Characteristics of Prototype 850-GHz LEKID Arrays for Terahertz Astronomy

2025/12/16

Uv. Tsukuba 2nd-year master's degree
Sato Yuma

A. Monfardini,[2] M. Calvo,[2] U. Chowdhury,[2] J.F. Macías-Pérez,[3] S. Honda,[1] N. Kuno,[1]
1 Univ. Tsukuba, Tsukuba, Ibaraki 3050006, Japan
2 Univ. Grenoble Alpes, CNRS, Grenoble INP, Institute Néel, 25 rue des Martyrs, 38042 Grenoble, France
3 Univ. Grenoble Alpes, CNRS, LPSC/IN2P3, 38000 Grenoble, France

Acknowledgments

Number of positions: 2
Eligibility: Students in the Master's or Doctoral program
Support: 400,000 JPY for overseas research stay

May – Jun | application
Nov. | report meeting

Tsukuba Kyomei Kyoiku Program

Host institution: **University of Grenoble Alpes**, Grenoble, France

(2024. Oct. – Dec.)

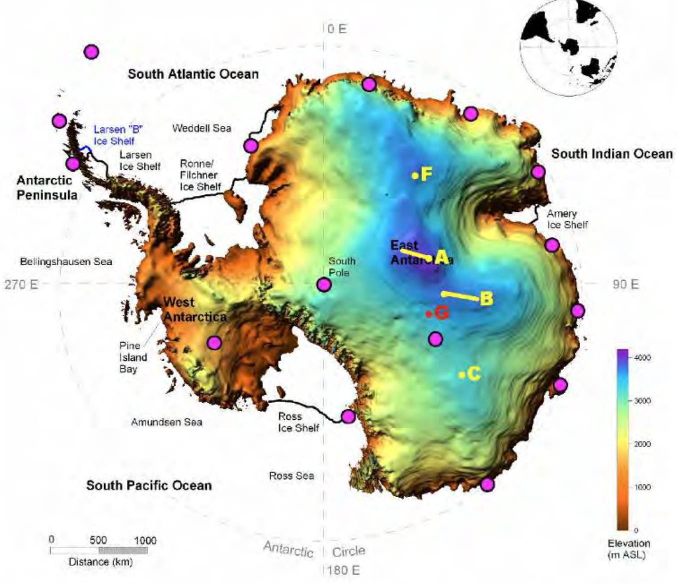
NIKA project , led by University of Grenoble Alpes, was the first in the world to successfully use LEKID for astronomical observations

(2012 ~ 2014)

University of Tsukuba is currently co-developing 100 GHz LEKID with NIKA team

Antarctic Project (ATT12)

Reference : Will Saunders et al. (2009) 「Where is the best site on Earth?」 arXiv:0905.4156



Dome Fuji

3810m altitude

Precise **surveys of dust emission** in the **submillimeter and terahertz** bands

(less affected by dust attenuation)

to detect distant dust galaxies

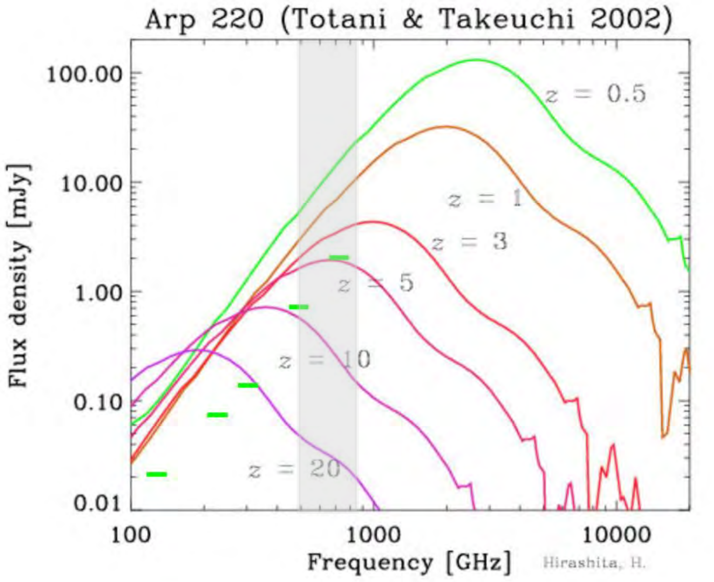
ATT 12

aperture	12m
observation frequency	200GHz~2THz
observation site	Dome Fuji
observation mode	spectroscopic / imaging observation
receiver	heterodyne receiver / superconducting detector

spectral energy distribution (SED)

(assuming dust temperature = 42K, far-infrared luminosity = $1.4 \times 10^{12}\ L_{sun}$)

850 GHz observation enable to determine dust temperature and redshift because it is near the SED peak of distant galaxies

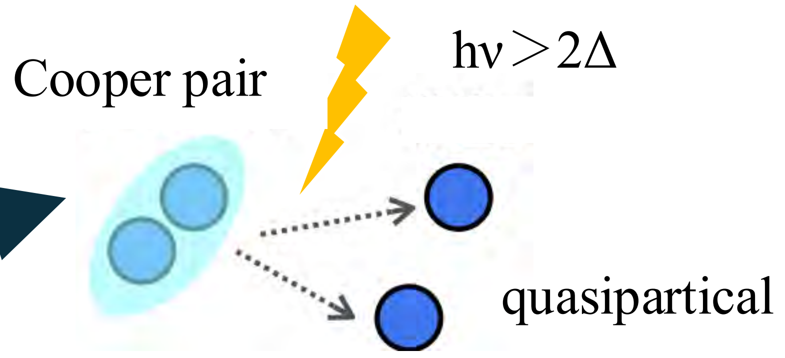


Reference : Totani, Takeuchi (2002) 「Deep Near-Infrared Universe Seen in the Subaru Deep Field

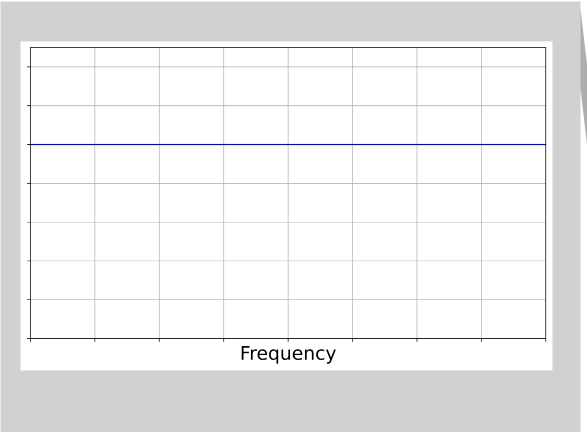
Operating principle of LEKID

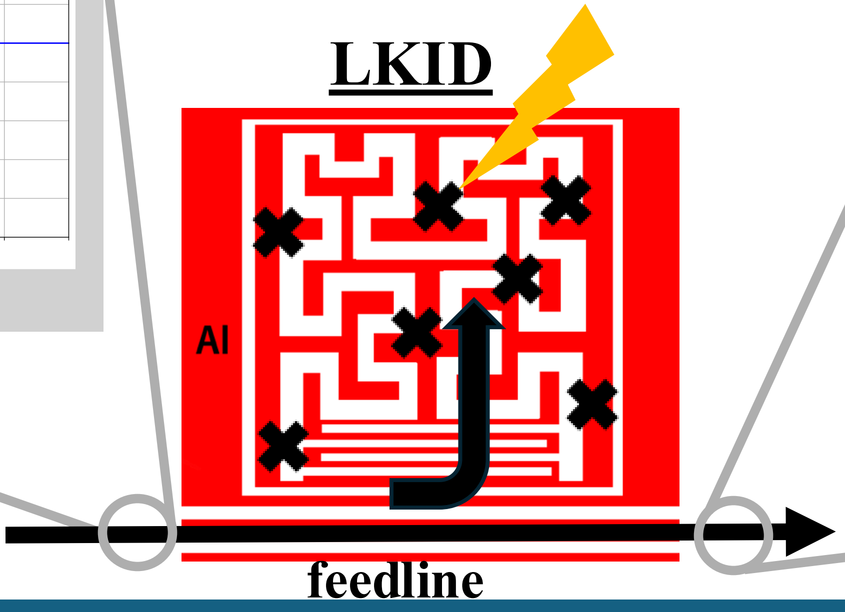
In the superconducting state, electrons form Cooper pairs

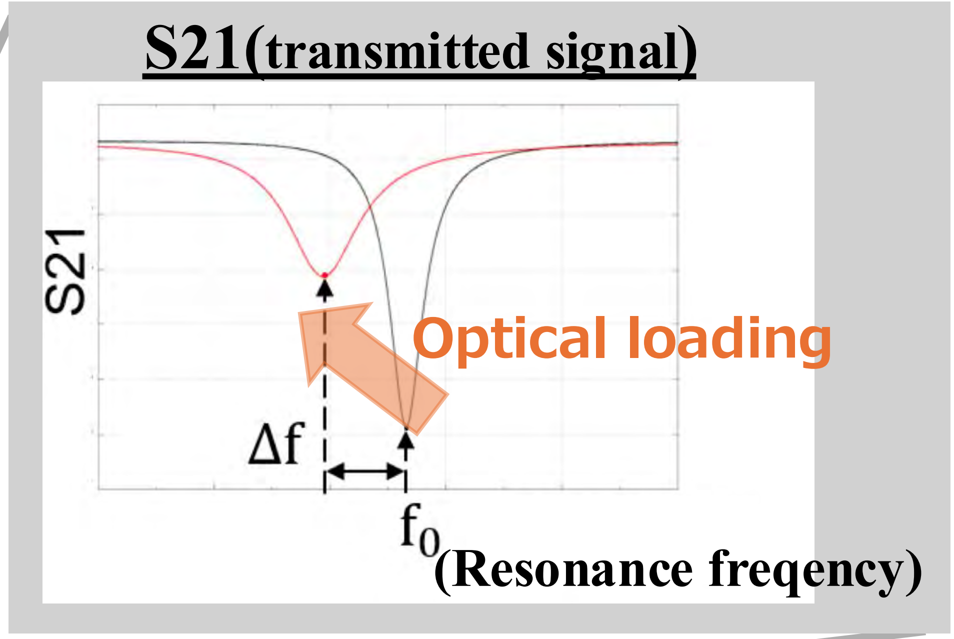
Optical loading with energy exceeding the superconducting energy gap breaks Cooper pairs into **quasiparticles**(electron)



Inductance depends on the quasiparticle density, shifting the resonance frequency





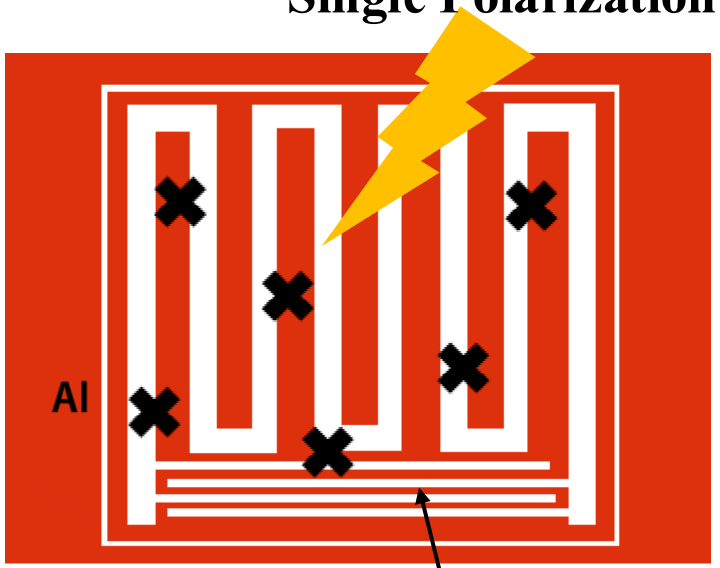


Incident radiation can be detected by measuring the shift in resonance frequency!

LEKID

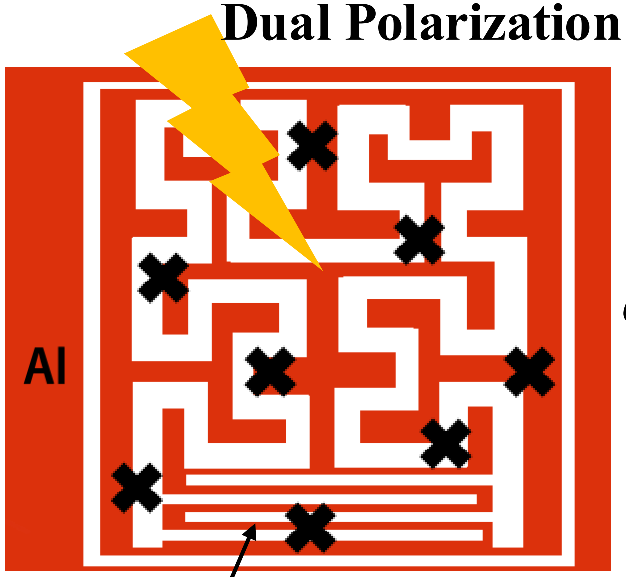
Classic line

Single Polarization

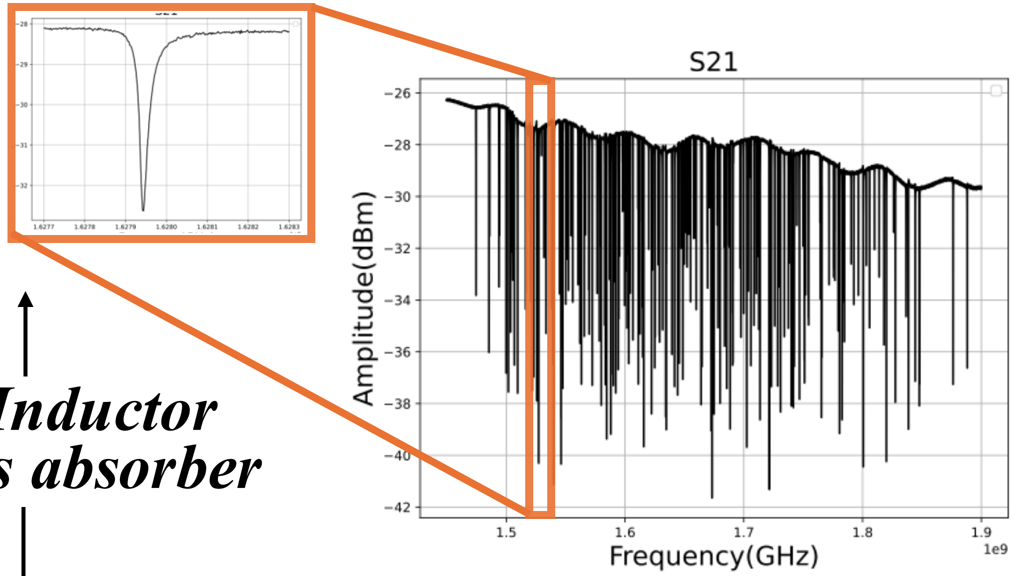


Hilbert

Dual Polarization



Capacitor tuning resonance freqency for each pixel



Inductor as absorber

224 resonance frequencies tuned by capacitor

Advantage

Since the entire pixel functions as absorber, incident radiation can be detected without using lenses or antennas

→ ease of multiplexing

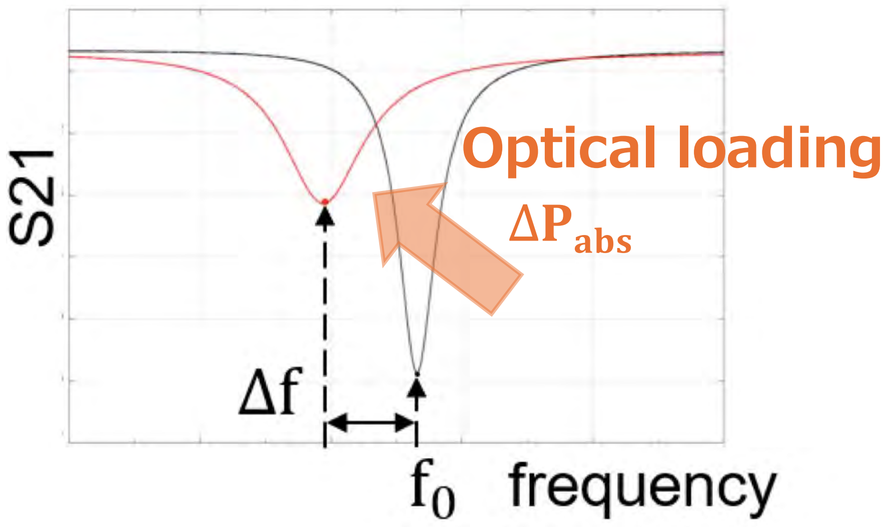
Sensitivity characterization (NEP)

minimum incident power required to achieve signal-noise-ratio = 1 within 1 Hz bandwidth

S_{n} ; noise level

$\Delta f/\Delta \mathrm{P}_{\mathrm{abs}}$; response

$$\mathrm{NEP} = \frac{S_{\mathrm{n}}}{\Delta f/\Delta \mathrm{P}_{\mathrm{abs,\ BB}}}$$



Smaller NEP indicates better performance

However, due to photon fluctuations, there exists minimum NEP that can't be reduced further (photon-noise-limited conditions)

Goal

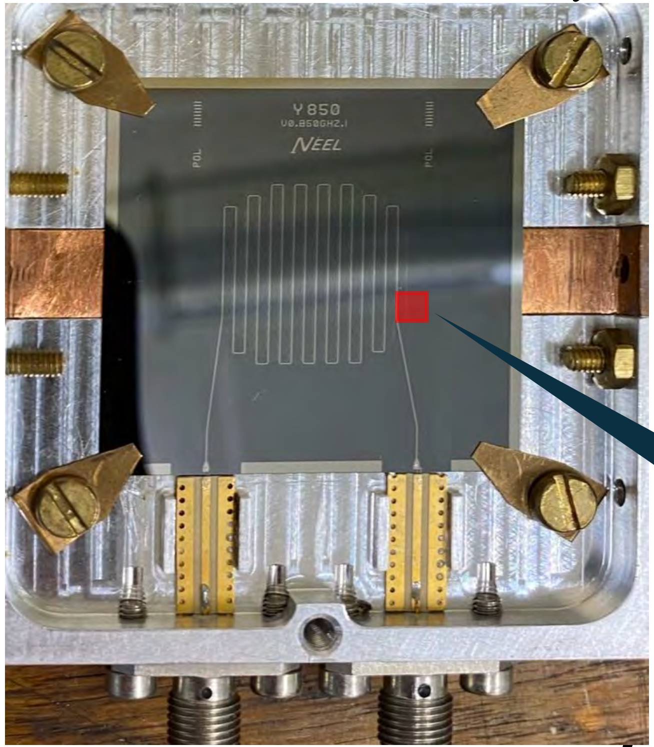
Achieve photon-noise-limited conditions under the Dome Fuji

Measurement

850GHz LEKID

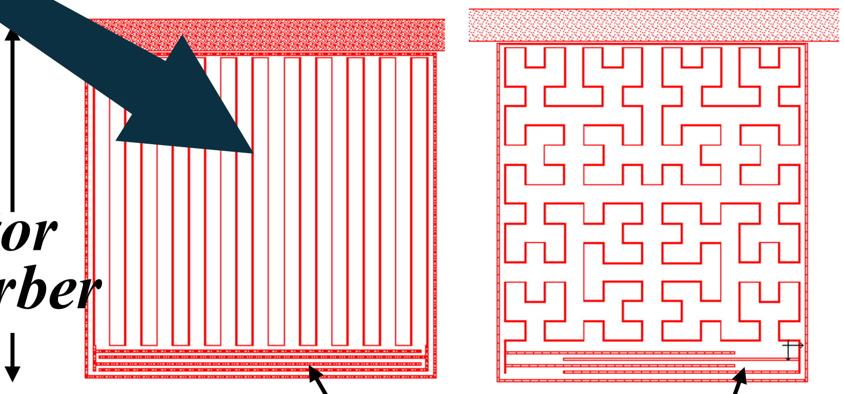
Chip on holder

Fabricated at the Plateforme Tech-nologique Amont Grenoble micro-fabrication facility



film material	Al single layer
film thickness	25 nm
substrate thickness	130 um
pixel size	1 x 1 mm^2
number of pixels	224
meander design	classic line / hilbert

classic line (single pol.) **or** **Hilbert (dual pol.)**

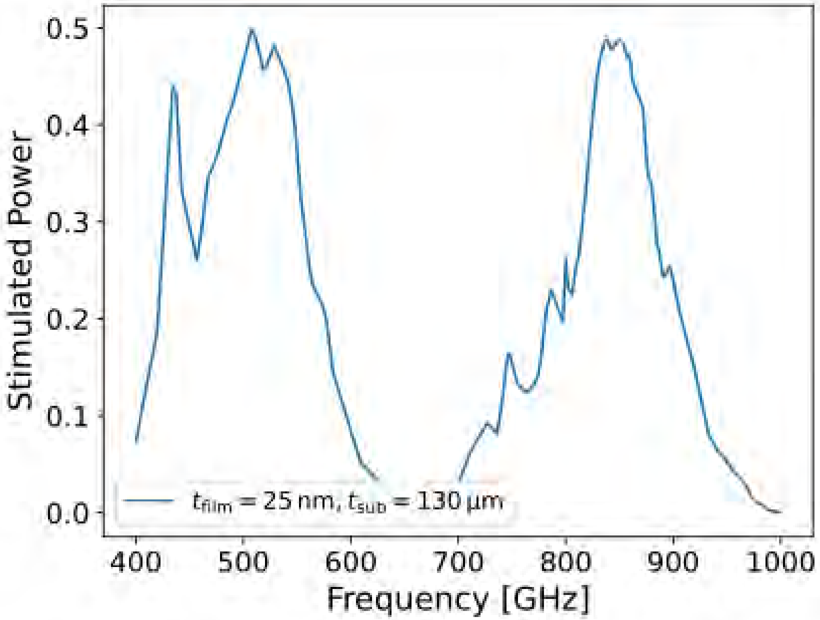


Inductor as absorber

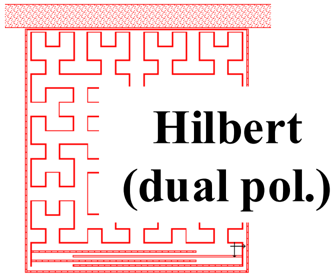
Capacitor tuning fr for each pixel

The simulated optical response

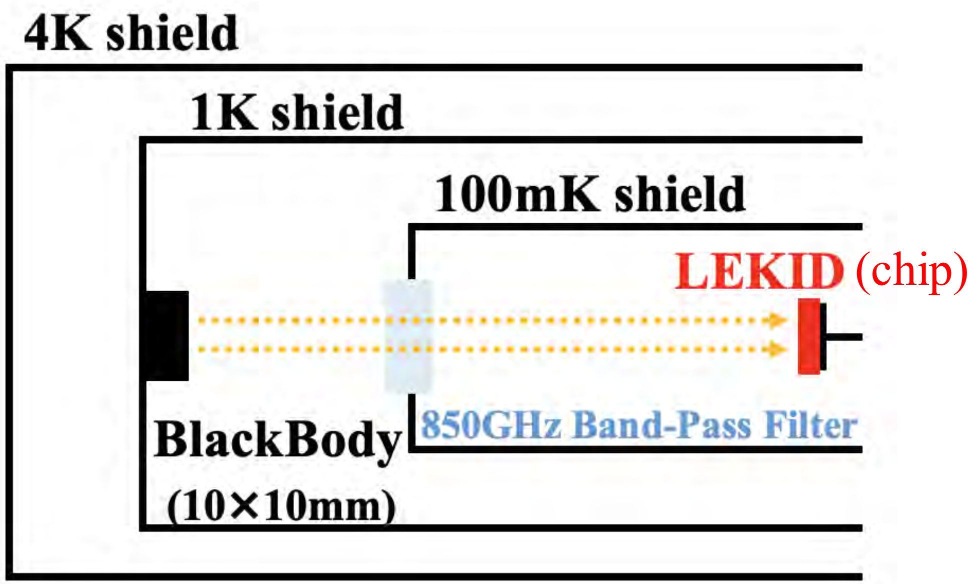
sensitive to 850GHz and to 500GHz



Measurement setup



cryostat

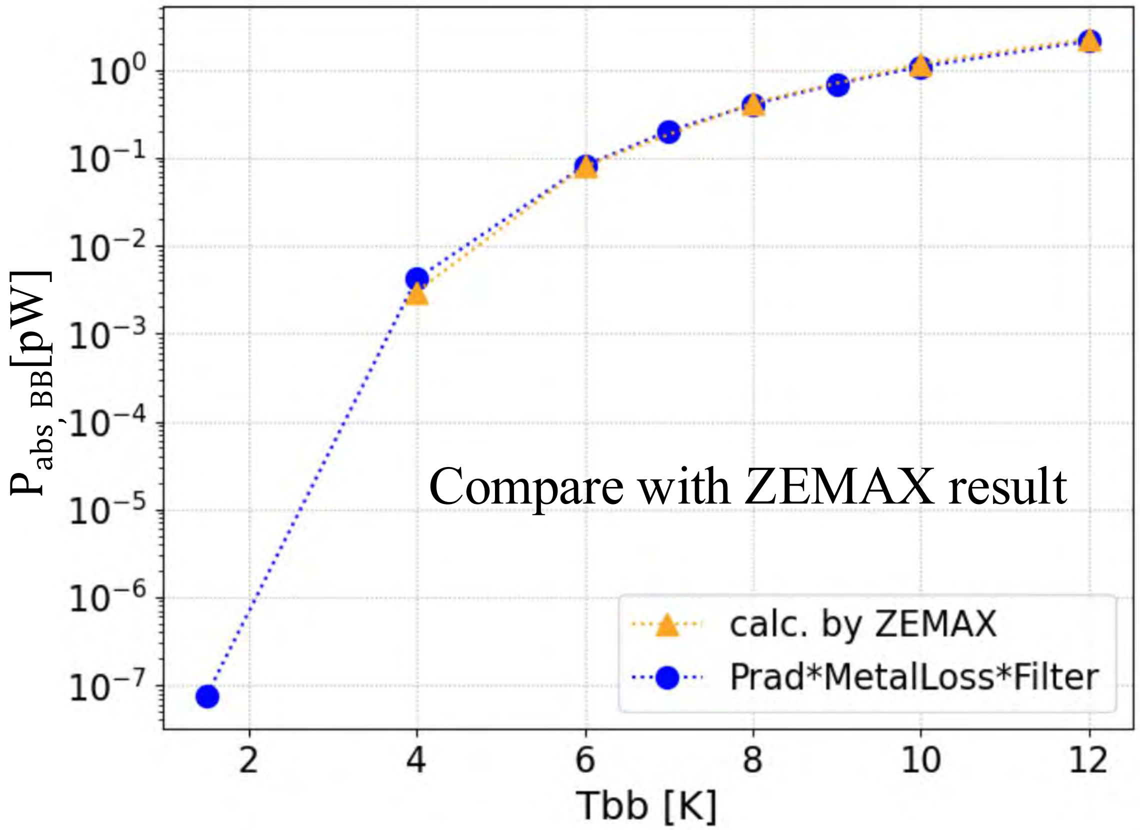


Install BlackBody in 1K shield
850-GHz Bandpass filter

Measurement; Hilbert (single pixel)

The optical loading per pixel : $P_{abs,BB}$[W]

yellow ; ZEMAX simulation result
blue ; Radiation from Blackbody × filter transmission × detector optical efficienc



Noise Measurement (S_n)

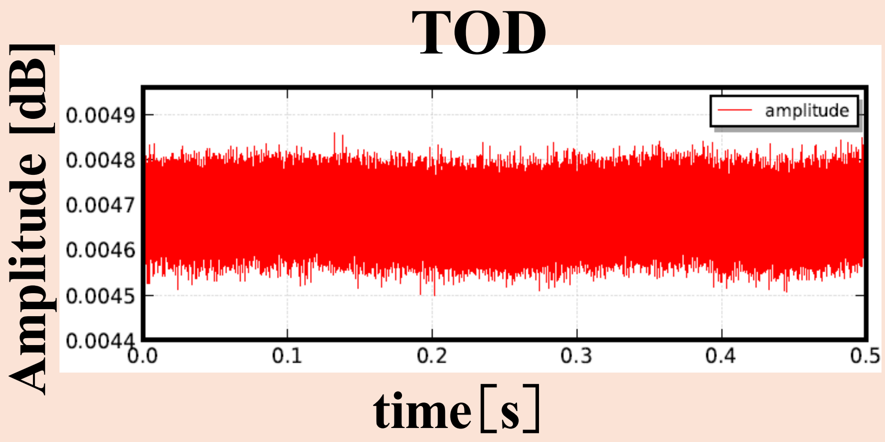
Power Spectral Density (PSD) ↓ T_{bb} = 6K

Photon + GR noise ; noise of the incident photons + generation - recombination noise induced by the incident photons

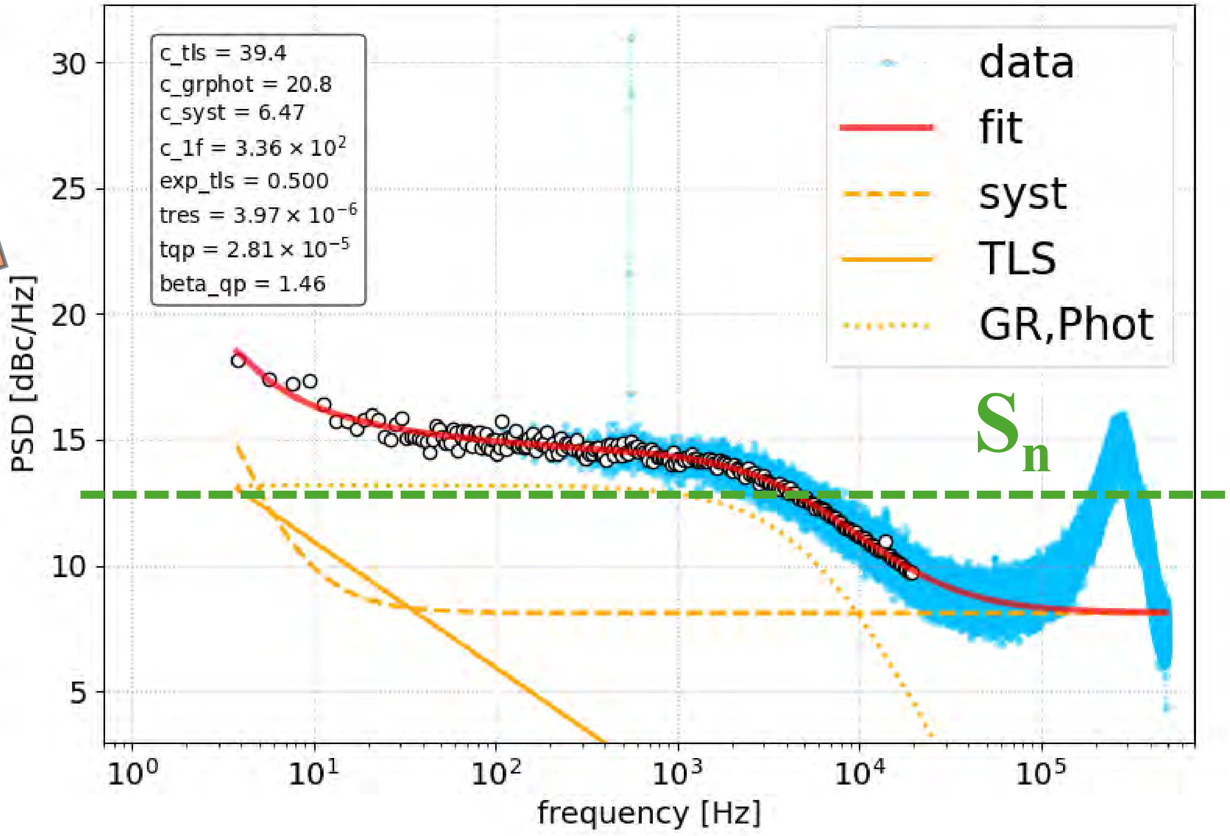
System noise ; the thermal noise of the cryogenic low-noise amplifier

TLS noise ; noise caused by electrical fluctuations on substrate surface

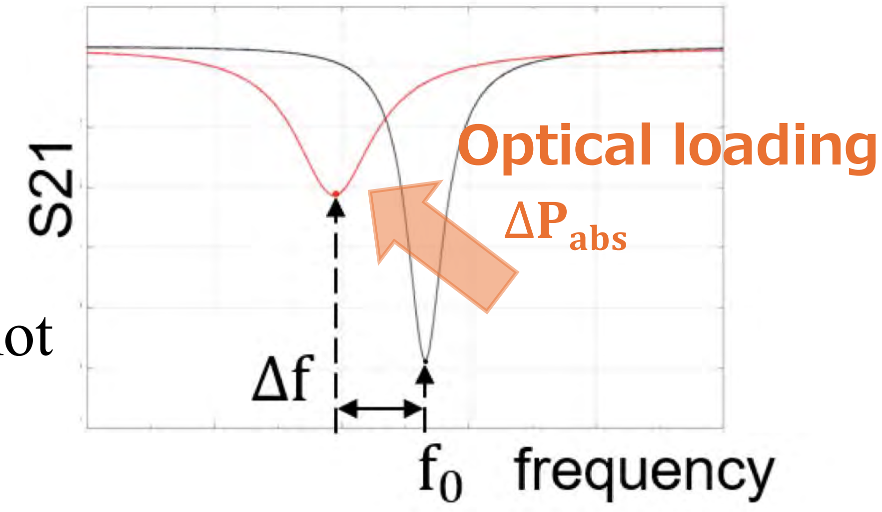
time-ordered data (TOD)



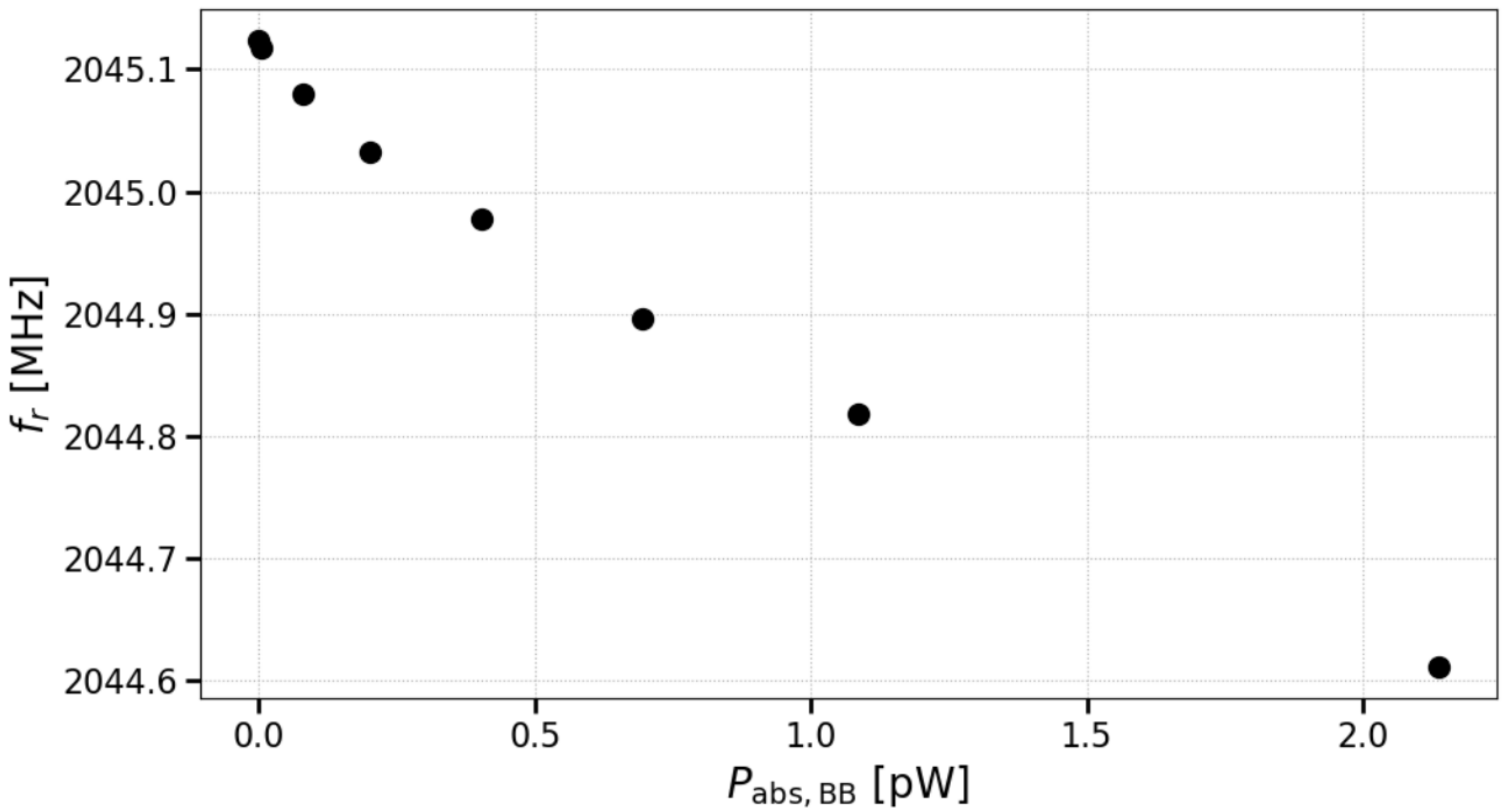
Fourier transform



Response Spectra ($\Delta f/\Delta P_{abs,BB}$)

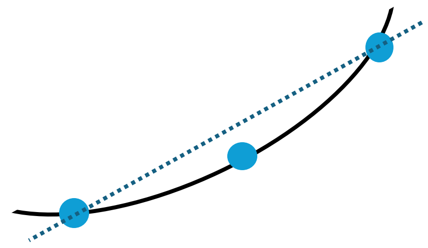


$\Delta f/\Delta P_{abs,\,BB}$ was derived from the slope of the $P_{abs,BB}$ versus f plot



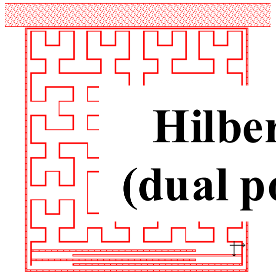
Due to the nonlinearity,
I use the central difference method

<u>central difference method</u>



Result

Sensitivity characterization; Hilbert (NEP)



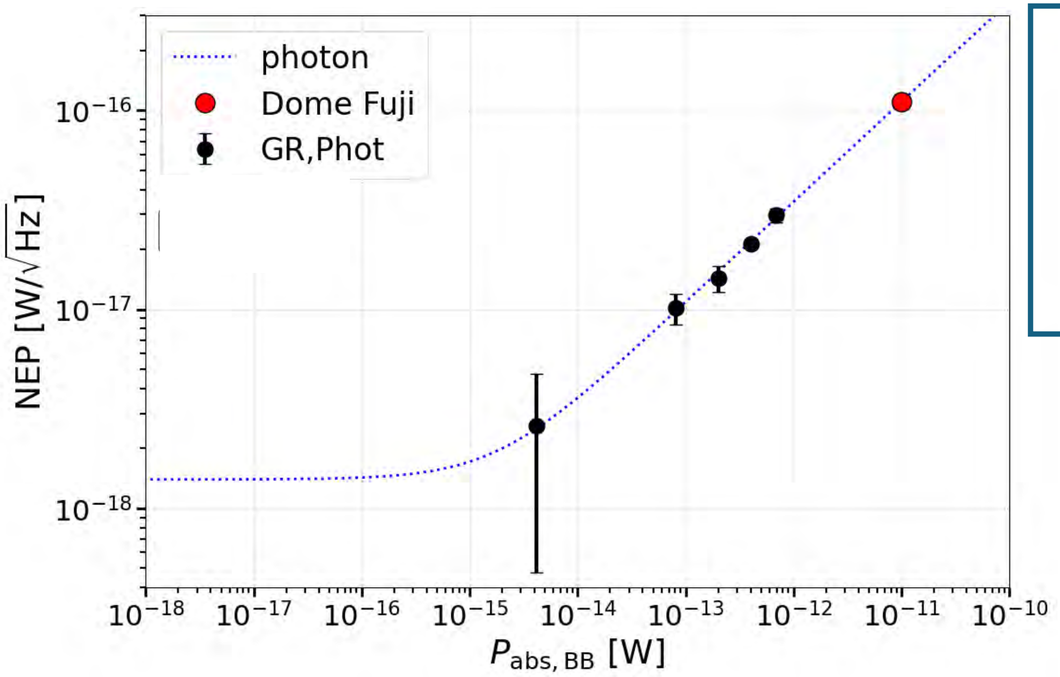
$$\mathrm{NEP} = \frac{S_n}{\Delta f / \Delta P_{\mathrm{abs,\ BB}}}$$

fitting function

Considering only the photon background–limited

$$\mathrm{NEP}^2_{\mathrm{ph}} = \int_{450\mathrm{GHz}}^{1\mathrm{THz}} \frac{(P_{\mathrm{abs,\ BB}} + P_{\mathrm{abs,\ stray}})(2h\nu + 4\Delta/\eta_{\mathrm{pb}})}{\zeta_{\mathrm{missmatch}}}$$

Ideal $\zeta_{\mathrm{missmatch}} = 1$



$\eta_{\mathrm{pb}} = 0.57$; the pair braking efficiency

↓ determined by fitting

$\zeta_{\mathrm{missmatch}}$; parameter quantifying the deviation from the optical efficiency

$P_{\mathrm{abs,\ stray}}$; stray-light absorbed by the detector

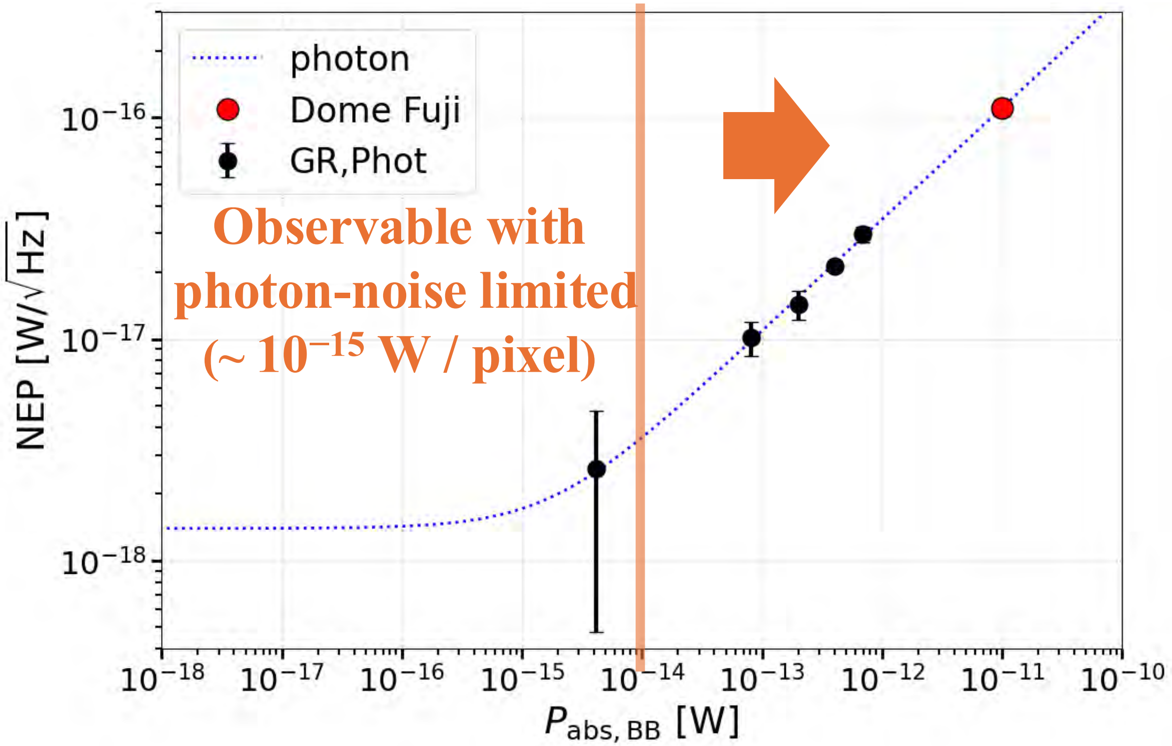
$\zeta_{\mathrm{missmatch}}$(deviation from the optical efficiency) $= 1.1 \pm 0.0512$

$P_{\mathrm{abs,\ stray}}$ (stray-light loading) $= 1.79 \times 10^{-15}$ W

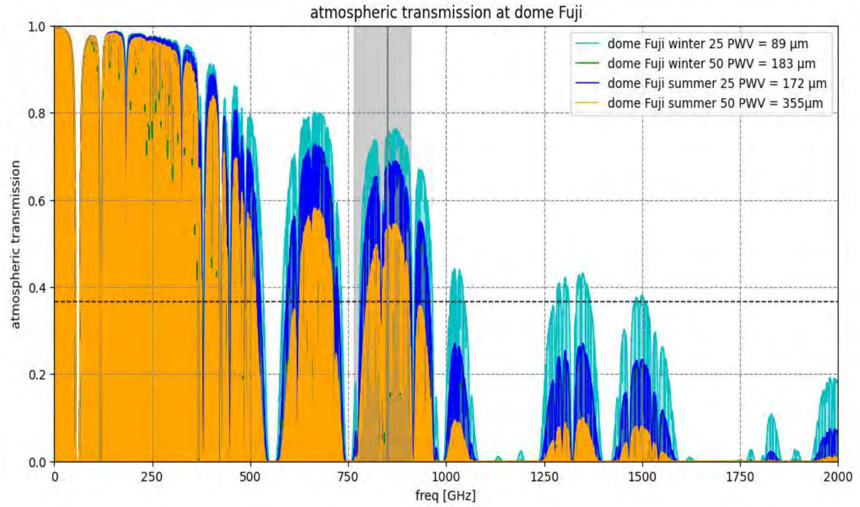
Sensitivity characterization; Hilbert (NEP)

fitting function

$$\mathrm{NEP}^2{}_{\mathrm{ph}} = \int_{450\mathrm{GHz}}^{1\mathrm{THz}} \frac{(P_{\mathrm{abs,\,BB}} + P_{\mathrm{abs,\,stray}})(2h\nu + 4\Delta/\eta_{\mathrm{pb}})}{\zeta_{\mathrm{missmatch}}}$$



Atmospheric Transmittance at Dome Fuji

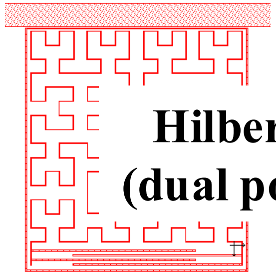


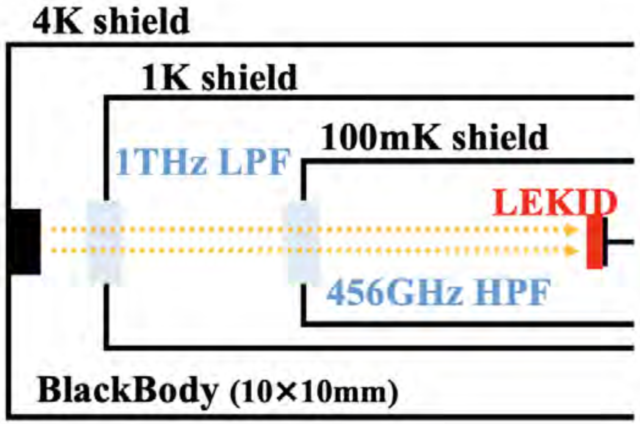
$$P = A\Omega\tau \int_{800\mathrm{GHz}}^{900\mathrm{GHz}} B(T_{\mathrm{BB}}, \nu)\, d\nu$$

A ; effective aperture area
Ω ; solid angle of blackbody as seen from pixel
τ ; atmospheric transmittance + optical system efficiency(=0.25)
$B(T_{\mathrm{BB}}, \nu)$; blackbody radiation

expected background at Dome Fuji = **~10^{-11} W / pixel**

Sensitivity characterization; Hilbert (NEP)

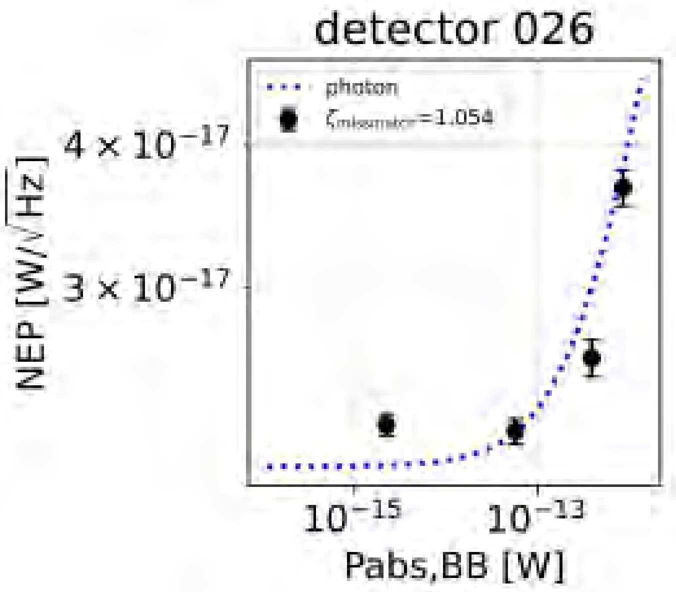


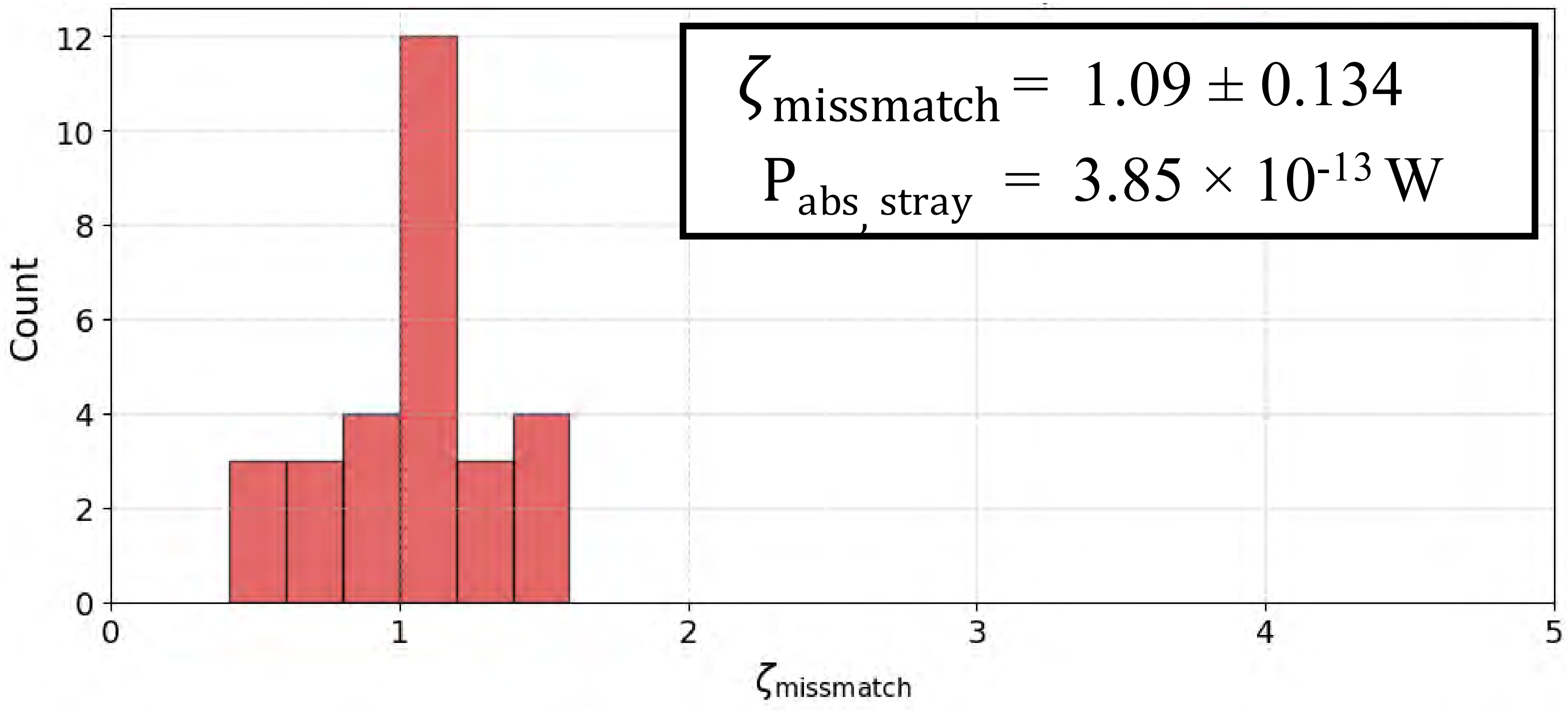


1THz low pass filter & 456GHz high pass filter
Install BlackBody in 4K shield

Hilbert (multi-pixel)

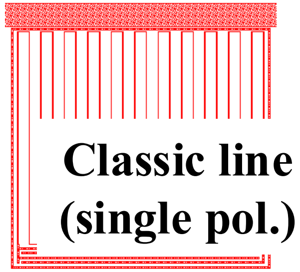
↓ Example of a single pixel



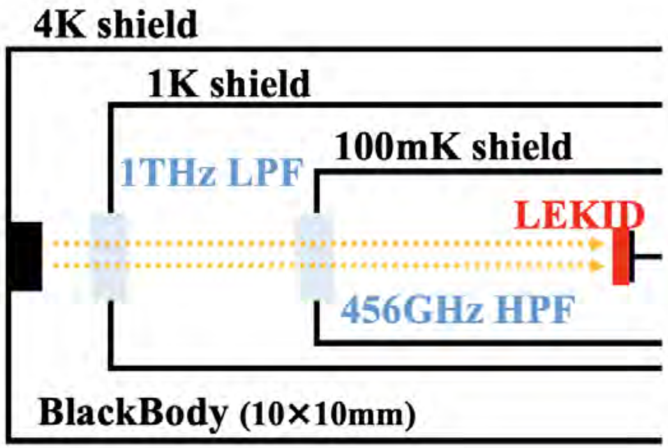


$$\zeta_{missmatch} = 1.09 \pm 0.134$$
$$P_{abs,\ stray} = 3.85 \times 10^{-13}\ \mathrm{W}$$

Sensitivity characterization; Single Line (NEP)

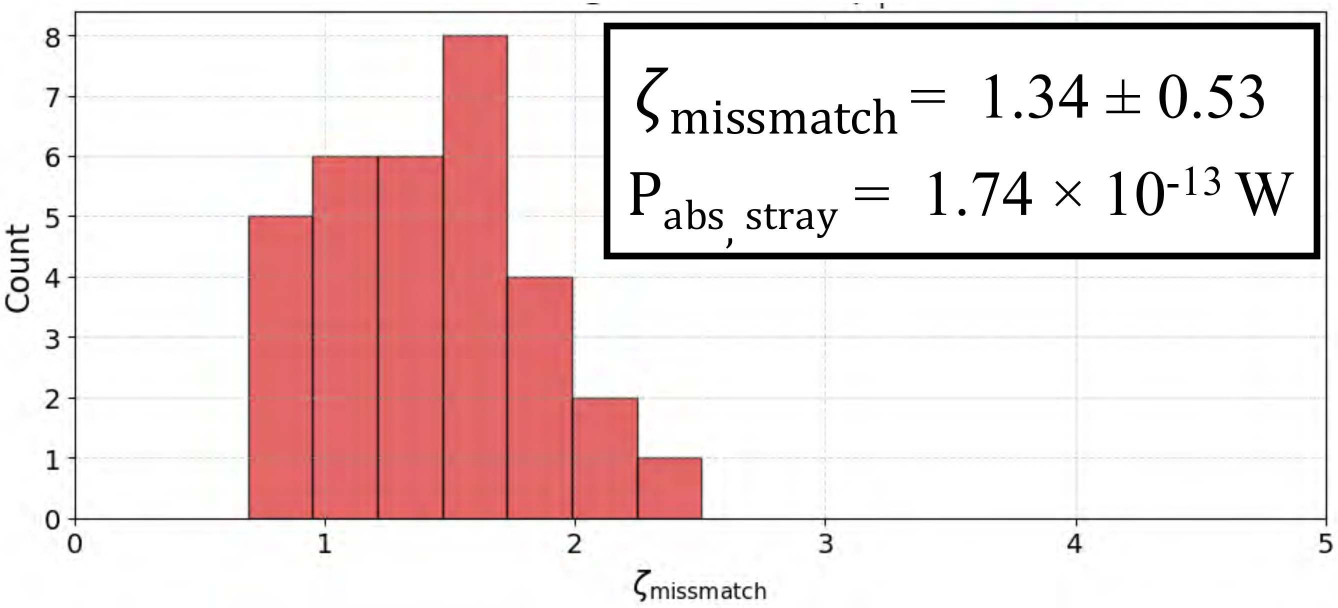


1THz low pass filter & 456GHz high pass filter
Install BlackBody in 4K shield

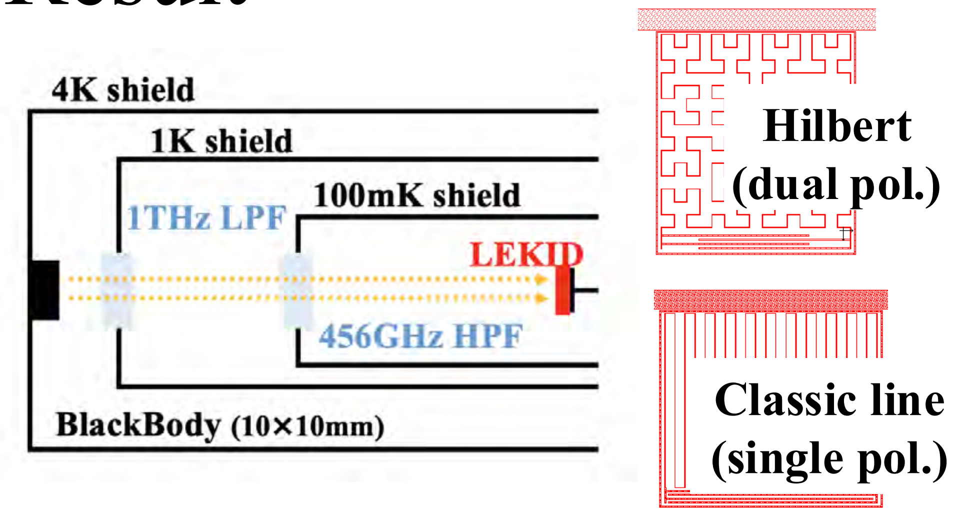


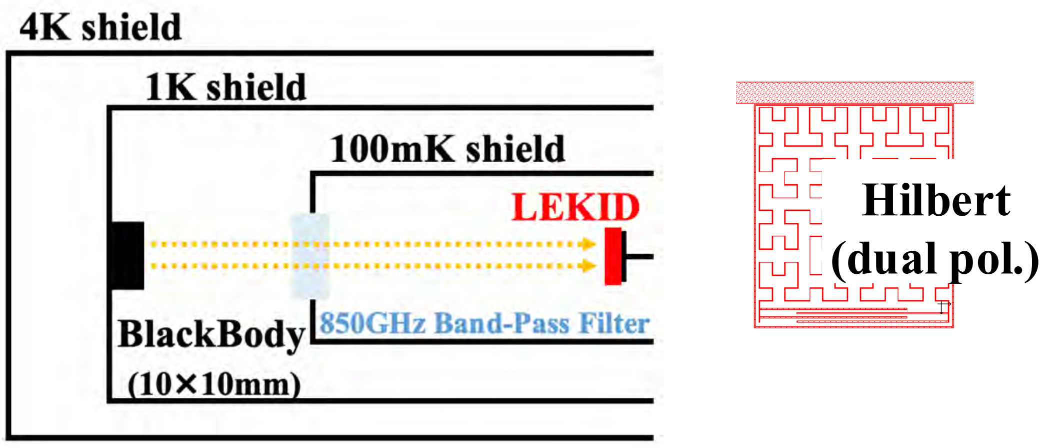
Discussion of causes for $\zeta_{missmatch} > 1$

Resonanse freqency fifference (Δf) between T_{bb} = 10 ~ 20K differ from pixel-averaged value obtained from sweep measuremanet
→ suggesting that external factor affected measurement



Result





	$\zeta_{missmatch}$ (deviation from the optical efficiency)	P_{abs_stray} (stray-light loading)
Hilbert (single pixel)	1.1 ± 0.0512	1.79×10^{-15} W
Hilbert (multi pixel)	1.09 ± 0.134	3.85×10^{-13} W
Classic line (multi pixel)	1.34 ± 0.531	1.74×10^{-13} W

The setup on the left exhibits a higher stray light

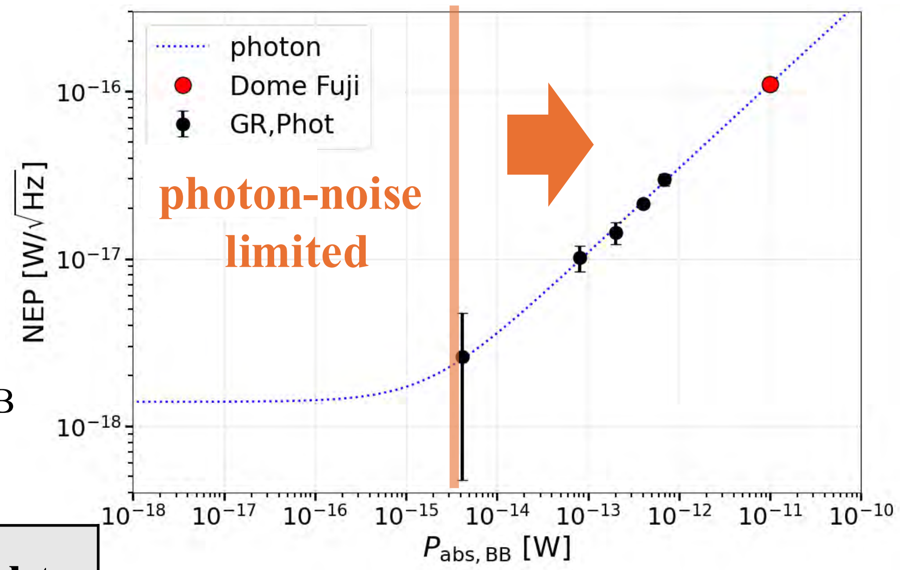
→Stray-light mitigation in 4 K shield

The stray-light of Hilbert is twice that of single-line

(As anticipated)

Summary

summary



- measurement

By varying the blackbody temperature, we measured S_n and $\Delta f/\Delta P_{abs,BB}$

- result

	$\zeta_{missmatch}$ **(deviation from the optical efficiency)**	$P_{abs,\ stray}$ **(stray-light loading)**
Hilbert (single pixel)	1.1 ± 0.0512	1.79×10^{-15} W
Hilbert (multi pixel)	1.09 ± 0.134	3.85×10^{-13} W
Classic line (multi pixel)	1.34 ± 0.531	1.74×10^{-13} W

Satisfy sensitivity requirements anticipated in Antarctic

Enable to detect expected background at Dome Fuji

$\sim 10^{-11}$ W / pixel

- Future work

Based on these results, we will scale up to thousands of pixels

Mitigate the 4K shield