Quasi-optical submillimeter-wave SIS mixers with NbN/AlN/NbN tunnel junctions

Yoshinori UZAWA, Zhen WANG, and Akira KAWAKAMI

Kansai Advanced Research Center, Communications Research Laboratory,
Ministry of Posts and Telecommunications, 588-2 Iwaoka, Iwaoka-cho, Nishi-Ku,
Kobe, 651-24 JAPAN

Abstract

We report on low-noise heterodyne mixing with NbN/AlN/NbN tunnel junctions in the submillimeter-wave region for the first time. The receiver consists of the quasi-optical NbN SIS mixer with an integrated tuning circuit in which a radial short stub tuner is incorporated to resonate out the junction capacitance for RF matching and a balanced IF circuit for broadband IF matching. The prepared NbN SIS junction has a current density of 20 kA/cm^2 and is about 1 μm in diameter, supplying a small $\omega C_J R_N$ product ($\omega C_J R_N$ = 3 at 300 GHz). The junctions showed good dc I-V characteristics, excellent submillimeter-wave responses and sensitive heterodyne mixing responses. From 254 to 350 GHz the average receiver noise temperature measured using by the standard Y-factor method was about 250 K (DSB) at 5 K. The lowest receiver noise temperature, 200 K (DSB), was obtained at around 303 GHz. Comparing NbN/AlN/NbN and Nb/AlOx/Nb tunnel junction performance with the same tuning circuit showed that the frequency dependence of the receiver noise temperature agreed well in the two receivers. These results suggest that our well-controlled NbN SIS junctions can be used for terahertz mixer elements instead of Nb SIS junctions.

1. Introduction

In widely used Nb SIS mixers, noise performance deteriorates rapidly at frequencies higher than about 700 GHz, which is the superconducting gap frequency of Nb [1]. All-NbN tunnel junctions with the high gap frequency of about 1.5 THz, on the other hand are promising for SIS mixers operating in the submillimeter wave region. However, it is very important that tunnel junctions have small $\omega C_J R_N$ products in the path to SIS mixers operating at high frequencies. To obtain $\omega C_J R_N = 5$ at 500 GHz, for example, the Nb junctions usually need to have an area of 1 μm^2 and a current density of 10 kA/cm^2 [2], while the NbN junctions need to have a critical current density of about 20 kA/cm^2. Thus, even though the NbN junctions have a high gap frequency, there have been no reports on their use in submillimeter-wave SIS mixers because it is difficult to fabricate high-quality NbN tunnel junctions that have a high current density. The operating frequency reported for NbN/MgO/NbN tunnel junctions is at most 205 GHz, and the receiver DSB noise temperature is about 460 K [3].

We have recently developed high-current-density NbN/AlN/NbN tunnel junctions fabricated on MgO substrates. The junctions have excellent Josephson tunneling properties and submillimeter-wave responses with a large gap voltage, small gap voltage width, small subgap leakage currents, and sharp photon-assisted tunneling steps at frequencies up to 762 GHz [4-6]. The next step is to investigate the noise performance of these junctions in the heterodyne receiver set-up at submillimeter wavelengths. In this report we demonstrate low-noise heterodyne mixing with our high-current-density NbN/AlN/ NbN tunnel junctions.

2. Mixer Design

In our experiments we used a quasi-optical structure employing a substrate lens to couple the RF radiation to the junctions. An optical micrograph of our mixer chip is shown in Fig. 1. On a 0.3-mm-thick single-crystal MgO substrate, two NbN/AlN/NbN junctions in series were integrated with a single-crystal NbN planer self-complementary log-periodic antenna and Nb tuning circuits. The procedures for fabricating the junctions are described in Ref. [4]. The antenna is placed on the back of a MgO hyperhemispherical lens. The antenna has a frequency-independent impedance of $Z_{ant} \sim 80\ \Omega$ over several octaves. The tuning circuit incorporates a radial short stub tuner. A microstrip inductance was placed in parallel with the junction for resonating out the junction capacitance by using the radial stub as an RF short circuit. A $\lambda/4$ impedance transformer was used for matching between the junction resistance and the antenna impedance. A mirror symmetrical circuit pattern, located at the feed point of the antenna, yields the antenna source impedance of $Z_{ant}/2$ for each half of the circuit. These tuning structures utilize superconducting microstriplines that use the arms of the antenna as a ground plane.

The tuning circuit was designed for $\omega C_J R_N = 4$ at 300 GHz, using a specific capacitance value of 70 fF/μm^2 estimated by measuring a dc SQUID resonant voltage step for the junctions with a current density of 10 kA/cm^2. Since we had not measured the magnetic penetration depth of NbN thin films fabricated on the SiO underlayers, we used Nb to make microstriplines for the tuning structures. The size of the Nb(300 nm)/SiO(230 nm)/NbN(200 nm) microstripline was calculated with Chang's formulas, using the London penetration depth of 84 nm for Nb [7], 180 nm for NbN [8, 9], and the dielectric constant of 5.5 for SiO.

3. Receiver Assembly

A schematic layout of the measuring system is shown in Fig. 2. The mixer chip, whose dimensions are 4 x 4 x 0.3 mm, is clamped on the flat surface of a 3-mm radius hyperhemispherical MgO lens in a mixer block made of OFHC copper. To avoid the excessive insertion losses associated with dielectric lenses, an off-set parabolic mirror made of Al was placed at the proper position in front of the MgO lens. The IF signal from the mixer was brought out, in a balanced method, at each edge of the antenna and coupled to the 1.25-1.75 GHz HEMT IF amplifier, which has a noise temperature of about 10 K. A balun transformer, using a stripline 1-2 GHz 180-degree hybrid coupler for broadband IF matching [10, 11], was used to transform the balanced signal from the mixer into an unbalanced signal for the IF amplifier.

The incoming radiation entered the dewar through a 0.5-mm-thick Teflon vacuum window. A Teflon filters cooled to 77 K and 4.2 K were used to block infrared radiation from the 4.2-K components in order to reduce thermal load and temperature gradients. The mixer block, off-set parabolic mirror, IF amplifier and hybrid coupler were attached to the 4.2-K cold plate of the dewar. The junctions were cooled to about 5 K by the conducted cooling. Local oscillator (LO) power was provided by a mechanically tunable Gunn oscillator [12], [13] followed by a Schottky varactor tripler [12], [14] and was introduced into the signal path through a 25-μm-thick mylar beam splitter. The heterodyne receiver noise measurements were made using the standard Y-factor method with room-temperature (295 K) and liquid-nitrogen-cooled (77 K) loads. A magnetic field was applied perpendicular to the junctions to suppress unwanted noise from the Josephson effect. No corrections were made for losses in front of the receiver.

4. Results and Discussion

A typical dc I-V characteristic for an array of two NbN/AlN/NbN tunnel junctions at 4.2 K is shown in Fig. 3. The Josephson critical current of the junctions is 140 μA, and the junction size is about 1 μmϕ. This give a current density of about 20 kA/cm^2 for these junctions. Even though the junctions have a very high current density, the figure shows excellent tunneling characteristics with a large gap voltage, a small gap voltage width, and a low subgap leakage current. From the normal-state resistance R_N = 22 Ω for each junction, $\omega C_J R_N$ of the junctions become about 3 at 300 GHz. These results suggest good heterodyne mixing with our NbN/AlN/NbN junctions as well as Nb/AlOx/Nb junctions. Figure 4 shows I-V characteristics for the receiver at 306 GHz with and without LO power. The receiver IF output in response to hot and cold loads is also shown in Fig. 4 as a function of bias voltage.

Photon-assisted tunneling steps were clearly observed with LO applied. The distinct IF responses to hot and cold loads show a maximum Y-factor of about 1.8, corresponding to a receiver noise temperature of 200 K (DSB). Figure 5 shows the DSB noise temperature of the receiver as a function of LO frequency. The average receiver noise temperature measured in the frequency band from 254 to 350 GHz was about 250 K, and the minimum receiver noise temperature of 200 K was obtained around 303 GHz, although the RF coupling has not yet been optimized.

To compare NbN/AlN/NbN and Nb/AlOx/Nb junction performance, we designed another tuning circuit at 270 GHz for NbN tunnel junctions. This is the same type used for Nb mixer design at 270 GHz in our previous work [15]. The tuning circuit consists of two junctions separated by an inductance [2]. This two-junction circuit achieves perfect impedance match by placing the two junctions at opposite ends of a trasmission line whose length is selected so that the net junction admittance $Y = 1/R_N + j\omega C_J$ is transformed to its complex conjugate Y*. In the two receiver configurations, the same LNA, IF system, mixer block design and cryostat were used. The difference was only the material of the substrate lens. In the Nb mixer, we used quartz as the substrate lens material. Figure 6 shows the DSB noise temperature of the two receivers as a function of LO frequency. Even though the measured noise temperatures of the NbN receiver were a little bit higher than those of the Nb receiver entirely, it is interesting to note that the frequency dependence of the receiver noise performance agreed well in the two receivers. In other words, the fabricated NbN/AlN/NbN junction parameters were well controlled within the regions for which they were designed. These results suggest that NbN tunnel junctions can be used for terahertz mixer elements.

To investigate the noise contribution to the receiver, evaluations were made using the intersecting lines technique described in Refs. [16] and [17], which showed that the losses in front of the mixer element result in an input noise contribution of about 120 K. The most likely reason for the high input loss is that the lens-coupled log-periodic antenna has a poor beam pattern due to a high level of side-lobe. In addition, there is a large reflection loss at the surface of the MgO lens, which has a high dielectric constant of 9.6. We are going to reduce the input loss by optimizing the antenna parameter with a scaled model and putting an anti-reflection coating on the MgO lens. It is expected that optimizing and improving the optical input circuits will make the receiver noise performance with our NbN/AlN/NbN tunnel junctions comparable to that of waveguide receivers with Nb/AlOx/Nb tunnel junctions.

5. Conclusion

We have fabricated and tested the first quasi-optical submillimeter-wave SIS mixers using NbN/AlN/NbN tunnel junctions integrated with a thin-film antenna and microstrip-line tuning circuits. A receiver noise temperature as low as 200 K has been achieved around 303 GHz, although the optical RF input elements have not yet been optimized. In the experiment to compare NbN/AlN/NbN and Nb/AlOx/Nb junction performance with the same receiver set-up, the noise characteristics of the NbN receiver have been very consistent with those of the Nb receiver. The performances reported here are the best ever reported for SIS mixers with all-NbN tunnel junctions, and they show that our high-current-density NbN/AlN/NbN junctions can be expected to give excellent mixing performance for terahertz SIS mixers. We are continuing to explore the fabrication of NbN/AlN/NbN tunnel junctions with NbN tuning elements and to test their noise performance at frequencies above the gap frequency of Nb.

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References

[1] J. Zmuidzinas, N. G. Ugras, D. Miller, M. Gaidis, H. G. LeDuc, and J. A. Stern, IEEE Trans. Appl. Supercond. 5, 3053 (1994).

[2] J. Zmuidzinas, H. G. LeDuc, J. A. Stern, and S. R. Cypher, IEEE Trans. Microwave Theory Tech. MTT-42, 698 (1994).

[3] W. R. McGrath, J. A. Stern, H. H. S. Javadi, S. R. Cypher, B. D. Hunt, and H. G. LeDuc, IEEE Trans. Magn. MAG-27, 2650 (1991).

[4] Z. Wang, A. Kawakami, Y. Uzawa, and B. Komiyama, Appl. Phys. Lett. 64, 2034 (1994).

[5] Y. Uzawa, Z. Wang, A. Kawakami, and B. Komiyama, Appl. Phys. Lett. 66, 1992 (1995).

[6] Z. Wang, A. Kawakami, Y. Uzawa, and B. Komiyama, IEEE Trans. Appl. Supercond. 5, 2322 (1995).

[7] R. L. Kautz, J. Appl. Phys. 49, 308 (1978)

[8] B. Komiyama, Z. Wang, and M. Tonouchi, Appl. Phys. Lett. 68, 562 (1996)

[9] Z. Wang, A. Kawakami, Y.Uzawa, and B. Komiyama, to be published in J. Appl. Phys.

[10] G. J. Laughlin, IEEE Trans. Microwave Theory Tech. MTT-24, 135 (1976).

[11] A. I. Harris, K.-F. Schuster, and L. J. Tacconi, Int. J. IR & MM Waves 14, 715 (1993).

[12] Millitech Corp., P. O. Box 109, S. Deerfield, MA 01373, U.S.A.

[13] J. E. Carlstrom Co., Chicago, IL 60613, U.S.A.

[14] Farran Technology Limited, Ballincollig, Cork, Ireland.

[15] Y. Uzawa, A. Kawakami, Z. wang, and T. Noguchi, to be published in IEICE Trans. Electron.

[16] R. Blundell, R. E. Miller, and K. H. Gundlach, Int. J. IR & MM Waves 13, 3 (1992).

[17] Q. Ke and M. J. Feldman, IEEE Trans. Microwave Theory Tech. MTT-42, 752 (1994).

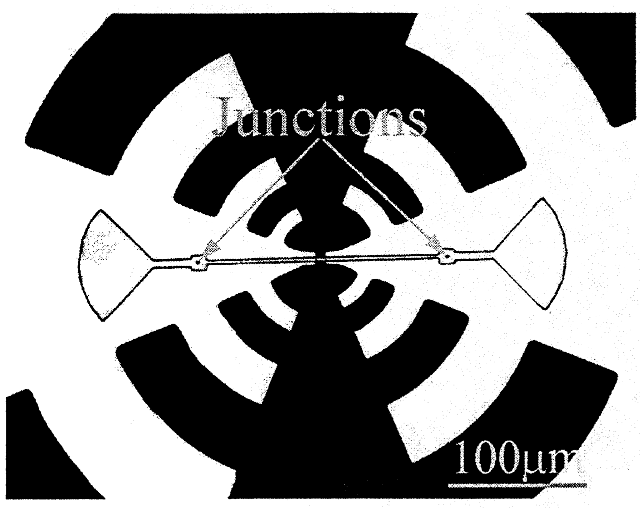

Fig. 1. Optical micrograph of NbN/AlN/NbN mixer. NbN junctions with integrated tuning circuits are fabricated with a self-complementary log-periodic antenna as their ground plane. Each junction is approximately 1 μm in diameter.

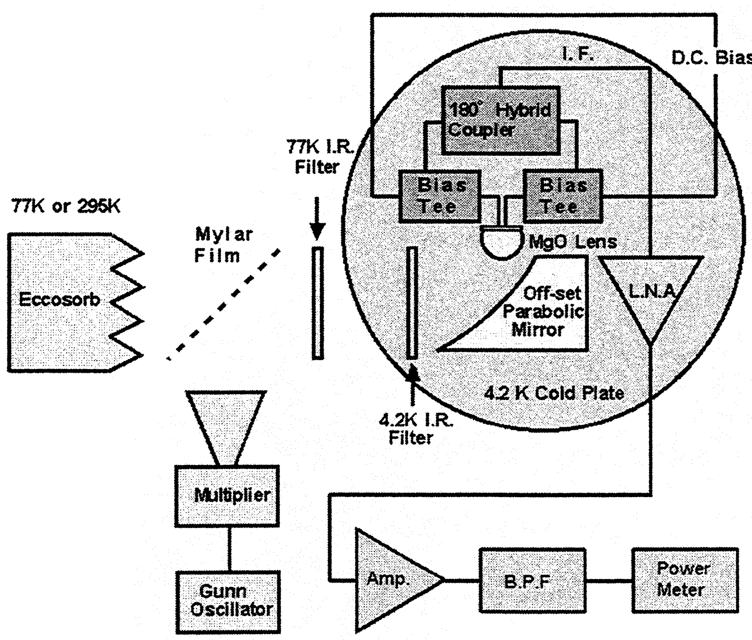

Fig. 2. Schematic layout of the measuring system. Two bias tees are used to bring out the IF signal in a balanced way from the mixer and also play a role in electrically isolating the mixer from the GND.

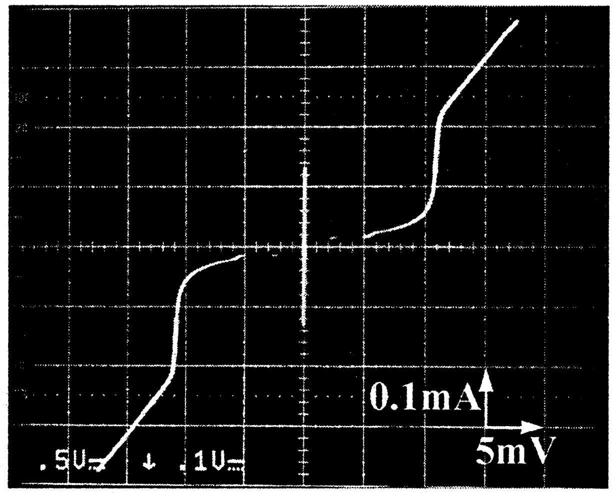

Fig. 3. I-V characteristics of two NbN/AlN/NbN junctions array. In spite of junctions having a high current density (20 kA/cm^2), good tunneling characteristics are observed.

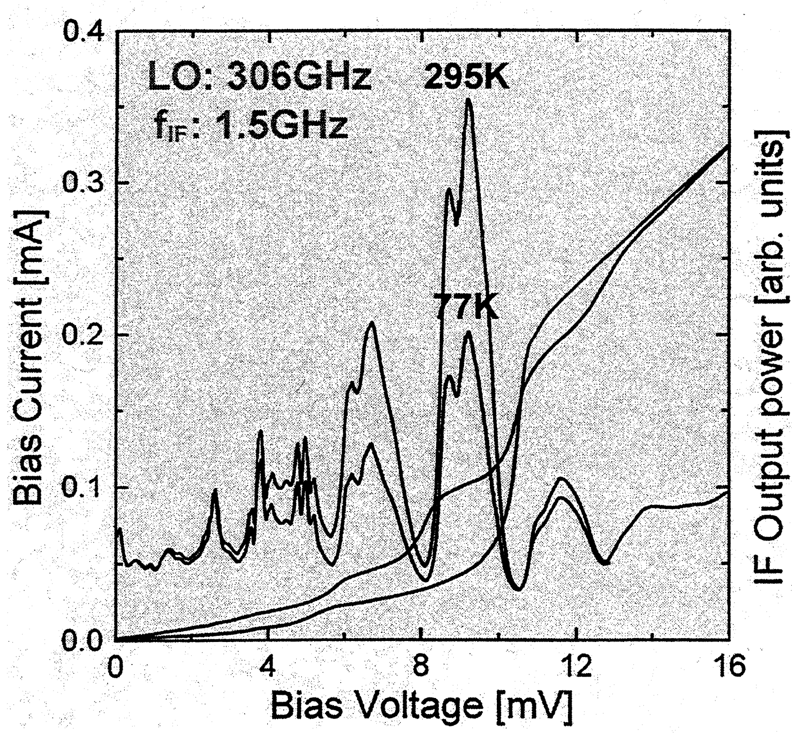

Fig. 4. Heterodyne response of the receiver at 306 GHz. Shown are the I-V characteristics for the array of two NbN/AlN/NbN tunnel junctions with and without LO power. Also shown is the IF power as a function of bias voltage for hot (295 K) and cold (77 K) loads.

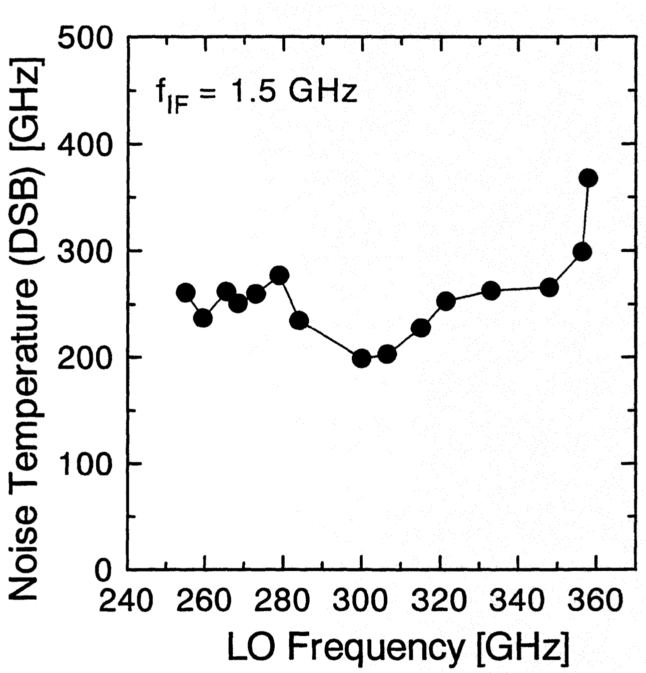

Fig. 5. DSB noise temperature of the receiver as a function of LO frequency. (No data was obtained below 254 GHz because no LO source was available.)

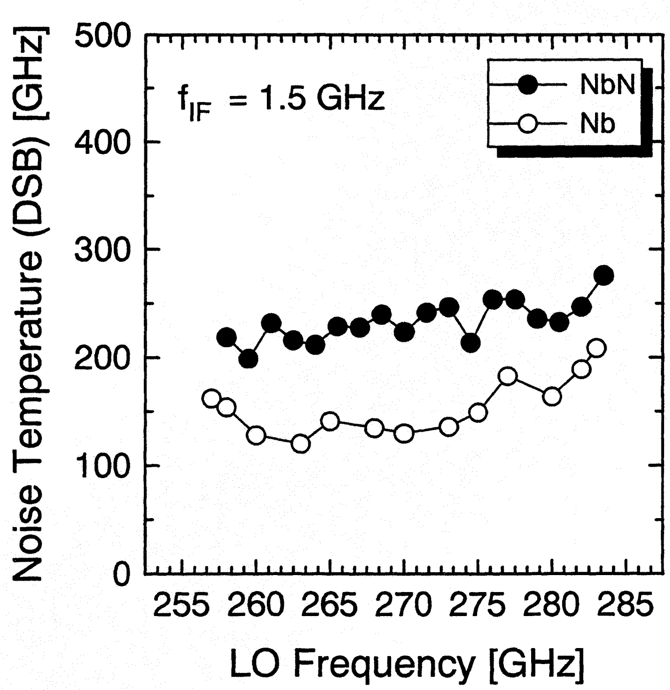

Fig. 6. DSB noise temperature of Nb receiver and NbN receiver using the same measurement set-up as a function of LO frequency.