Direct Detection and Interferometer Technologies in Terahertz Region

Hiroshi Matsuo

***Abstract*—Two innovative direct detection technologies in terahertz region are reviewed. One is superconducting direct detector and another is bolometric interferometer. Combination of the two technologies would be useful for high dynamic range imaging in terahertz frequencies. We have developed SIS photon detectors, which have band-pass response in the atmospheric window at 675 GHz. With 300 K background radiation, detectors operate under shot noise limit with NEP of about 10^{-15} W/Hz$^{0.5}$ at 0.3 K. The same detector give NEP of 10^{-14} W/Hz$^{0.5}$ at 4.2 K with thermal shot noise limit, which is better than 4.2 K bolometers. Integrated cryogenic readout is designed using GaAs-JFETs. We are also working on Multi-Fourier Transform interferometer (MuFT), which is a kind of bolometric interferometer. Martin-Puplett type interferometer with double input aperture is used to make aperture synthesis images in wide band with spectral and polarization information. Dynamic range of the obtained images are superior to heterodyne interferometers because of good u-v coverage owing to the wide frequency band. Combined with heliostat installed in Nobeyama Radio Observatory we made imaging experiments with astronomical sources. Installation of focal plane array of bolometric detectors or SIS photon detectors is planned to increase observing field of view appreciably.**

***Index Terms*—superconducting direct detector, SIS photon detectors, focal plane array, bolometric interferometer, Martin-Puplett type interferometer, high dynamic range imaging**

I. Introduction

DEVELOPMENT of direct detector technology is important because of their high sensitivity and broad frequency coverage as well as large number of detector pixels to make wide field observations. What is more important for terahertz imaging system is high dynamic range imaging not only for intensity scale but also for frequency coverage and field of view.

Direct detection systems have great advantage over heterodyne system for its simplicity and their sensitivity which is not limited by the heterodyne quantum limit. For this reason two dimensional array of TES bolometers and superconducting direct detectors have been developed. I will discuss on the importance of high dynamic range imaging system using superconducting direct detectors and bolometric interferometers. Both of these technologies have recently been applied for astronomical observations [1], [2].

This work was supported by grant-in-aid of the Japan Society of Promotion of Science No.13304015, 16204010 and 18206042.

H. Matsuo is with Advanced Technology Center, National Astronomical Observatory of Japan, Mitaka, Tokyo 181-8588 Japan (e-mail: h.matsuo@nao.ac.jp).

II. High Dynamic Range Imaging in THz Region

A. Intensity Scale

For submillimeter-wave ground-based observation, atmospheric background is around 100 pW and background limited NEP is about 10^{-16} W/Hz$^{0.5}$. Hence, dynamic range of 10^{6} is required. Observation from space requires NEP of 10^{-18} to 10^{-19} W/Hz$^{0.5}$ to achieve background limited performance. For calibration purpose we would observe planet or asteroid which have 10-100 pW of input radiation power and high dynamic range of about 10^{8} is required. These numbers are not easy to realize with bolometric detectors. Superconducting direct detectors have advantage over TES bolometer because of their quantum response with high dynamic range [3].

B. Frequency Coverage

Instantaneous frequency coverage of direct detectors is much larger than heterodyne receivers in terahertz frequencies. For spectroscopic observation with direct detectors, either Fourier transform spectrometer, grating spectrometer or Fabry-Perot spectrometer is used in front of focal plane detectors. The size of the spectrometer typically limit spectral resolution to about 100 MHz or $\nu/\Delta\nu < 10^{4}$ for 1 THz in case of Fourier transform spectrometers. Because spectrometers with direct detectors do not suffer from the quantum limit of heterodyne receivers, they can achieve higher performance at higher frequencies.

C. Field of View and Angular Resolution

Focal plane array of bolometric detectors are being built. However, for single dish observations, angular resolution is limited by the diffraction of the telescope aperture. Aperture synthesis interferometers give much higher angular resolution, but have limited field of view. It is not easy to install focal plane array of heterodyne interferometer with wide frequency coverage. On the other hand, bolometric interferometers combined with focal plane array is an attractive solution, which can be accommodated with focal plane array of direct detectors with wide frequency coverage.

D. High Fidelity Image

Combination of all the features discussed above result in high fidelity imaging in terahertz frequencies. This is the goal of our imaging instrument with superconducting direct detectors and bolometric interferometers, which could be applied to variety field of terahertz technologies [4].

III. SIS Photon Detectors

We have developed SIS photon detectors in submillimeter-wave, which are antenna-coupled superconducting direct detectors based on photon assisted tunneling of quasi-particle [5], [6]. Their input coupling is designed using distributed junction array to match atmospheric window at 675 GHz. Fig. 1 shows a schematic I-V curve of superconducting tunnel junction with and without photon illumination. When incident photon is coupled to antenna connected to each electrode of a tunnel junction, quasi-particle tunneling step is observed.

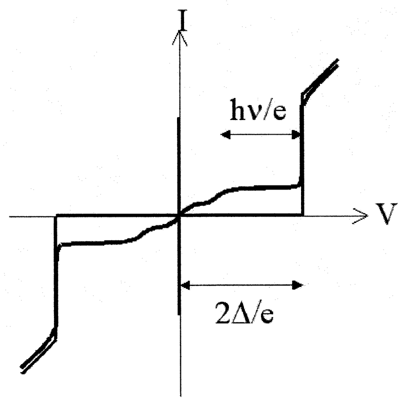

Fig. 1. Idealized current vs. voltage characteristics of SIS junctions, with no radiation input (thin line) and with input photon energy (hν) of about 2/3 of the gap energy (2Δ), where photon assisted tunneling step (thick line) is shown [3].

The current increase is observed so that one photon creates one quasi-particle tunnel through the junction. Responsivity of the SIS photon detector and their noise performance can be expressed as:

$$S = \eta \cdot \frac{e}{h\nu}\ [\mathrm{A/W}] \quad (1)$$

$$N = \sqrt{2eI}\ \left[\mathrm{A}/\sqrt{\mathrm{Hz}}\right] \quad (2)$$

$$\mathrm{NEP} = N/S = \frac{h\nu}{\eta} \cdot \sqrt{\frac{2I}{e}}\ \left[\mathrm{W}/\sqrt{\mathrm{Hz}}\right] \quad (3)$$

where η is a quantum efficiency and I is a leakage current. For leakage current of 100 pA and quantum efficiency of 0.5, we could get NEP of 3×10^{-17} W/Hz$^{0.5}$. Actual performance we have measured for 650 GHz SIS photon detectors is quantum efficiency of 0.2 and optical NEP of 1.6×10^{-16} W/Hz$^{0.5}$ [5].

One of the features of these detectors is that they work under shot noise limit under various operating conditions. Under background loading of effective temperature of 300 K, they show close to a shot noise limited performance with NEP of about 10^{-15} W/Hz$^{0.5}$ [1]. For operating temperature of 4.2 K, they also show shot noise limited performance of thermal leakage current of the tunnel junction and their NEP is about 10^{-14} W/Hz$^{0.5}$ [3].

Another feature is that SIS photon detectors have high saturation current of the order of 100 μA, and their dynamic range is expected to be larger than 10^9 [3], whereas measurement have shown that dynamic range is larger than 10^7 and can be used for variety of terahertz application fields [4].

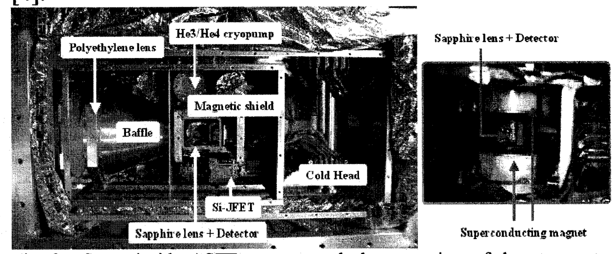

Fig. 2. Setup inside ASTE cryostat and close up view of detector part. Cryostat is cooled by GM cooler and He3-He4 sorption fridge. SIS photon detectors are installed at backside of hyper-hemispherical sapphire lens [1].

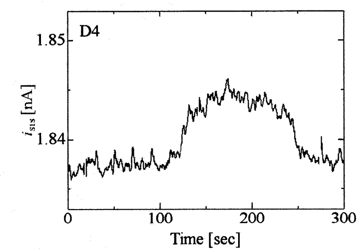

Fig. 3. Drift scan observation of the moon with SISCAM-9 in ASTE under estimated atmospheric transmittance of 1% [1].

We have fabricated 9-element array of 650 GHz SIS photon detectors and installed in a cryostat for submillimeter-wave astronomical observations. Fig. 2 shows the setup inside the cryostat. We call the observing system as SISCAM-9 or superconductive submillimeter-wave camera with nine detector element. SISCAM-9 is installed in a 10-m diameter submillimeter-wave telescope in Atacama, ASTE, Atacama Submillimeter Telescope Experiment [7].

The performance of SIS photon detectors in the ASTE cryostat is that their noise is about ten larger than the shot noise of input photo current through the junction that is 3 nA on average.

After we have made evaluation of I-V characteristics and noise measurement in ASTE, we have performed observation of moon, which is the first run to observe an astronomical source with superconducting direct detectors. Fig. 3 shows the drift scan measurement of the moon for one of the detector channel.

To realize large format array of SIS photon detectors, integrating amplifier with multiplexed readout is being developed using GaAs-JFET technology [8]. GaAs-JFETs operate as low noise device at 0.3 K with power dissipation of less than 1 μW. Using capacitive trans-impedance amplifier (CTIA) photo current of SIS photon detector can be integrated on feedback capacitor and the signal can be multiplexed.

IV. MuFT Interferometer

The multi Fourier transform interferometer, or MuFT, is an aperture synthesis bolometric interferometer with spectroscopic and polarization information [9]. Focal plane array could be used to increase observing field of view. Schematic presentation of MuFT is given in Fig. 4. Light collecting part, LiC, defines the baseline of the interferometer. Fourier interferometer part, FI, have two input polarizer and a beam combiner, each made of wiregrid for the Martin Puplett

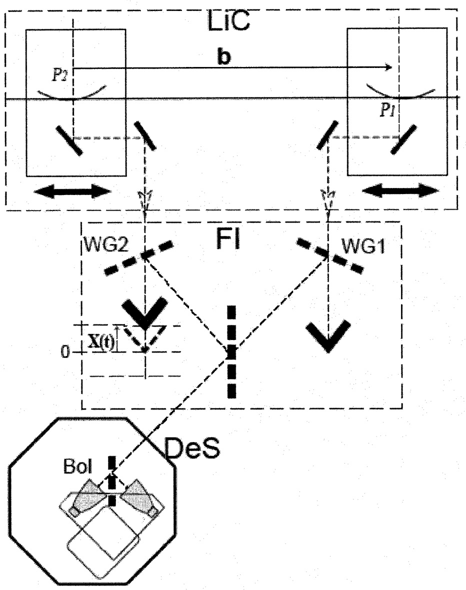

Fig. 4. Schematic optical arrangement of the MuFT. This is based on Martin-Puplett interferometer using wire grids as input polarizers and a beam combiner [9].

type interferometer. Dual polarization bolometric detectors can be used as detector and sampling part, DeS. Because the interferometer is Martin Puplett type with wiregrid polarizers, combination of wire direction gives independent measure of four stokes parameters, I, Q, U and V.

Actual optical setup of MuFT is shown in Fig. 5. The beam diameter is 50 mm and input beams coming from above are reflected by wiregrids aside to rooftop mirrors. The reflected beams then go through the wiregrid to the combiner to the left. One of the rooftop mirrors is continuously driven by a voice coil at right bottom in the figure.

We have made laboratory experiment to image a blackbody source to confirm the basic principle of MuFT interferometers with 1.5 K bolometers that operate from 100 GHz to 900 GHz. Because of the large frequency coverage of bolometric detectors, u-v sampling is good enough to get low sidelobe images even with limited number of baselines [10].

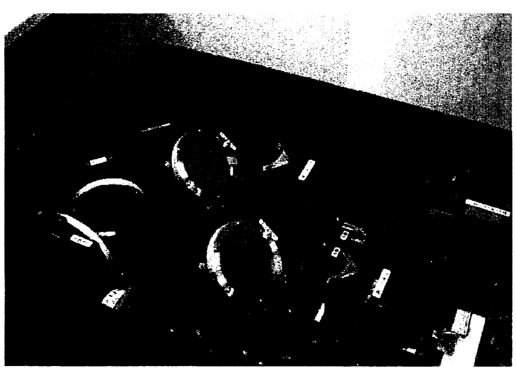

Fig. 5. Picture of the MuFT interferometer. Two input beams come from the top into the wire grid polarizers, then reflected aside to corner reflectors.

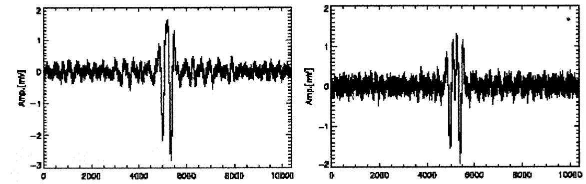

Fig. 6. Mutual coherence interferograms of the sun obtained by the MuFT with baseline lengths of 12 cm (left) and 16 cm (right) [2].

We have installed the MuFT with a heliostat in Nobeyama Radio Observatory. The heliostat has 700 mm diameter primary mirror and maximum baseline is about 400 mm, which is limited by optical configurations. Fig. 6 shows an example of mutual correlation interferogram obtained during observation of the sun. We used single element bolometer operating at 1.5 K. for the measurement. Frequency range of the detector is from 100 GHz to 900 GHz. But because of the limitation of atmospheric transmittance, observation is essentially made in millimeter-wave frequencies. Fourier transformation of these interferograms show the interference fringe is consistent with the size of the sun with different baseline spacing [2].

V. Combination of Two Technologies

Although the developments of SIS photon detectors and MuFT interferometers are being done separately, combination of these technologies would enhance observing capability appreciably. Because MuFT interferometer is a direct detection interferometer, amount of data rate is small. Hence, focal plane imaging array can be easily accommodated with MuFT interferometer, that is identical to Fourier transform spectrometers with focal plan imaging array.

As an example, using two 1-m diameter telescopes with maximum baseline of 100 m in space and 1000-element focal plane array detectors at 1 THz with NEP of 10^{-18} W/Hz$^{0.5}$, we could achieve sensitivity of 100 μJy/Hz$^{0.5}$ with observing field of view of more than 1000 arcmin^2 and angular resolution of less than 1 arcsecond. With MuFT interferometer, spectral and polarization information is also acquired. High dynamic range imaging in intensity scale, frequency range and observing field of view, could be achieved simultaneously.

VI. Conclusion

We have presented development of two direct detection technologies, which could be used to make high dynamic range imaging in terahertz frequencies. These technologies have already shown their performance as astronomical instrumentation. It is of great interest to combine these technologies for future high dynamic range imaging in terahertz frequency region.

Acknowledgment

The author acknowledge Terahertz development groups in NAOJ and RIKEN, and Hirohiko M. Shimizu of KEK for supporting developments of superconducting direct detectors. MuFT interferometer is being developed under collaboration between Tohoku University and NAOJ.

References

[1] Y. Mori et al., "Development of Superconductive Imaging Submillimeter-wave CAMera with nine detector elements (SISCAM-9)", 2006, Proc. SPIE 6275, in press.

[2] I.S. Ohta et al., "Astronomical mm and sub-mm observations with Multi-Fourier Transform interferometer in 2005 and 2006 ", 2006, Proc. SPIE 6275, in press.

[3] H. Matsuo et al., "Performance of SIS photon detectors for superconductive imaging submillimeter-wave camera (SISCAM)", 2006, Proc. SPIE 6275, in press.

[4] S. Ariyoshi et al., "Terahertz imaging with a direct detector based on superconducting tunnel junctions", 2006, Appl. Phy. Lett. 88, 203503.

[5] S. Ariyoshi et al., "Characterization of an STJ-based direct detector of submillimeter waves", 2005, IEEE trans. Appl. Supercond. 15, 920-923.

[6] H. Matsuo et al., "Design of wide-field submillimeter-wave camera using SIS photon detectors", 2004, Proc. SPIE 5498, 371-380.

[7] H. Ezawa, R. Kawabe, K. Kohno, S. Yamamoto, "The Atacama Submillimeter Telescope Experiment (ASTE)", 2004, Proc. SPIE 5489, 763-772.

[8] H. Nagata, J. Kobayashi, H. Matsuo, M. Fujiwara, "Progress on GaAs cryogenic readout circuits for SISCAM", 2006, Proc. SPIE 6275, in press.

[9] I. S. Ohta, M. Hattori and H. Matsuo, "Development of Multi-Fourier Transform interferometer: Fundamental", 2006, Applied. Opt. 45, 2576-2585.

[10] I. S. Ohta, M. Hattori, H. Matsuo, "Development of super broadband interferometer in FIR", 2004, Proc. SPIE 5487, 1563-1570.