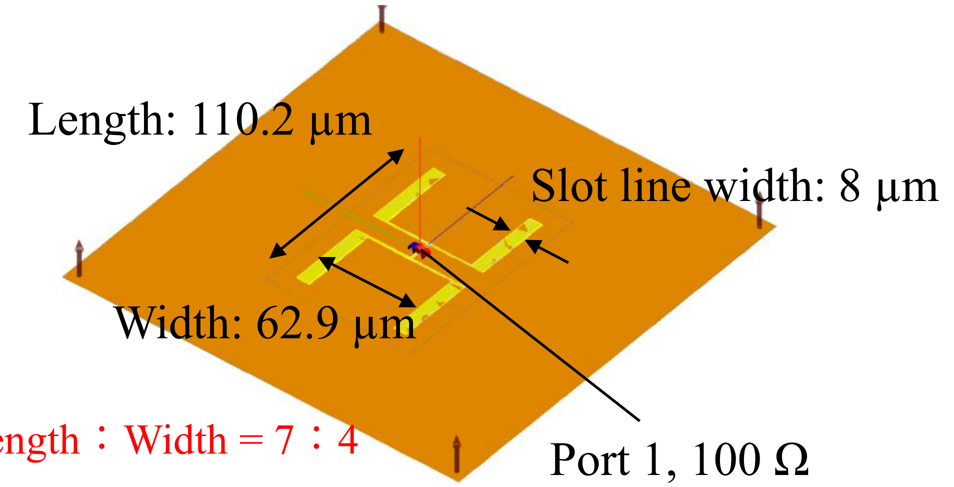
– Electromagnetic calculations of double slot antenna

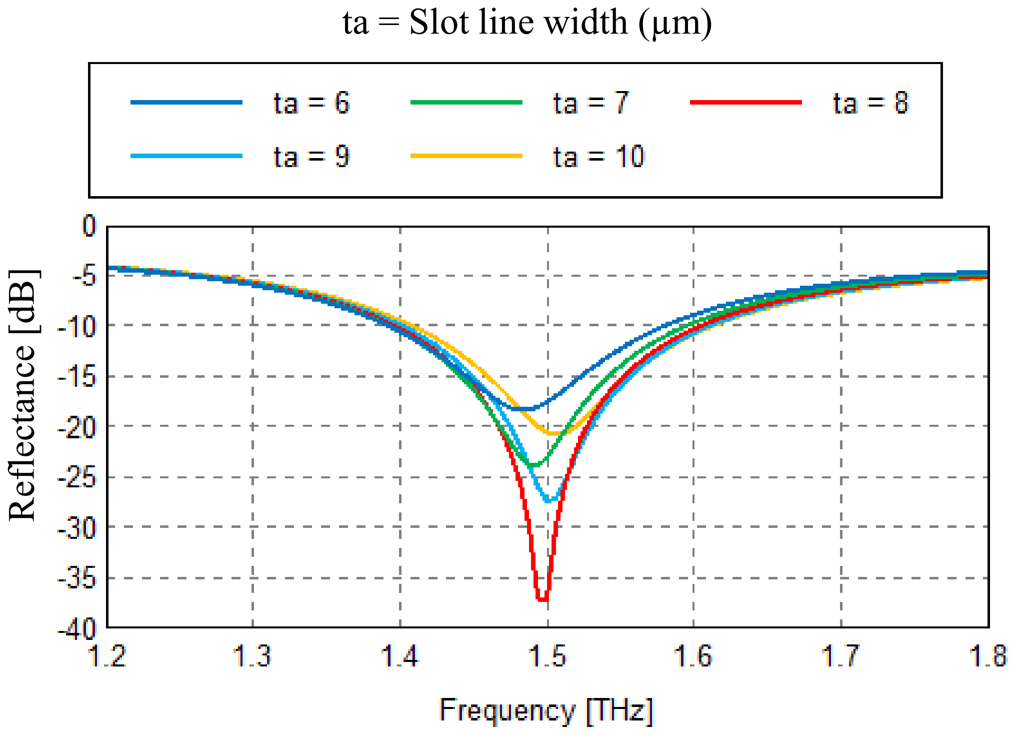
Length and width: Larger effect on resonance frequency than on impedance.

Note that the aspect ratio affects beam shape distortion.

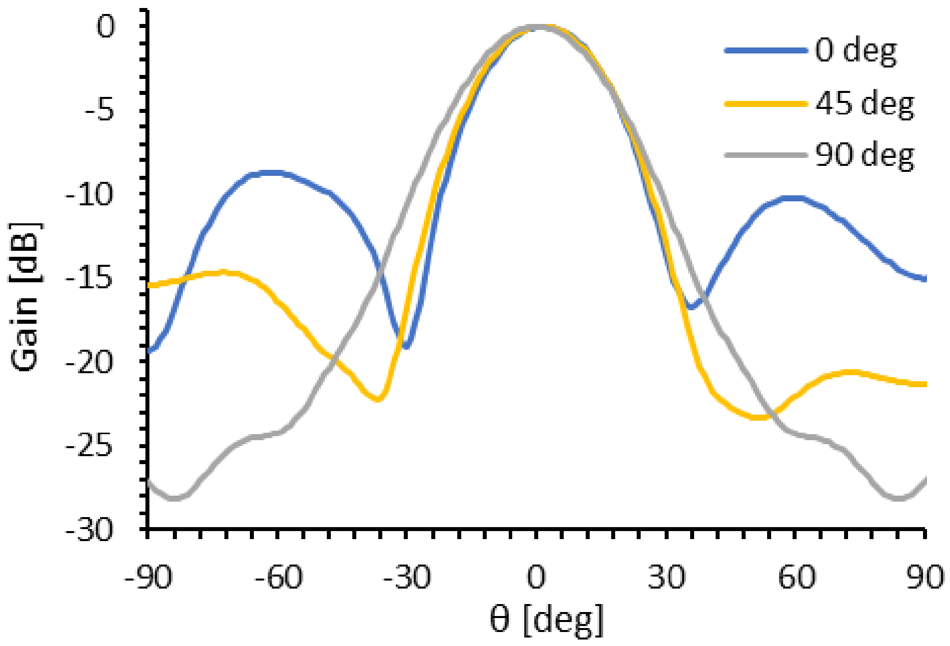
Following the 7:4 aspect ratio of a previous study (Filipovic et al., 1953)

Slot line width: Larger effect on impedance than resonant frequency.





Antenna reflectance (Calculated with FEKO).

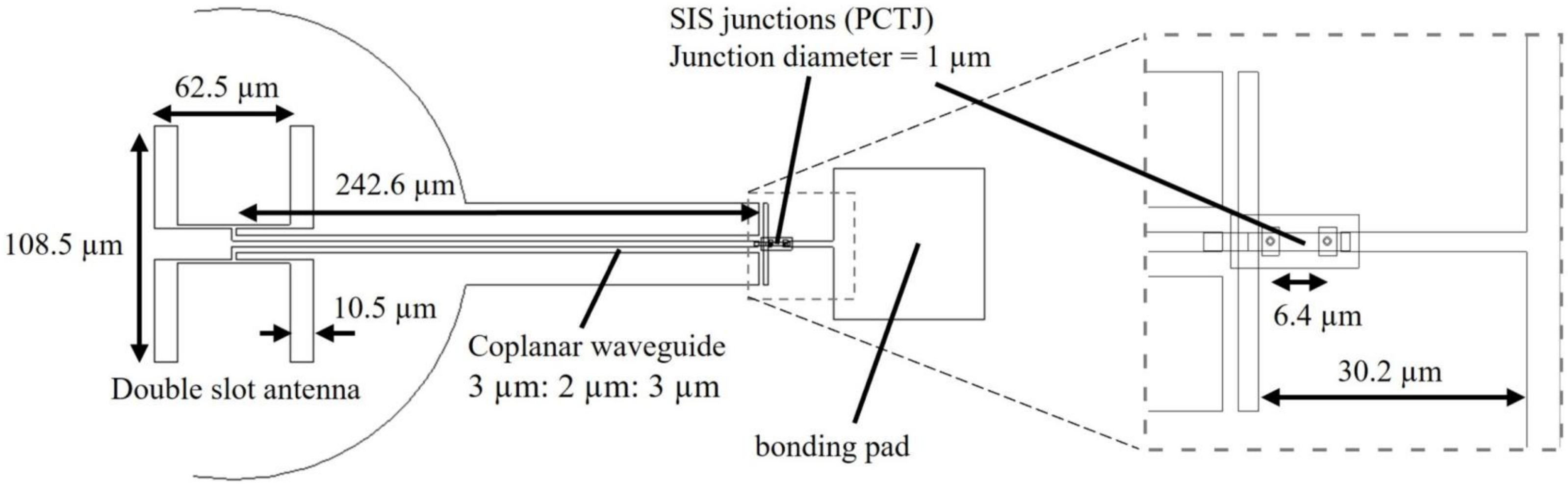


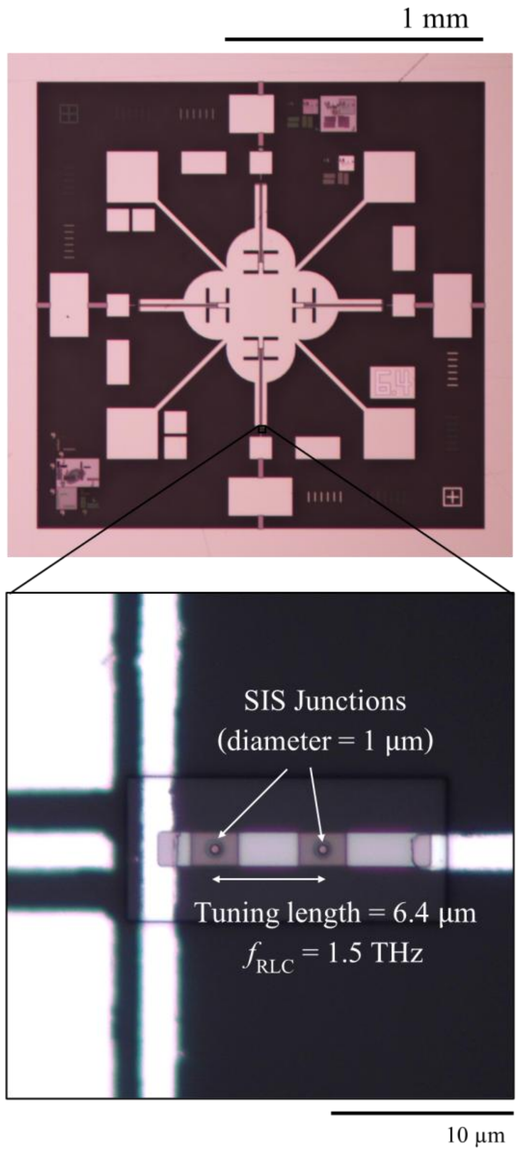
Antenna beam pattern at 1.5 THz (Calculated with HFSS).

The design of 1.5 THz photon detectors
– Schematics of the detectors and fabricated detectors

We designed and fabricated the detectors.

- Fabrication facility: ATC clean room in NAOJ
- Fabrication terms: 1〜3 months



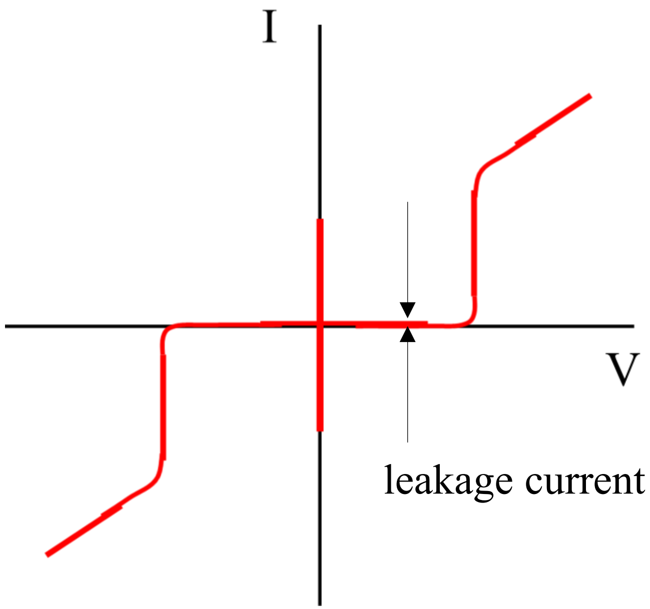


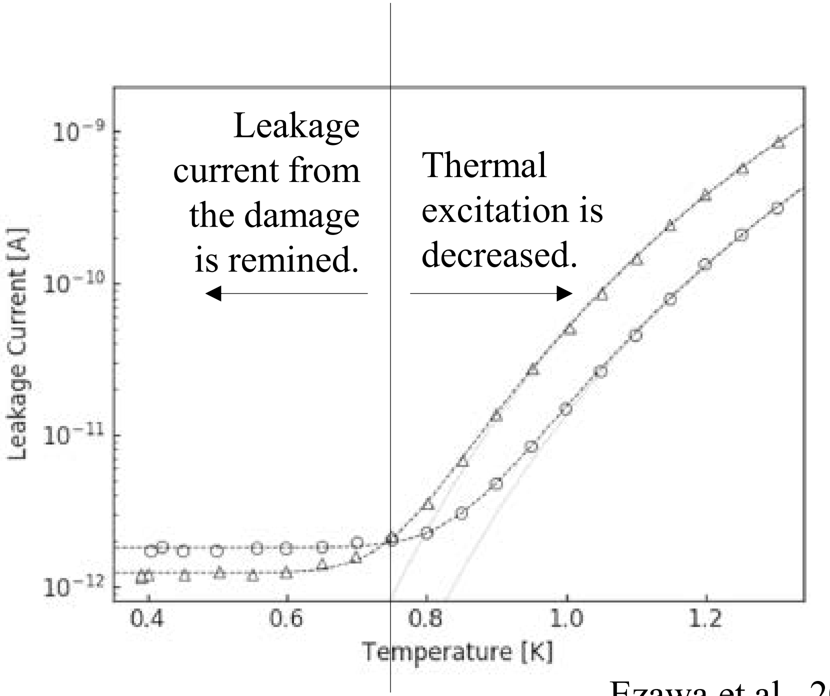
Evaluations of 1.5 THz photon detectors
– IV characteristics and leakage current

Low leakage current* is preferred for the 1.5 THz photon detectors.
*Leakage current: one of the current noise for the SIS caused by thermal excitation and damage of the insulator in the SIS junctions.

Under 240 K background radiation, **the 1.5 THz photon detectors require the leakage current to be below 2.5 nA.**

We clarified that leakage current caused by thermal excitation is suppressed at below 0.8 K.





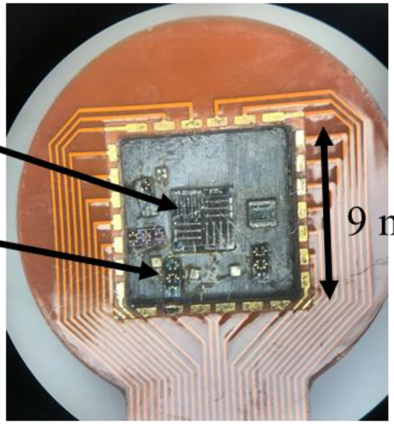
Ezawa et al., 2020

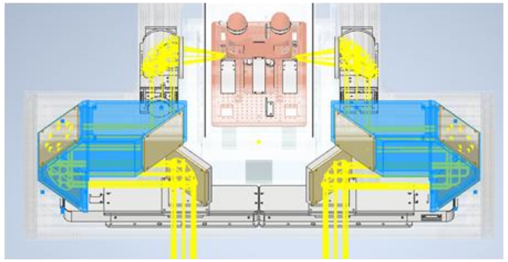
Low speed readout circuits at low temperature
– Design of the circuit

Capacitance between SIS and current amplifier inhibits high-speed readout.

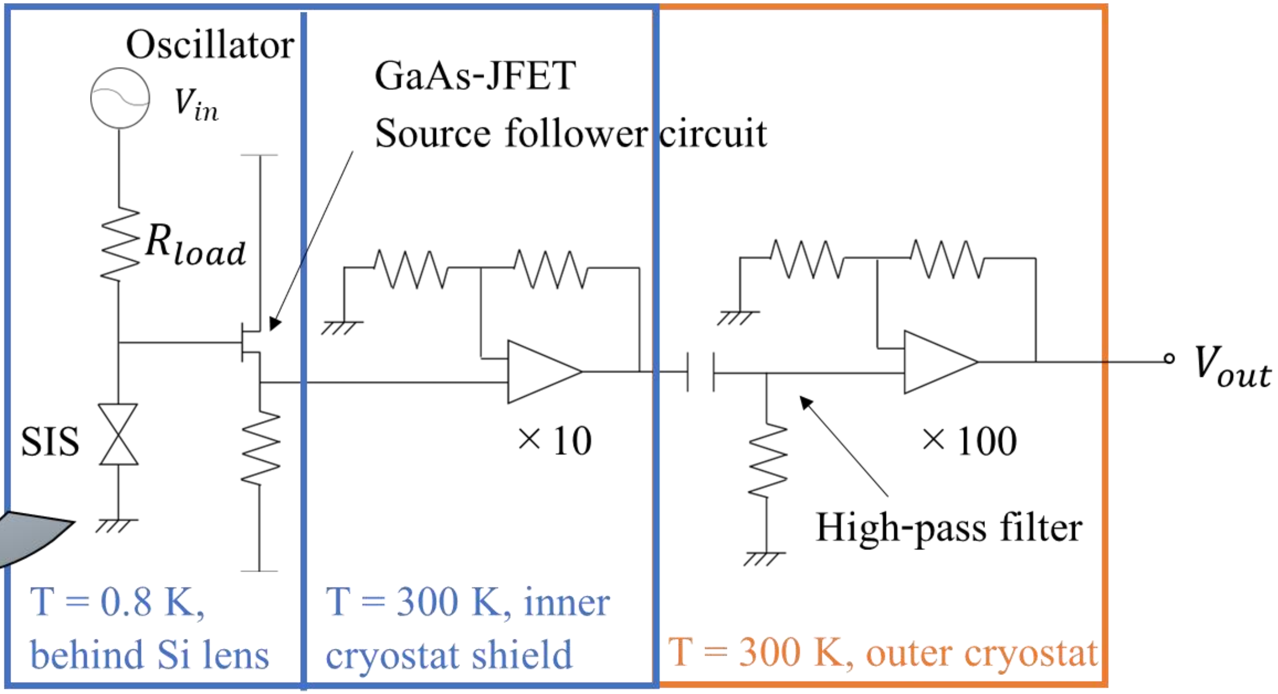
GaAs-JFET can operate at low temperature ≈ 0.8 K and be placed at a few millimeters next to SIS.

$$V = \frac{V_{out}}{G}, \quad I = \frac{V_{in} - V}{R_{load}}$$





Cryostat image, LTD20, MP-057

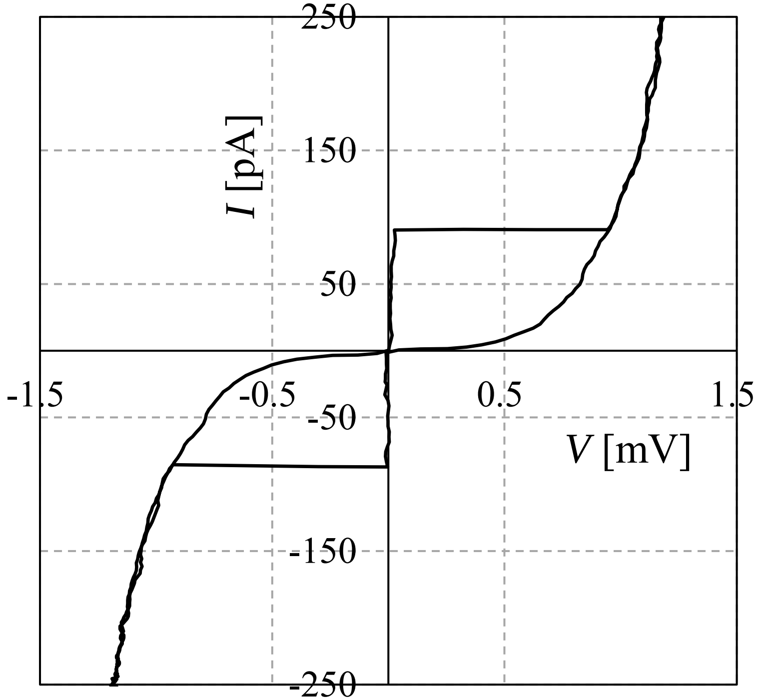


Low speed readout circuits at 0.8 K

– Evaluation of the circuit with 660 GHz photon detectors

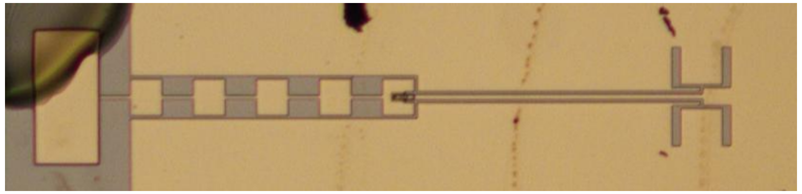
The leakage current is 15 pA@0.6 mV at 0.8 K.

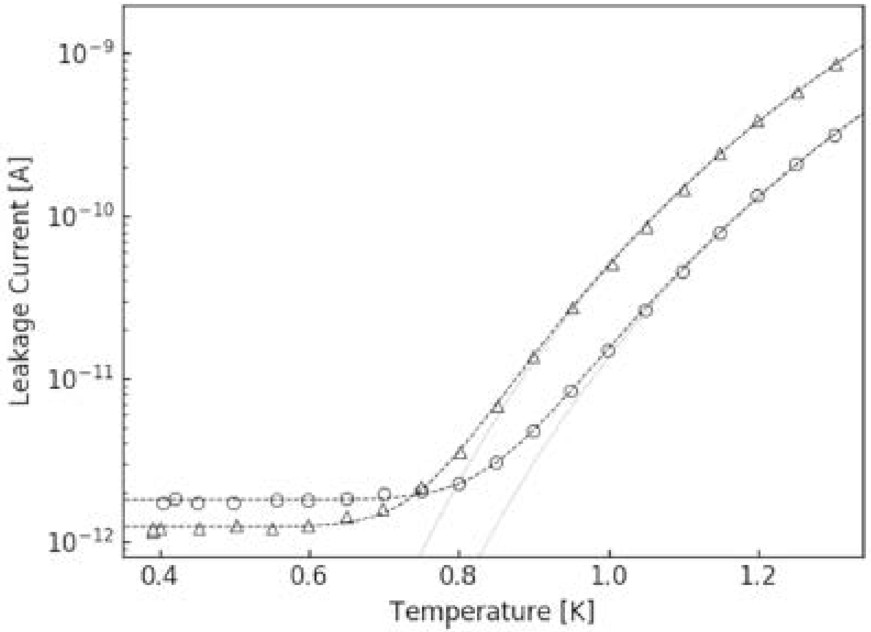
This result is nearly consistent our previous measurement with filter (no AR) + liq. He4 dewar (3pA@0.6mV at 0.8 K).



IV characteristics at 0.8 K

660 GHz photon detectors

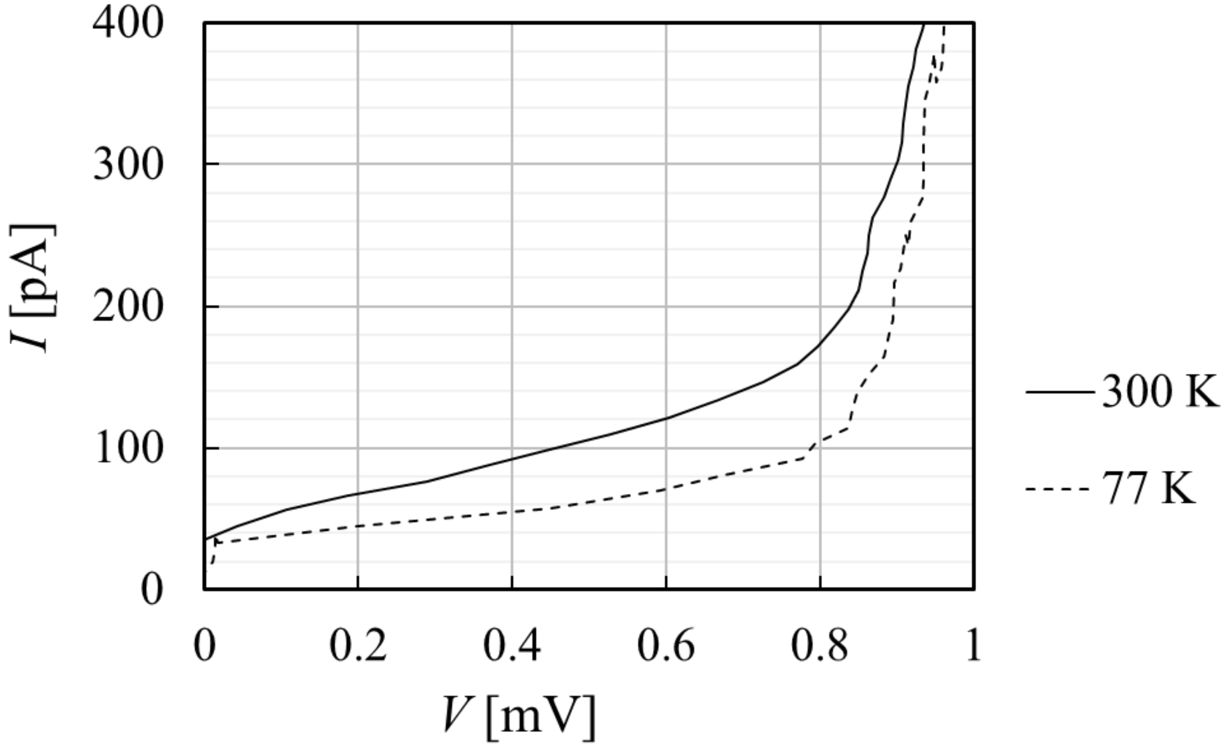




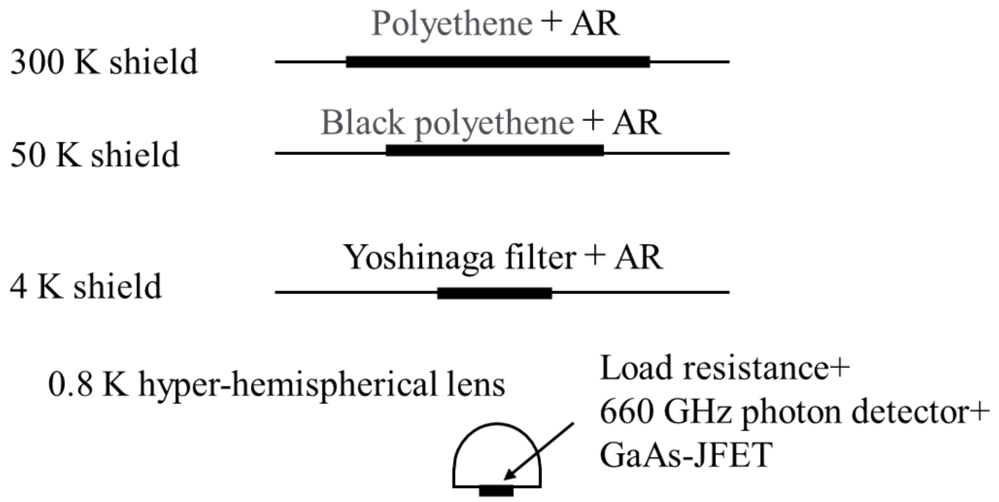
Low speed readout circuits at 0.8 K
– Evaluation of the circuit with 660 GHz photon detectors

Optical efficiency η=0.12%.

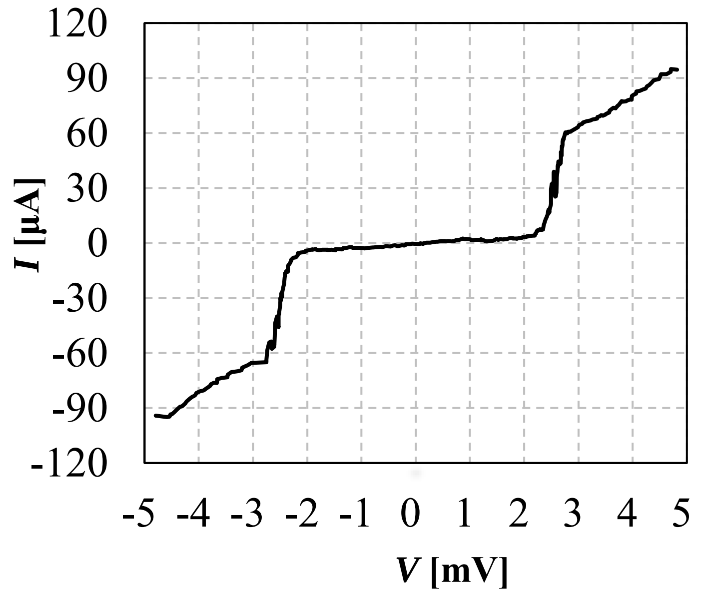
This result is worse than our previous measurement with filter (no AR) + liq. He4 dewar (η=1.3%).



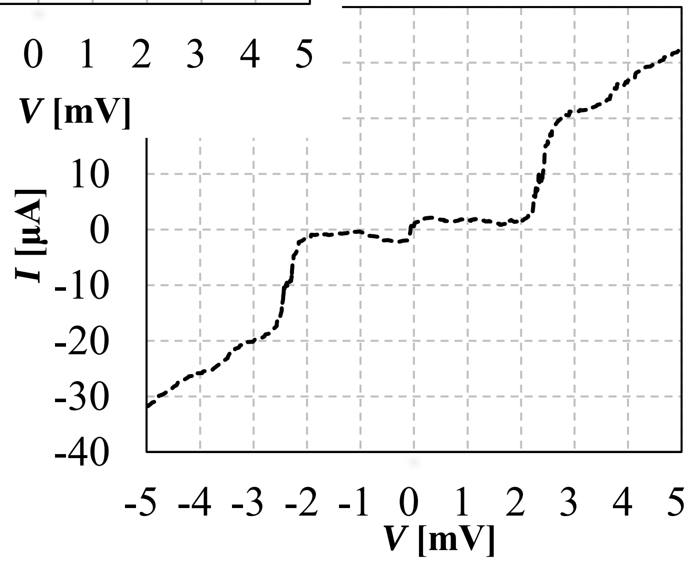
Measurement setup



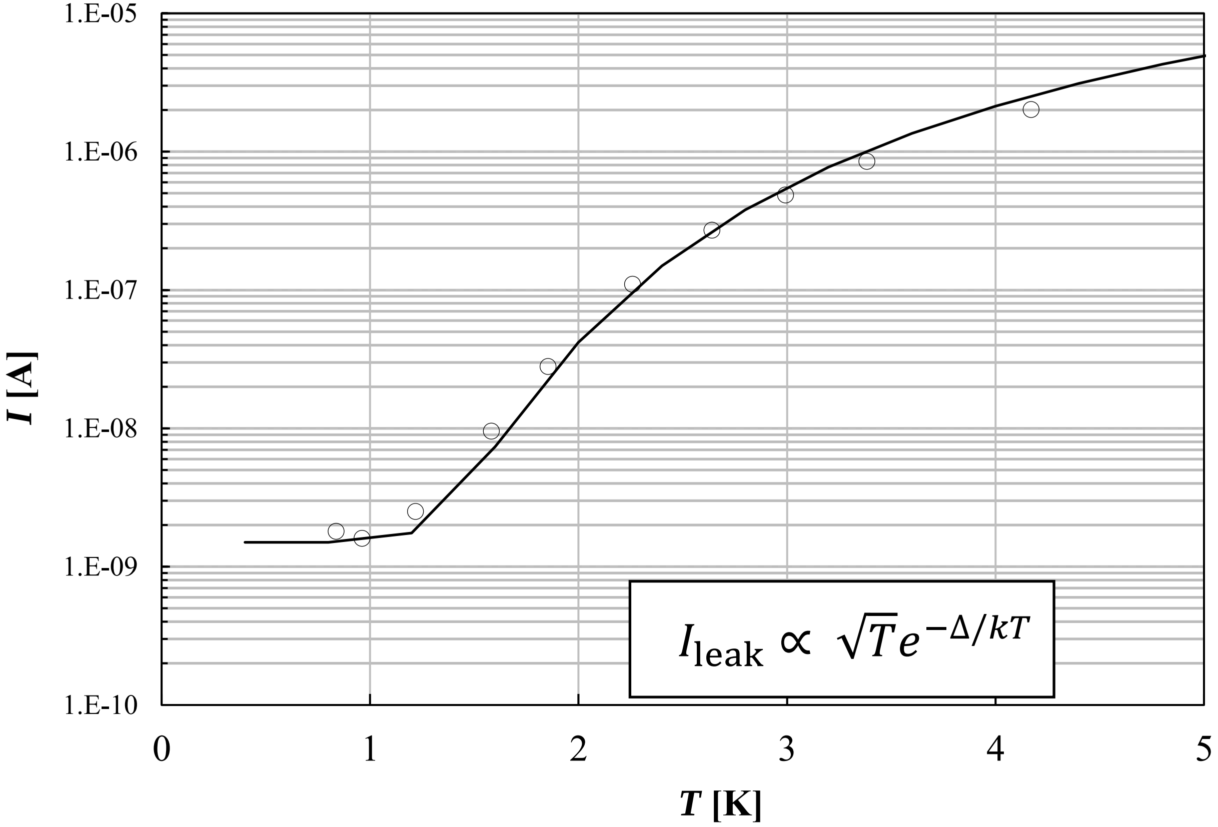
Evaluations of 1.5 THz photon detectors
– IV characteristics at low temperature



3 µm junction



1 µm junction



Temperature v.s. Leakage current of 3 µm junction
The solid line shows BCS model.

Summary and Future works

We are developing 1.5 THz photon detectors to use for the Antarctic TII experiment.

– I-V characteristics measurements at 4 K
  The fabricated detectors show reasonable I-V characteristics.
  However, the performance is not ideal and needs more fabrication parameter tuning.

– Low speed readout circuits is developed and evaluated at low temperature.

We will continue the following developments:

– The evaluation of the 1.5 THz photon detectors

– Iterate fabrication to reduce the leakage current and to optimize critical current density

– (Additional option) Set up an experimental system with optical fibers for pulse input
  We measure the time resolution of 660 GHz photon detector for the first time.