A 200–285-GHz Waveguide SIS Mixer With an Inhomogeneous Distributed Junction Array

Masanori Takeda and Takashi Noguchi

***Abstract*—In this paper, we present the experimental results of a waveguide superconductor–insulator–superconductor (SIS) mixer with an inhomogeneous distributed junction array. The mixer consists of five Nb–AlOx–Nb SIS junctions with different dimensions distributed on a superconducting microstrip. The critical current density of the fabricated junctions was 3100 A/cm^2. Detailed measurements of the receiver noise temperature have been made in the frequency range from 190 to 284 GHz at 4.2 K. A double-sideband (DSB) receiver noise temperature of $5\hbar\omega/k$ was obtained in the frequency range from 202 to 284 GHz and the lowest DSB receiver noise temperature of 46 K was obtained at 210 GHz.**

***Index Terms*—Broad-band, distributed junction array, heterodyne receiver, noise temperature, submillimeter, superconductor–insulator–superconductor (SIS) mixer, waveguide.**

I. Introduction

It is well known that superconductor–insulator–superconductor (SIS) quasi-particle tunnel junctions can be operated as the most sensitive mixer available at millimeter and submillimeter wavelengths. SIS mixers with broad-band performance are highly desirable for use in complex systems such as interferometer arrays and multibeam receivers. Though Kooi *et al.* developed a low-noise receiver that operated in the frequency range from 202 to 290 GHz using two mechanical tuning elements [1], it is quite inconvenient to adopt such mechanically tuned mixers to actual receivers. Some tuneless or fixed tuned broad-band SIS mixers have been reported to date [2], [3]. In those conventional SIS mixers using a single SIS junction or series junction array, the bandwidth is strongly dependent on the critical current density of the junction, as SIS mixers with broader bandwidth performance require a higher critical current density. Unfortunately, a high critical current density may have various disadvantages such as large sub-gap leakage current and a reduction of the yield of junctions in fabrication [4]. These will become more serious problems as the signal frequency increases.

Two different types of broad-band SIS mixers having junctions with low critical current density have been proposed. One is an SIS mixer made of a nonlinear thin-film transmission line [5]. It has been shown that the required critical current density of this type of SIS mixer to achieve a reasonable bandwidth can be lowered in contrast with the conventional single-junction SIS mixers. The receiver noise temperature is frequency independent over a broad bandwidth. However, this type of SIS mixer has a very small linewidth ($\sim$0.1 μm) and requires the use of electron-beam lithography for fabrication.

The other type of mixer is the SIS mixer with a distributed junction array, which consists of a number of junctions with identical dimensions homogeneously distributed on a superconducting microstrip [6], [7]. This type of SIS mixer can overcome the difficulty of fabrication of the former. However, it has been found that a large increase in noise and degradation of the conversion gain at certain frequencies occurs in the SIS mixer unless the number of junctions or the critical current density is increased.

We proposed a new type of broad-band SIS mixer with an inhomogeneous distributed junction array to overcome the above-mentioned problems [8]. This mixer uses different dimensions for the junctions and spacings between adjacent junctions. In the theoretical investigation, we demonstrated that the amplitude of the increase of noise, which always occurs at certain frequencies in homogeneous distributed junction arrays, is considerably reduced in SIS mixers with inhomogeneous distributed junction arrays, and that the number of junctions can be further reduced from that of the homogeneous distributed junction array if the mixing properties of both are nearly the same. Following theoretical prediction, we fabricated and tested SIS mixers with inhomogeneous distributed junction arrays. In this paper, the experimental results of the mixing properties of a waveguide SIS mixer with an inhomogeneous distributed junction array in the frequency range from 190 to 284 GHz are described.

II. Mixer Design

The inhomogeneous distributed junction array consists of multiple junctions having different dimensions located on a superconducting microstrip where the spacings between adjacent junctions are different. We designed the inhomogeneous distributed junction array of five Nb–AlOx–Nb junctions with a junction critical current density of 3000 A/cm^2 in the frequency range from 190 to 300 GHz. The dimensions of the junctions and the spacings between adjacent junctions were optimized so as to minimize the reflection coefficient at the input port of the array in a given signal frequency range using microwave computer-aided design (CAD) (Microwave Design System).[1] To simplify the calculation, we assumed that every SIS junction could be represented by a combination of normal-state resistance and geometrical capacitance connected in parallel. The specific capacitance of an SIS junction was assumed to be 90

[1]Hewlett-Packard Company, Palo Alto, CA.

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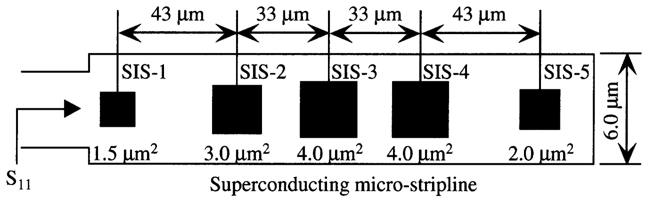

Fig. 1. Schematic representation of an inhomogeneous distributed junction array with five junctions.

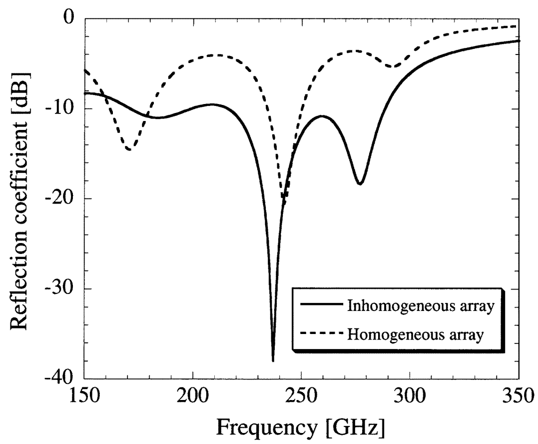

Fig. 2. Calculated reflection coefficient for inhomogeneous (solid line) and homogeneous (dashed line) distributed junction arrays with five junctions.

fF/μm^2. In the determination of the dimensions and spacings, there are many possible sets of dimensions and spacings that satisfy the condition of the optimization for the reflection coefficient. From among those sets of dimensions and spacings, we chose the best one by trial and error carrying out a noise calculation.

The schematic representation of an optimized inhomogeneous distributed junction array is shown in Fig. 1. The normal-state resistance of the inhomogeneous distributed junction array is 5.0 Ω. Fig. 2 shows the reflection coefficients at the input of the inhomogeneous distributed junction array and homogeneous distributed junction array, which consists of five junctions having the same dimensions and the same spacings between adjacent junctions as a function of frequency. The dimensions of junctions and spacings between adjacent junctions in the homogeneous distributed junction array were set to be 1.5 μm^2 and 67 μm, respectively. As shown in Fig. 2, the reflection coefficient was considerably improved over the given frequency range in the inhomogeneous distributed junction array compared with the homogeneous distributed junction array. Since the improvement of the reflection coefficient is related to the improvement of the mixer conversion gain, it is predicted that the inhomogeneous distributed junction array behaves as a more excellent SIS mixer than the homogeneous distributed junction array.

The calculated results of the receiver noise temperature of the SIS mixers with the inhomogeneous distributed junction array, homogeneous distributed junction array, and a single junction are shown in Fig. 3. In the calculation, it was assumed that they had the same critical current density, which was 3000 A/cm^2. The calculations were based on the quantum theory of mixing modified

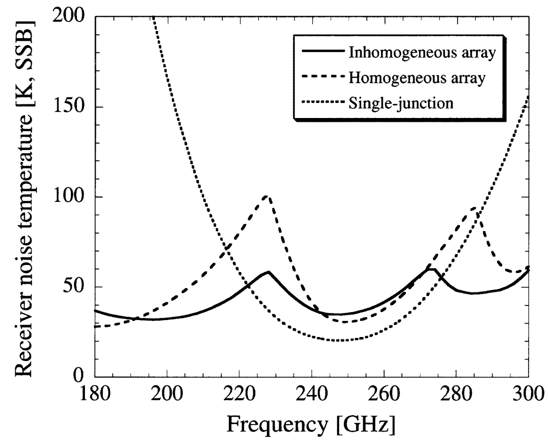

Fig. 3. Calculated receiver noise temperature for inhomogeneous (solid line), homogeneous (dashed line) distributed junction arrays with five junctions, and a single-junction (doted line) as a function of frequency. All have the same critical current density of 3000 A/cm^2. The IF frequency and noise temperature of the IF network were assumed to be 1.5 GHz and 10 K, respectively.

for the SIS mixers with distributed junction arrays [8], [9]. In the analysis, we have adopted the quasi-five-port approximation, in which five sidebands are allowed [10]. In the calculation, the IF and the noise temperature of the IF network were assumed to be 1.5 GHz and 10 K, respectively, and the loss and noise temperature of the input circuit are not included. It was found that SIS mixers with the distributed junction arrays showed a low noise temperature over a broader bandwidth compared with the single-junction SIS mixer if their junction critical current densities were the same. In the SIS mixer with the homogeneous distributed junction array, the receiver noise temperature was seriously increased at certain frequencies. The amplitude of the noise increase can be considerably suppressed in the SIS mixer with the inhomogeneous distributed junction array.

It is possible to reduce a distributed junction array to an equivalent single junction, as in the case of a series array, and the mixer noise temperature of distributed junction arrays would depend only weakly, if at all, upon the number of junctions, unless a total length of a distributed junction array becomes enough longer than a wavelength at an operation frequency. Therefore, we would speculate that the limitation of noise temperature in distributed junction arrays with a moderate number of junctions is given by $\hbar\omega/k$, where $\hbar, \omega$ and k are the reduced Plank's constant, angular frequency, and Boltzmann's constant, respectively. It is possible to design complex tuning circuits, which have multiple resonances with single-junction SIS mixers. In fact, most of the published broad-band SIS mixers have at least two resonant frequencies. The distributed junction arrays inherently have multiple resonances, whose number is dependent on the number of junctions. Consequently, broad-band operation can be achieved in the distributed junction array. It is possible to design the inhomogeneous distributed junction array so that the resonances continuously occur over the bandwidth. The fluctuations of noise temperature and conversion gain can then be reduced. The detailed analysis of the distributed junction arrays is described in [6] and [8].

The waveguide mount of the 190–300-GHz band SIS mixer is a scaled version of that used in an experimental 470-GHz

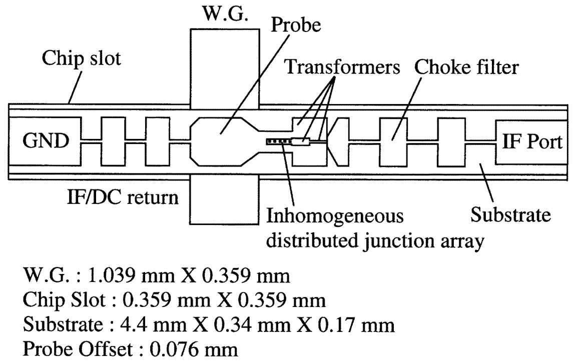

Fig. 4. Schematic layout of the SIS mixer chip.

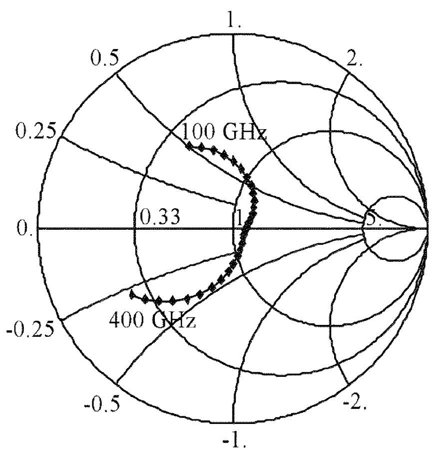

Fig. 5. Calculated RF embedding impedance seen from the input of the array as a function of frequency. The Smith chart is normalized to the normal-state resistance of the array (5 Ω).

waveguide SIS mixer with a scaling factor of 1.95 [11]. A waveguide probe, which converts the RF signal from the waveguide mode to the microstrip mode without loss over a broad band, RF matching circuit, SIS junctions, RF choke filter, and IF/dc return path are integrated with the SIS mixer chip. The layout of the mixer chip is shown in Fig. 4. The embedding impedance at the input of the array normalized to the normal-state resistance of the SIS junction array is plotted on a Smith chart in Fig. 5. It was found that the locus of the normalized impedance was concentrated around unity.

For the SIS mixer complete with an RF choke filter, the static (low-frequency) capacitance at the IF port on the substrate is 1604 fF. This consists of 76 fF from the RF choke, 223 fF from the RF matching circuit, and 1305 fF from the array of SIS junctions. The low-frequency inductance of the IF circuit is 556 pH, of which only 22 pH is from the RF matching circuit. Since the cutoff frequency of the IF circuit can estimated at 5.3 GHz, the IF frequency of 1.5 GHz is well available in the experiment.

III. Junction Fabrication

The Nb–AlOx–Nb SIS junctions were fabricated on a crystalline quartz wafer 35 mm in diameter and 0.3 mm in thickness. The fabrication process was basically selective niobium etching process (SNEP) incorporating anodization around junctions in order to suppress the leakage current. The trilayer of Nb–AlOx–Nb was formed by dc sputtering and thermal oxidation in an oxygen atmosphere without breaking the vacuum. The Nb and Al were sequentially deposited in the sputtering chamber and the Al was oxidized in a load-locked chamber with a 350-mtorr 10% O_2–Ar mixture for 30 min. The thickness of the base and counter Nb were 200 and 100 nm, respectively, and the thickness of the AlOx was around 10 nm. After the liftoff of the photoresist, a 70-nm SiO_2 layer was deposited on the whole wafer by RF sputtering to prevent the surface of the top Nb of junctions from being oxidized in the later anodization process. An SIS-junction mesa was formed by reactive ion etching (RIE) with CF_4. In order to avoid short circuits at the junction edges, the periphery of the junctions were heavily anodized and then 270-nm SiO_2 and 90-nm Al_2O_3 layers were deposited sequentially. After the liftoff of the photoresist, the 70-nm SiO_2 layer was removed by the RIE, and Ar plasma cleaning was performed to remove an oxidized layer of the surface of the counter Nb. Finally, the wiring Nb layer having a thickness of 675 nm was deposited and patterned.

The critical current density and normal-state resistance of the fabricated Nb–AlOx–Nb SIS array were 3100 A/cm^2 and 6.2 Ω, respectively. The discrepancy between the fabricated and designed values of the normal-state resistance of the array can be explained by the fact that the dimensions of the fabricated junctions are a little less than those of the designed ones. An extremely small sub-gap leakage current and strong nonlinearity are observed in the *I–V* curve of the fabricated array, in which the ratio of the sub-gap resistance at 2.0 mV to the normal-state resistance was around 20 at 4.2 K.

IV. Experimental Results

The receiver response as a function of frequency was measured by a Fourier transform spectrometer (FTS) using the fabricated Nb–AlOx–Nb SIS mixer as a direct detector prior to the estimation of receiver noise temperature. The FTS consists of a Martin–Puplett interferometer using wire grids as polarizers and an Hg arc lamp as a broad-band radiation source [12]. The mixer was cooled by liquid He in a cryostat and was set in front of the Teflon window of the FTS. The FTS response is directly related to the input coupling efficiency of the RF signal to the mixer. It is well known that the shape of the FTS response as a function of frequency correspond to the receiver noise temperature as a function of frequency and that the minimum receiver noise temperature can be obtained at the frequency where the maximum peak of the FTS response is observed. The FTS responses of the inhomogeneous and homogeneous distributed junction arrays are shown in Fig. 6. Although the sharp dips were observed in the homogeneous distributed junction array at frequencies around 210 and 280 GHz, where it was predicted that the receiver noise temperature would increase, those are considerably improved in the inhomogeneous distributed junction array, as predicted in the theoretical analysis. It was found that the input coupling efficiency of the inhomogeneous distributed junction array was considerably improved over a wide band compared with that of the homogeneous distributed junction array.

The noise temperature was calculated by the conventional Y-factor method using the black-body radiation on 295- and 80-K loads as the RF signal source. A schematic layout of the

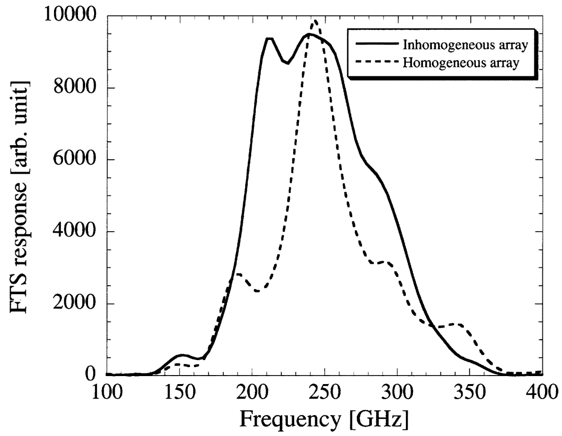

Fig. 6. FTS responses of the fabricated inhomogeneous (solid line) and homogeneous (dashed line) distributed junction arrays as a function of frequency.

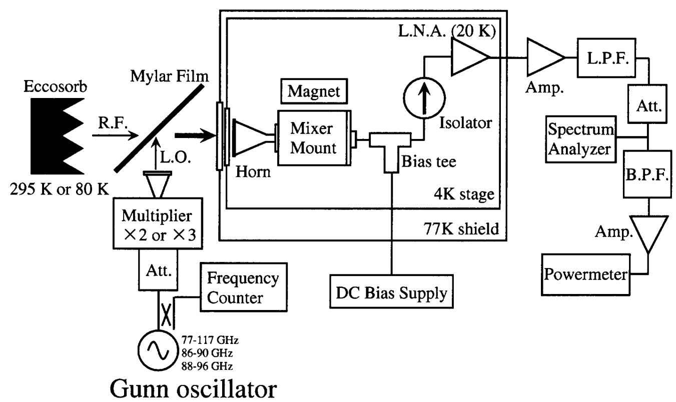

Fig. 7. Schematic layout of noise measurement system.

noise measurement system is shown in Fig. 7. The RF signal was quasi-optically coupled to the local oscillator (LO) signal through a 50-μm-thick Mylar film and was guided to the mixer mount cooled to 4.2 K through a vacuum window of 25-μm-thick Mylar film and a corrugated feed horn, which was connected to the mixer mount through a tapered adapter. A doubler with a Gunn oscillator at 77–117 GHz and a tripler with Gunn oscillators at 86–90 and 88–96 GHz were used as LO sources and dc bias was supplied to the mixer through a bias tee. A permanent magnet attached to a sidewall of the mixer mount in order to suppress the Josephson current. The IF output signal was firstly amplified by a high electron-mobility transistor (HEMT) amplifier cooled to around 20 K with a bandwidth of 500 MHz centered at 1.5 GHz, without an IF impedance transformer, through an isolator at 4.2 K, and then amplified by a room-temperature post-amplifier. The IF signal was finally fed to either a spectrum analyzer or a power meter through an adjustable attenuator in order to calibrate the IF output power.

The *I–V* characteristic and IF power as a function of bias voltage at an LO frequency of 210 GHz are shown in Fig. 8. When an LO signal was applied, photon-assisted tunneling steps of approximately 0.87-mV intervals were clearly observed. Two curves of IF output powers (P_{295} and P_{80}) were obtained with black-body sources at 295 and 80 K as the RF signals. The receiver noise temperature was derived from Y-factor P_{295}/P_{80}, defined as the ratio

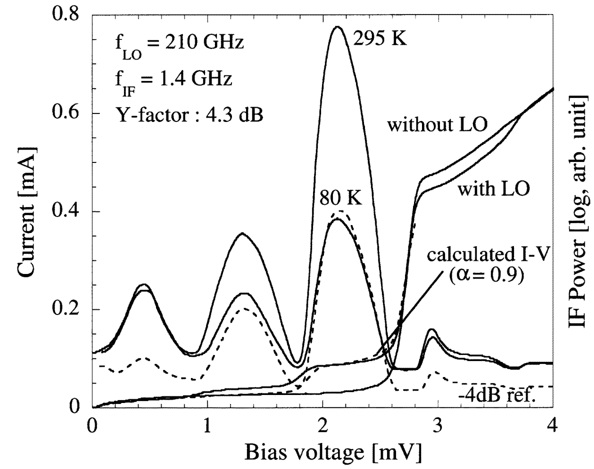

Fig. 8. Measured dc current–voltage characteristics (solid lines) of the inhomogeneous distributed junction array with and without an LO at 210 GHz, and a calculated current–voltage characteristic (dashed line) with an LO at 210 GHz with α of 0.9. Also shown is the receiver IF output power as a function of bias voltage for hot- and cold-input loads. A maximum Y-factor of 4.3 dB was obtained at a bias voltage of 2.1 mV.

of the IF output powers. A 4-dB reference curve, which is the IF output power for the 295-K input in association with an IF attenuation of 4 dB, is also presented to calibrate the ratio of the two IF output-power levels. In Fig. 8, a maximum Y-factor of 4.3 dB was obtained at a bias voltage of 2.1 mV, and this gives a double-sideband (DSB) receiver noise temperature of 47 K, which is about five times as large as the photon temperature $\hbar\omega/k$. No serious degradation of the receiver noise temperature was found in the band of the HEMT amplifier.

We estimated the required LO power for the array by the comparing the theoretical calculation and measured *I–V* curve. When the reduced LO voltage $eV_{\rm LO}/\hbar\omega$ was 0.9, the height of the photon-assisted tunneling step corresponded very well at 210 GHz to both, as shown in Fig. 8. Since the input resistance of this array is 6.2 Ω, the required LO power to pump the array at 210 GHz can be estimated as 49 nW, but this does not included the loss due to the input circuit and waveguide. This value is substantially the same for the single-junction SIS mixers with high critical current density.

The receiver noise temperature in the heterodyne measurement and FTS response as a function of frequency are shown in Fig. 9. These measurements were performed using two different corrugated feed horns. One had a WR-4 (1.01-mm wide and 0.51-mm high) and the other had a WR-3 output port (0.83-mm wide and 0.42-mm high). It was found that the bandwidth characteristics of the receiver noise temperature were in good agreement with those of the FTS response. In the FTS measurement using the WR-4 corrugated feed horn, the 3-dB bandwidth is from 195 to 292 GHz and the receiver noise temperature is about five times the photon temperature in the band. One may think that the SIS mixer with the inhomogeneous distributed junction array is inferior to that with the homogeneous distributed junction array reported in [7], which shows about four times the photon temperature in the minimum noise temperature. The receiver noise temperature of the SIS mixer with the inhomogeneous distributed junction array, however, is independent of frequency in the band for the sacrifice of the minimum noise temperature, whereas that

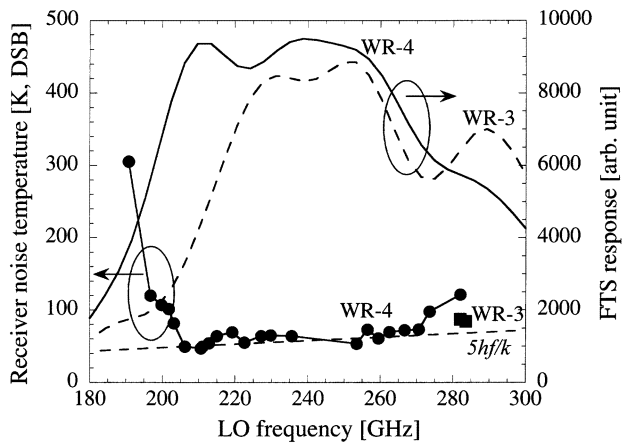

Fig. 9. Receiver noise temperature and FTS response of the SIS mixer with the inhomogeneous distributed junction array using a corrugated feed horn with the output ports of WR-4 and WR-3 waveguides as a function of frequency.

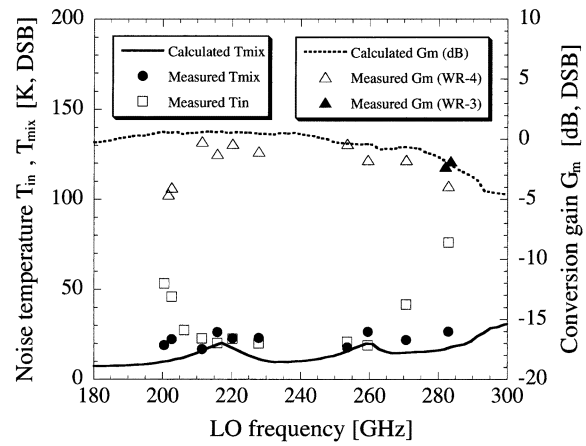

Fig. 10. Input noise temperature $T_{\rm in}$, mixer noise temperature $T_{\rm mix}$, and conversion gain G_m of the SIS mixer with the inhomogeneous distributed junction array as a function of frequency. Comparison between the theoretical and experimental performance of the SIS mixer with the inhomogeneous distributed junction array is also shown.

of the homogeneous distributed junction array extremely fluctuate in the band. This relation between the minimum noise and the fluctuation is similar to behaviors of Chebyshev filters. The frequency-independent performance of the receiver noise will be useful in the practical applications such as astronomical and atmospheric observations. The degradation of the FTS response and receiver noise temperature at the lower frequencies was mainly caused by the degradation of the input coupling efficiency in the waveguide-to-microstrip transition.

However, in the measurements performed using the WR-4 corrugated feed horn, degradation of the FTS response and receiver noise temperature was found above 270 GHz. In order to find the cause of the degradation, we estimated a noise temperature due to input losses, mixer noise temperature, and conversion gain using standard measurement techniques [13], [14]. Fig. 10 shows the estimated conversion gain and input and mixer noise temperatures, as well as the calculated conversion gain and mixer noise temperature as a function of frequency. In the calculation, the dimensions of junctions used those of the fabricated mixer. The calculation results are in reasonably agreement with the measured data. The difference between the calculated and measured conversion gains at lower frequencies occurs due to the fact that the input losses are not included in the calculation. From the measurement, the IF network noise of 9 K was obtained. It was found that the mixer noise temperature is still low at frequencies above 270 GHz, less than 26 K (DSB) in the frequency range from 200 to 282 GHz. However, the noise temperature due to input losses considerably increased at frequencies above 270 GHz. It is well known that the conversion gain is strongly dependent on the input coupling efficiency of the RF signal to the array. It is considered that the input coupling efficiency to the array was degraded by the input RF circuit, especially in the WR-4 waveguide. Therefore, we measured the FTS response and receiver noise temperature using the WR-3 corrugated feed horn, which shows a lower loss than the WR-4 corrugated feed horn at frequencies above 270 GHz. It was found that FTS response, receiver noise temperature, and conversion gain were greatly improved at frequencies above 270 GHz, as shown in Figs. 9 and 10. A DSB receiver noise temperature about five times as large as the photon temperature can be obtained in the frequency range from 202 to 284 GHz by using WR-4 and WR-3 corrugated feed horns. From the above discussion, it is apparent that the SIS mixer with the inhomogeneous distributed junction array has a much broader bandwidth at least from 200 to 284 GHz in spite of its low critical current density. The upper and lower frequency limit for this SIS mixer cannot be clearly recognized since the frequency is usually limited by the RF input circuit, a waveguide, a feed horn, or a waveguide probe. If those limitations do not exist or can be removed by improving the input circuit, the SIS mixer will operate in the bandwidth predicted by the theoretical analysis, i.e., 190 to 300 GHz.

V. Conclusion

An Nb–AlOx–Nb SIS mixer with an inhomogeneous distributed array of junctions, which has a broader bandwidth performance than a conventional single junction mixer, has been developed. The characteristics of the SIS mixer have been experimentally studied by heterodyne and FTS measurements. The DSB receiver noise temperature is approximately five times the photon temperature in the frequency range from 202 to 284 GHz using the WR-4 and WR-3 corrugated feed horns with the output port of the WR-4 and WR-3 waveguide. The minimum noise temperature of the receiver is 47 K (DSB) at 210 GHz, which is comparable to that of the conventional single-junction SIS mixers.

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