DESIGN OF SUBMILLIMETER-WAVE CAMERA WITH SUPERCONDUCTING DIRECT DETECTORS

Seiichirou Ariyoshi[a], Hiroshi Matsuo[b], Masanori Takeda[c] and Takashi Noguchi[c]

[a] *Astronomical Institute, Tohoku University, Sendai, Miyagi 980-8578, Japan*
[b] *National Astronomical Observatory, Mitaka, Tokyo 181-8588, Japan*
[c] *Nobeyama Radio Observatory, Minamimaki, Minamisaku, Nagano 384-1305, Japan*

Abstract

We have designed and are fabricating submillimeter-wave focal plane array based on superconducting direct detectors for Atacama Submillimeter Telescope Experiment (ASTE). Antenna-coupled SIS junctions with low leakage current can be used as sensitive submillimeter-wave detectors. Distributed junction array coupled to log-periodic antenna is designed to realize high quantum efficiency and wide frequency coverage. The observing center frequency using Nb/Al-AlOx/Nb junctions is about 650 GHz (450 μm). The electrical characteristics of the single SIS junction are measured. The achieved leakage current and current noise at 0.5mV-bias is 6.3 pA and 1.8 fA/$\sqrt{\text{Hz}}$, respectively. This measured current noise is consistent with the calculated shot-noise limited one. The expected noise equivalent power (NEP) is an order of 10^{-18} W/$\sqrt{\text{Hz}}$. Bandwidth of the antenna-coupled SIS junctions is calculated to be more than 60 GHz (FWHM)@650 GHz with $J_c = 1$ kA/cm^2.

1 Introduction

The submillimeter-wave region plays an important role in the next generation of radio astronomy as the most suitable probe to realize the search of primordial galaxies and the observational clarification of galaxy formation epoch. It is necessary for astronomical continuum observations to develop a submillimeter-wave camera with wide frequency coverage and wide field of view. Bolometer arrays have been widely used for submillimeter-wave continuum observations. But these systems have many difficulties because of low operating temperature and fabrication of two-dimension arrays. On the other hand, antenna-coupled SIS junctions with low leakage current can be used as sensitive submillimeter-wave detectors and are expected to have capabilities beyond these bolometer systems. Direct photon detection at microwave band was first predicted theoretically by Tucker and Millea (1978) [1], and then proved experimentally by Richards et al. (1979) [2]. They tested a Pb(In,Au) SIS junction which cooled down to 1.4 K, and succeeded in the 36 GHz photon detection. NEP was $2.6 \pm 0.8 \times 10^{-16}$ W/$\sqrt{\text{Hz}}$. They pointed out the need of fabricating SIS junctions with low leakage current for further improvement. Until recently, we have discussed the possibility for realization of superconducting direct detectors (SIS photon detectors) [3] [4].

In this paper, we propose to use SIS photon detectors for future instrument as submillimeter-wave wide field imaging array. We also discuss the design of the antenna-coupled SIS photon detectors and present situations.

2 Atacama Submillimeter Telescope Experiment

The Atacama Submillimeter Telescope Experiment(ASTE) is a Japanese experimental project previous to the Atacama Large Millimeter/Submillimeter Array(ALMA), as the first large submillimeter telescope in the southern hemisphere. The ASTE 10m-diameter telescope will be

Figure 1: ASTE 10m-diameter telescope

equipped with submillimeter-wave focal plane array based on superconducting direct detectors for astronomical continuum observations and SIS mixers (100, 230, 345, 490, 670, 850 GHz) for spectral line observations at Pampa La Bola(4800m altitude), Atacama, Northern Chile. Nobeyama Radio Observatory of Japan manages the ASTE project. Figure 1 shows a picture of the ASTE 10m telescope in Nobeyama Radio Observatory to be installed in Atacama in late 2001. Figure 2 shows the atmospheric transmission at ASTE site [5]. We plan to observe using

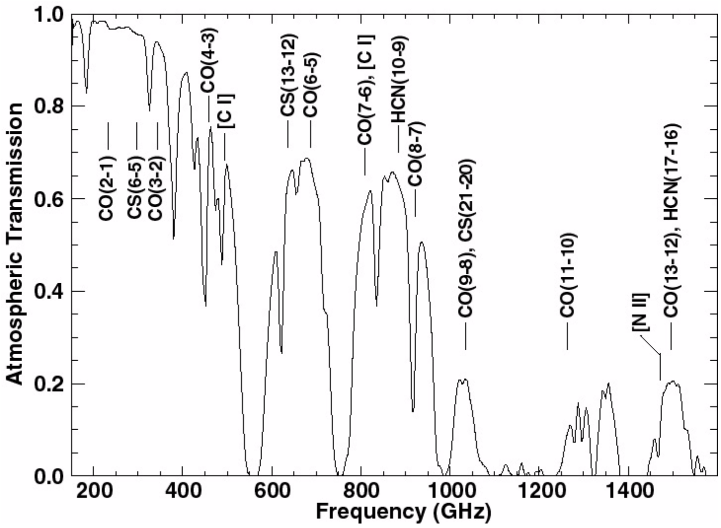

Figure 2: Measured atmospheric transmission spectrum at ASTE site

the atmospheric windows at 650 GHz and 350 GHz using niobium and tantalum based SIS junctions, respectively.

3 The submillimeter-wave camera

The submillimeter-wave camera for the ASTE project requires low noise superconducting direct detectors for continuum observations. The superconducting direct detectors have two kinds of operating principles. One is called 'photon detection', when an incident photon energy($h\nu$) is larger than the gap energy(2Δ) of Cooper-pair. In this case, Cooper-pair can be broken directly by a photon. This principle is often used as the photon-counting UV and optical detectors. The other is called 'video detection', when $h\nu$ is less than 2Δ, then SIS junction need to be connected to an antenna, and an incident photon can be detected by the principle of 'photon-assisted-tunneling(PAT)'. Niobium SIS junctions have 2Δ of about 3 meV which correspond to the radiation frequency of about 700 GHz. As shown in Figure 2, because the observable center frequency is about 650 GHz, we adopt the latter case. It is necessary to apply the bias voltage of 0.5 mV at both sides of a SIS junction.
Distributed junctions coupled to a log-periodic antenna are designed to realize high quantum efficiency and wide frequency coverage. First, the electrical characteristics of niobium SIS junctions are measured. Second, we estimate the input coupling efficiency of SIS distributed junction array with a log-periodic antenna.

3.1 Electrical characteristics of the SIS junction

Before we show our measurement of the leakage current and current noise of the single SIS junction, we estimate the parameters of detector performance. Johnson noise (N_j) and the shot noise (N_s) associated with the leakage current is expressed as follows.

$$N_j = \sqrt{\frac{4k_BT}{R}} \quad \mathrm{A}/\sqrt{\mathrm{Hz}} \tag{1}$$

$$N_s = \sqrt{2eI_0} \quad \mathrm{A}/\sqrt{\mathrm{Hz}} \tag{2}$$

T, R, I_0, e and k_B indicate temperature, resistance, leakage current of the SIS device, electron charge and Boltzmann's constant, respectively.
According to Tucker's theory[6], the current responsivity(S_ν) using as 'video detection' is expressed by

$$S_\nu = \eta \cdot \frac{e}{h\nu} \quad A/W. \tag{3}$$

η and h indicate the quantum efficiency and Planck's constant.
When $N_j \ll N_s$, Noise Equivalent Power(NEP) is expressed by

$$\begin{aligned}\mathrm{NEP} &= \frac{N_s}{S_\nu} \\ &= \frac{h\nu}{\eta} \cdot \sqrt{\frac{2I_0}{e}} \quad \mathrm{W}/\sqrt{\mathrm{Hz}}\end{aligned} \tag{4}$$

For example, when I_0 and η are 10 pA and 0.1 respectively, the expected shot-noise limited NEP is an order of 10^{-17} W/$\sqrt{\mathrm{Hz}}$ @650 GHz. We need to fabricate SIS junctions with low leakage current and high coupling efficiency to input radiation. It is advantageous to use low current density junctions to achieve low leakage current, but this degrade the coupling efficiency. In the following sections, we show that the current density of 0.5-1 kA/cm^2 is a good compromise to achieve low current density and high quantum efficiency at the same time.

3.1.1 I-V characteristic

The critical temperature of niobium is 9.2 K. A single SIS junction is cooled down to 0.3 K in order to reduce the leakage current caused by thermal excitation of Cooper-pair. The read-out circuit in this experiment is composed of a silicon J-FET used as a source follower and trans-impedance amplifier, as shown in Figure 3.

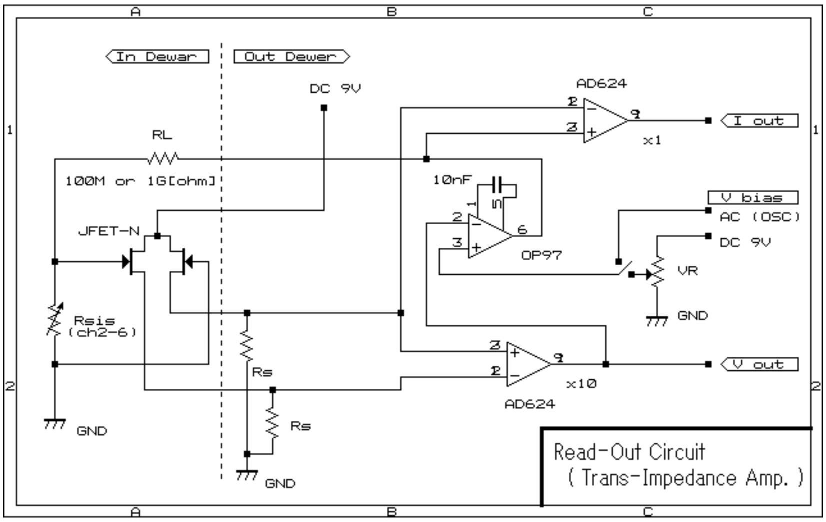

Figure 3: Read-out circuit

We measured the I-V characteristic of a single element niobium junction as shown in Figure 4. The critical current density(J_c) is 0.5 kA/cm^2 and the size is 4×4 μm^2 square. The achieved

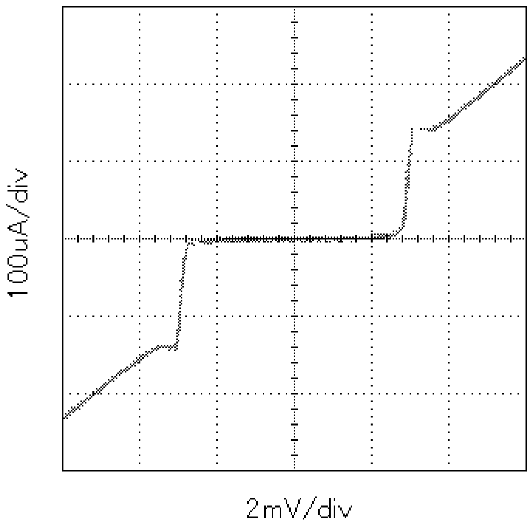

Figure 4: Bias-voltage vs. Leakage-current characteristic

leakage current is 6.3 pA at bias voltage of 0.5 mV, as shown in Figure 5.

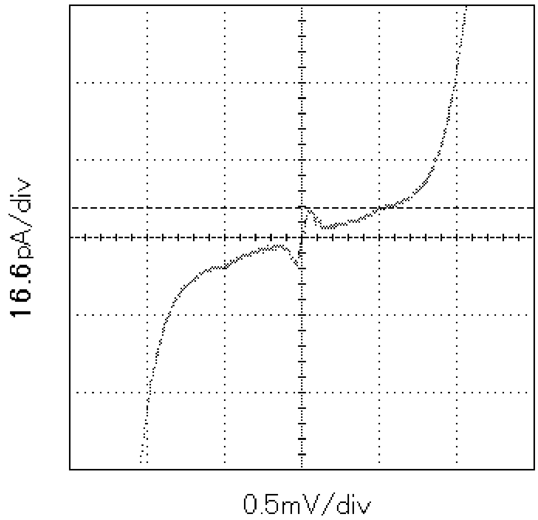

Figure 5: Bias-voltage vs. Leakage-current characteristic (magnified)

3.1.2 I-T characteristic

Figure 6 shows the leakage current as a function of temperature of the single SIS junction. In this figure, the fitted curve indicates temperature dependence of the leakage current associated with thermal excitation of Cooper-pair. We can see that the leakage current at 0.3 K decreases

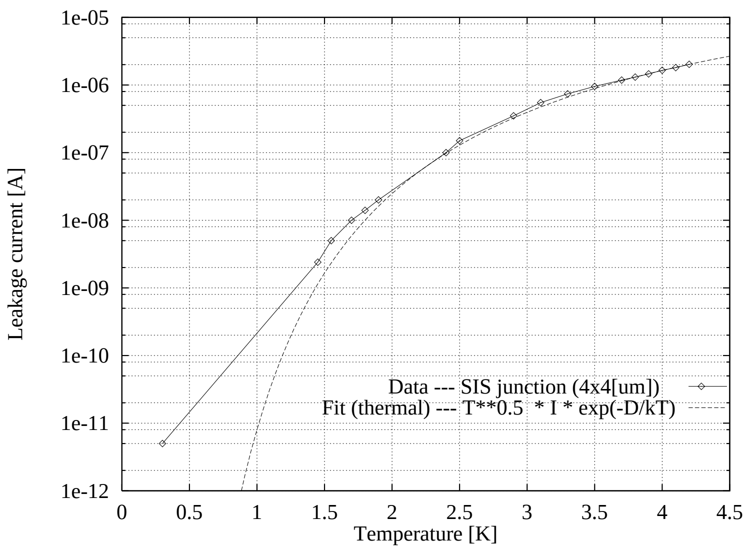

Figure 6: Temperature vs. Leakage-current characteristic

about 6 orders of magnitude as compared to the leakage current at 4.2 K. According to equation (4), when I_0 and η are 6.3 pA and 1, respectively, the expected shot-noise limited NEP is an order of 10^{-18} W/$\sqrt{\text{Hz}}$ @650 GHz. This measurement suggests that the operating temperature of less than 0.9 K is required to achieve NEP of an order of 10^{-18} W/$\sqrt{\text{Hz}}$, although we do not have measured value around 0.9 K.

3.1.3 Noise characteristic

Figure 7 shows the current noise as a function of frequency. The measured current noise is about 1.8 $\text{fA}/\sqrt{\text{Hz}}$ at white-noise level. This current noise is consistent with the shot-noise limited value calculated using I_0 at 0.3 K . Using the equation (4), the noise equivalent power (NEP) can be 4×10^{-18} $\text{W}/\sqrt{\text{Hz}}$.
Because the 300K atmospheric background limited NEP is an order of 10^{-16} $\text{W}/\sqrt{\text{Hz}}$, this detector NEP is sufficient for ground-based observations.

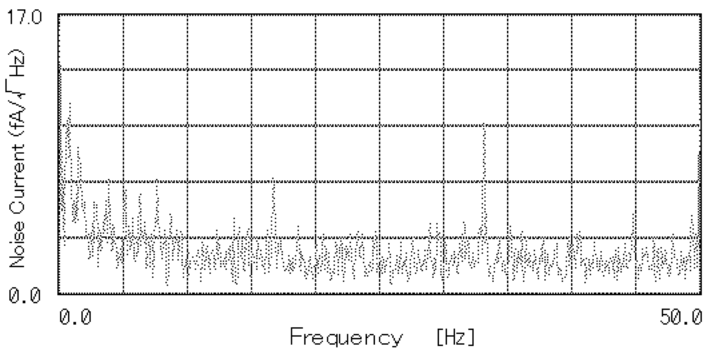

Figure 7: Noise Characteristic

3.2 Design of submillimeter-wave camera

3.2.1 SIS Distributed Junction Array

Using a low critical current density junction, the bandwidth of the detector becomes much narrower compared to the atmospheric window. For instance, when our single SIS junction

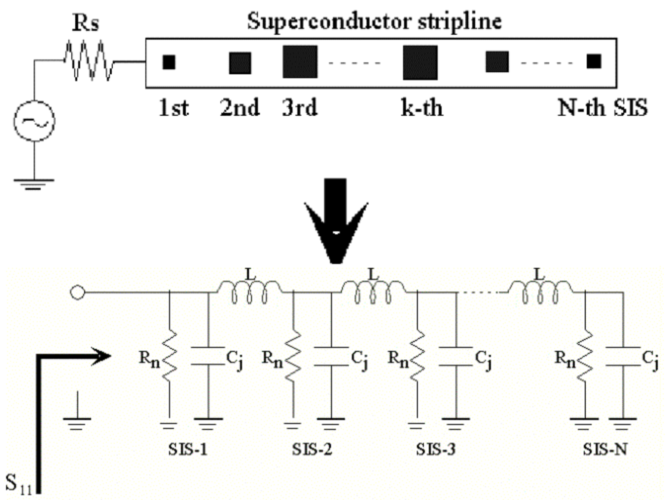

Figure 8: Equivalent circuit of SIS Distributed Junction Array

with $J_c = 1$ kA/cm^2 have the normal state resistance $R_n \simeq 220\ \Omega \cdot \mu$m^2 and the capacitance $C_j \simeq 85$ fF/μm^2, the $\omega R_n C_j$ product is about 75 at 650 GHz, when bandwidth is narrower about one order of magnitude as compared to atmospheric window around 650 GHz. Therefore, We need to fabricate the SIS junction with higher J_c ($\geq$1 kA/cm^2) and smaller size ($\simeq$ a few μm^2). To realize the much wider frequency coverage, we adopt distributed junction array proposed by Shi et al.(1997) [7] and inhomogeneous distributed junction array by Takeda et al.(2000) [8], that each SIS junction connected in parallel through superconducting micro-strip as shown in Figure 8. To optimize its frequency response, we modeled the distributed junctions with the equivalent circuits, and calculate its coupling efficiency. We adopt that the number of junctions is 6, each junction size is 4 μm^2 and J_c is 1 kA/cm^2. Each junction has same size, because we want to suppress DC Josephson current at same magnetic field. The frequency response is tuned by different inductance of each micro-strip line. According to our numerical calculations, the optimized input coupling efficiency is more than 0.5 with a bandwidth of more than 60 GHz where the observing center frequency is 650 GHz as shown in Figure 9. This frequency coverage is comparable to the bandwidth of good atmospheric transmission at 650 GHz.

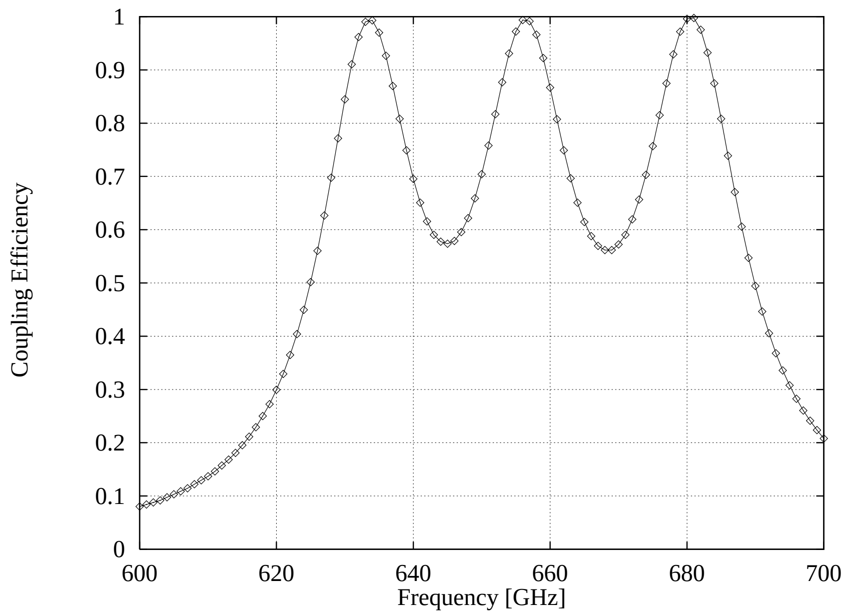

Figure 9: Coupling efficiency of SIS Distributed Junction Array

3.2.2 Superconducting direct detectors

Figure 10 shows the design of superconducting direct detectors based on the simulation in the previous section. Table 1 summarizes the design parameters. It is necessary for wide field and deep imaging observation to realize large two-dimensional imaging array. We adopt the log-periodic planner antenna, which have wide frequency bandwidth and can be fabricated easily in large number of pixels. It is designed to cover the frequency range of 200-1600 GHz and F-ratio of 1 for the compact optics.

The 6 junctions are fed symmetrically at both wings of a log-periodic antenna, which has the diameter of about 420 μm on sapphire substrate. A piece of hyper-hemispherical lense made of Sapphire focuses the input to the log-periodic antenna. The impedances of the log-periodic antenna and SIS distributed junction array are 41.3 and 9.1 Ω respectively, so

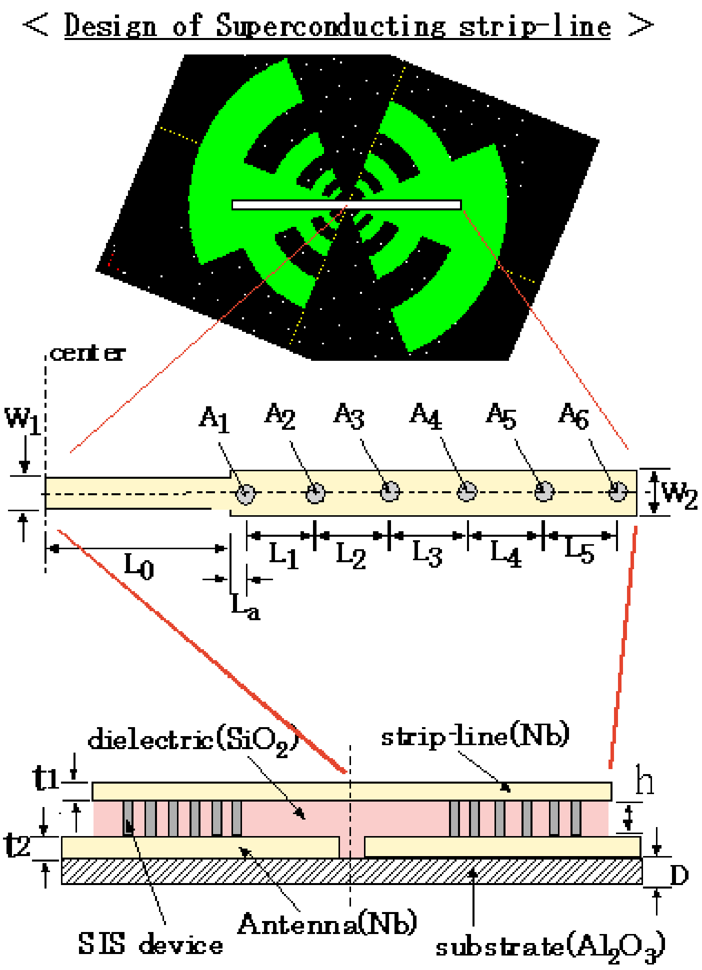

Figure 10: Design of superconducting direct detectors

that these two components are connected by an impedance transformer with a characteristic impedance of $\sqrt{41.3 \times 9.1} = 19.4\ \Omega$ with a quarter wavelength long($= 60.5\ \mu$m). At present, we have prepared the photo-masks in collaboration with RIKEN(The Institute of Physical and Chemical Research, Japan). Figure 11 shows the design of the photo-mask, on five millimeter square silicon wafer.

4 Summary and Future

We have designed and are fabricating submillimeter-wave focal plane array based on superconducting direct detectors for Atacama Submillimeter Telescope Experiment (ASTE). We have designed the antenna-coupled SIS junctions with a relatively low current density ($\simeq$ 1 kA/cm^2), low leakage current($\leq$10 pA at 0.5mV-bias voltage) and small size ($\simeq 4\ \mu$m^2). It is estimated that NEP is an order of 10^{-18} W/$\sqrt{\text{Hz}}$ using SIS junctions at less than 0.9 K. We have designed the antenna-coupled Nb junction with 3x3 pixels, and its fabrication and evaluation are underway. We are going to fabricate 10x10 pixels imaging array with superconducting direct detectors for the ASTE telescope in Atacama.

parameter name	parameter		unit
Width of Impedance Transformer	W1	3.0	μm
Width of DJ Array	W2	5.0	μm
Size of SIS junction	A1-A6	4.0	μm^2
Length of Inductance	L0	60.5	μm
	La	3.0	μm
	L1	4.6	μm
	L2	20.0	μm
	L3	4.8	μm
	L4	30.0	μm
	L5	4.6	μm
Thickness of upper strip-line(Nb)	t1	0.2	μm
Thickness of lower antenna(Nb)	t2	0.2	μm
Thickness of dielectric(SiO_2)	h	0.2	μm
Thickness of substrate(Al_2O_3)	D	$\simeq$ 500	μm

Table 1: Design parameters of a superconducting direct detector

Acknowledgments

The ASTE project is managed by Nobeyama Radio Observatory, National Astronomical Observatory of Japan. The low leakage SIS junction presented in this paper is provided by Oxford Instruments. The photo-mask with antenna-coupled SIS junction is made in RIKEN(The Institute of Physical and Chemical Research, Japan). We are gratful to these institutes.

References

[1] Photon detection in nonlinear tunneling devices, J.R. Tucker and M.F. Millea, *Appl. Phys. Lett.*, **33**, pp.611-613(1978).

[2] Superconductor-insulator-superconductor quasiparticle junctions as microwave photon detectors, P.L.Richards, T.M.Shen, R.E. Harris and R.L. Lloyd, *Appl. Phys. Lett.*, **36**, pp.480-482(1979).

[3] Development of Submillimer-wave Camera for Atacama Submillimeter Telescope Experiment, H.Matsuo, M.Takeda, T.Noguchi, S.Ariyoshi, H.Akahori, *Advanced Technology MMW,Radio, and Terahertz Telescopes, Proc.SPIE*, **4015**, pp.228-236(2000).

[4] Development of Submillimer-wave Camera for Atacama Submillimeter Telescope Experiment, H.Matsuo, S.Ariyoshi, H.Akahori, M.Takeda and T.Noguchi, *IEEE Trans. Appl. Supercond.*, in press (2000).

[5] FTS Measurements of Submilimeter-Wave Atmospheric Opacity at Pampa la Bola II : Supra-Terahertz Windows and Model Fitting, S.Matsushita, H.Matsuo, J.R.Pardo and S.J.E.Ranford, *Publ. Astron. Soc. Japan*, **51**, pp.603-610(1999).

[6] Quantum detection at millimeter wavelengths, J.R.Tucker, M.J.Feldman, *Review of modern physics*, **57**, No.4(1985).

[7] Analysis of the bandwidth performance of SIS mixers with Distributed Junction Arrays, S.-C.Shi, T.Noguchi and J.Inatani, *Proc. of Eighth Int. Symp. on Space Terahertz Tech.*, pp.81-90(1997).

[8] Predicted Performance of Superconductor-Insulator- Superconductor Mixers with Inhomogeneous Distributed Junction Arrays, M.Takeda, T.Noguchi and S.-C Shi, *Jpn. J. Appl. Phys.*, **39**, pp.5095-5098(2000).

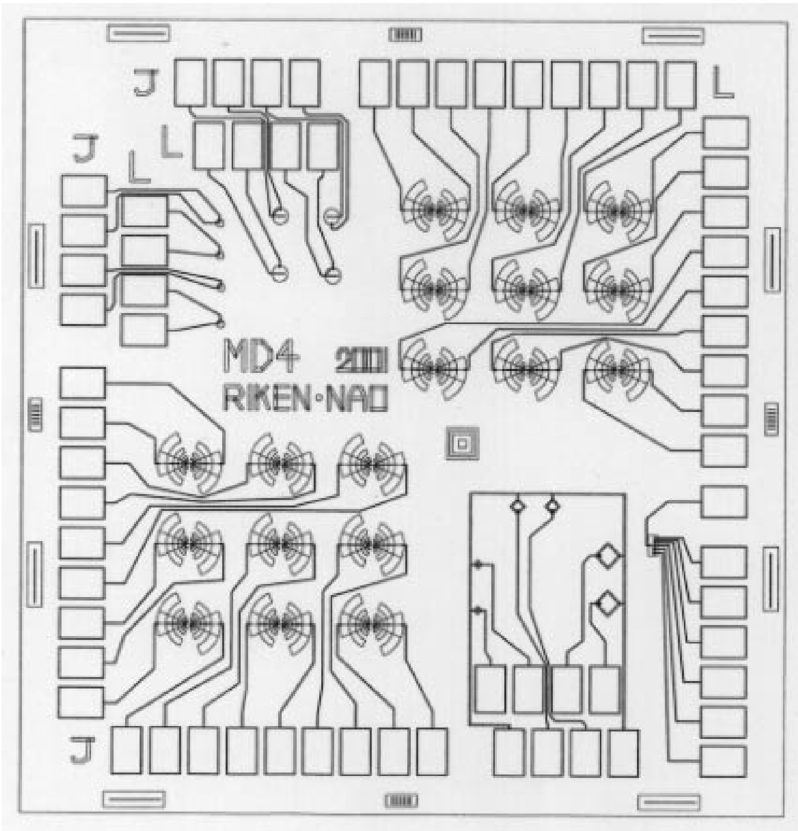

Figure 11: Mask design for 3x3 array