TERAHERTZ NbN/AlN/NbN MIXERS WITH Al/SiO/NbN MICROSTRIP TUNING CIRCUITS

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, 651-2401 JAPAN
e-mail: uzawa@crl.go.jp

Abstract

We have developed a low-noise quasi-optical NbN/AlN/NbN SIS mixer that operates at terahertz frequencies. The mixer uses a MgO hyperhemispherical lens with an anti-reflection cap, a single-crystal NbN log-periodic antenna, and two-junction tuning circuits which employ Al/SiO/NbN microstriplines. The NbN/AlN/NbN junction size was about 0.9 μm in diameter, and the current density was about 45 kA/cm^2. The frequency-dependence of the receiver noise temperature was investigated by using an optically pumped far-infrared laser and a backward-wave oscillator as a local oscillator at several frequencies from 670 GHz to 1082 GHz. The experimental results showed that the center frequency was around 800 GHz, and the receiver noise temperature measured by the standard Y-factor method was 457 K(DSB) at 783 GHz including a 9 μm-thick Mylar beam splitter loss and other optical losses at the physical bath temperature of 4.2 K. This is the first SIS mixer based on NbN with low-noise performance ($12h\nu/K_B$) above the gap frequency of Nb.

1. Introduction

Until now, the most sensitive elements in heterodyne mixers are the superconductor-insulator-superconductor (SIS) tunnel junctions. Both high RF-to-IF conversion efficiency and low noise are predicted for these mixers from theory [1], and ultra-low noise SIS mixers using Nb/AlOx/Nb tunnel junctions approach $\sim h\nu/k_B$ in the millimeter and submillimeter wave regions [2]. This good performance is mainly a result of using an Nb SIS junction with a ideal current-voltage (I-V) curve and a low-loss Nb tuning circuit to resonate out the junction capacitance. However, the low gap frequency of Nb (about 700 GHz) essentially limits its application as an ultra-low noise SIS mixer in the sub-terahertz band because the onset of pair breaking above the gap frequency results in a rapid increase in RF loss in the superconducting electrodes and tuning circuits. Therefore, the mixer noise performance is greatly degraded at frequencies above the gap frequency [3]. In order to develop a low-noise SIS mixer at the terahertz band, it is necessary to make SIS junctions based on materials which have energy gap higher than that of Nb. In addition, tuning circuits have to be high-quality superconducting films with a higher gap frequency of Nb, or high-conductivity normal-metal films.

NbN is the best candidate for developing a low-noise terahertz SIS mixer because it has large gap frequencies up to 1.4 THz. We have recently developed a process to grow single-crystal NbN thin films on MgO substrates [4] and to fabricate high-quality NbN/AlN/NbN tunnel junctions that have high current densities, up to 54 kA/cm^2, for high-frequency device applications [5]. Excellent noise characteristics in the 300-GHz band habe been obtained using these junctions with low-loss Nb/SiO/NbN microstrip tuning circuits [6]. However, an all-NbN SIS mixer designed for 1 THz operation has shown poor noise performance that was much worse than the value calculated using Tucker's quantum theory of mixing with measured I-V curve of the NbN SIS junction [7]. The large amount of noise was possibly caused by the large RF losses in the tuning circuits of polycristalline NbN on the SiO. In this paper, we report on the fabrication and testing of a quasi-optical NbN/AlN/NbN SIS mixer with Al/SiO/NbN microstrip tuning circuits that is capable of terahertz frequency operation. The low-noise operation above the gap frequency of Nb was the best ever reported for SIS mixers based on NbN.

2. Mixer Design

In our mixers, a quasi-optical structure employing a substrate lens was used to couple the RF radiation to the junctions. An optical micrograph of our mixer chip is shown in Fig. 1. Four NbN/AlN/NbN junctions and an Al wiring were integrated with a single-crystal NbN log-periodic antenna on a 0.3-mm-thick single-crystal MgO substrate. The tuning circuit consisted of two junctions separated by an inductor for tuning out the junction capacitance and a $\lambda/4$ impedance transformer for matching the resistance of the two-junction circuit to the antenna impedance [8]. A mirror-symmetrical-circuit pattern at the feed point of the antenna was employed in order to reduce the antenna source impedance of about 80 Ω. We designed the tuning circuit at the center frequency of 900 GHz for the NbN/AlN/NbN tunnel junctions with the size of 0.9 μm in diameter and the current density of 30 kA/cm^2. Because the J_CR_NA product is about 350 for such a NbN SIS junction, the normal state resistance is 18 Ω. Here, J_C is the current density in kA/cm^2, R_N is the normal state resistance in Ω, and A is the area of the junction in μm^2. The capacitance of the junction was 78 fF. This value was calculated from the following expression that was obtained from measurements on our high current density NbN SIS junctions ;

$$\mathrm{Log}C_S = 1.85 + 0.16\log J_C,$$

where C_S is the specific capacitance in fF/μm^2 [9]. Al/SiO/NbN microstriplines were utilized for tuning circuits. The ground plane of the microstripline which is the arm of the antenna was a 200-nm-thick single-crystal NbN base electrode, while the microstripline was a 120-nm-thick Al wiring layer. A 250-nm thick insulator layer of SiO was used to electrically isolate the NbN/AlN/NbN tunnel junctions. The loss, slow wave factor, and characteristic impedance of the microstripline were calculated from incremental inductance considerations described in Ref. [10]. The calculation included the surface impedance of the superconducting NbN thin-film and the normal metal Al thin-film as given by the Mattis-Bardeen theory and the theory of the skin effect. Figure 2 shows the calculated loss per wavelength as a function of frequency for the Al/SiO/NbN and Al/SiO/Al microstriplines that have widths of 3-μm. The parameters used for the calculation are described in Table 1. Our calculations showed that the loss of the Al/SiO/NbN microstripline at 900 GHz was 0.86 dB/wavelength which is about 2.5 dB better than the Al/SiO/Al microstripline. This result suggests that the power coupling efficiency of the Al/SiO/NbN microstrip tuning circuits from the feed point to the junctions should be approximately twice as good as that of Al/SiO/Al microstrip tuning circuits at frequencies below the gap frequency of NbN. The calculated coupling efficiency is shown in Fig. 3. The maximum coupling efficiency achieved was about 70 % at a center frequency of 900 GHz.

3. Results and Discussion

The mixer devices were prepared by the fabrication process described in Ref. [11]. The thickness of the NbN, SiO, and Al was 180 nm, 230 nm, and 300 nm, respectively. The Al wiring layer was deposited by thermal evaporation. The conductivity of the Al film at 4.2 K was able to be estimated from the slope of the supercurrent branch of the I-V curve. We obtained a high conductivity of about 2.8 x 10^8 $\Omega^{-1}m^{-1}$, which is better than the design value by a factor of 1.4. The Josephson critical current of two junctions in parallel was 570 μA, and the junction size was about 0.9 μm in diameter. This gave a current density of about 45 kA/cm^2 for these junctions.

The heterodyne receiver noise measurements were made using the standard Y-factor method for room-temperature (295 K) and liquid-nitrogen-cooled (77 K) loads. The receiver set-up was basically the same as described in Ref. [7]. The incoming radiation entered the dewar through a 0.5-mm-thick Teflon vacuum window and Zitex infrared filters cooled to 77 K and 4.2 K, respectively. Local oscillator (LO) power was introduced into the signal path through a 9-μm or 25-μm-thick Mylar beam splitter. No corrections were made for losses in front of the receiver. Figure 4 shows I-V characteristics of the receiver at 783 GHz with and without local oscillator (LO) power. The LO source was an optically pumped CH_2F_2 laser and the 9-μm-thick Mylar beam splitter was used. The receiver IF output in response to hot and cold loads is also shown in Fig. 4 as a function of bias voltage. The gap voltage was 4.9 mV, corresponding to a gap frequency of 1.19 THz. The normal state resistance was about 13 Ω. Photon-assisted tunneling steps were clearly observed when LO power was applied. The distinct IF responses to hot and cold loads showed a maximum Y-factor of about 1.41, which corresponded to a double sideband (DSB) receiver noise temperature of 457 K. This value is the best ever reported for SIS mixers based on NbN at frequency above the gap frequencies of Nb.

The frequency dependence of the receiver noise temperature was investigated at several frequencies from 670 GHz to 1082 GHz by using the optically pumped far-infrared laser and a backward-wave oscillator (BWO) as the local oscillator. A CH_3I laser was used for the 670 GHz measurement, and the CH_2F_2 laser was used for 760 and 783 GHz measurements, respectively. The other measurements were made by using the BWO. At all measured frequencies, the 25-μm-thick Mylar beam splitter was used. Figure 5 shows the receiver noise temperature as a function of frequency. Although it can be seen from the figure that the center frequency of the receiver is around 800 GHz, which is slightly lower than the design frequency of 900 GHz, the experimental results are in good agreement with the designed tuning properties. The main reason for the shift of the center frequency can be attributed to the lower gap voltage of the fabricated device. Since the thickness of the NbN film was comparable to the London penetration depth, the slow-wave factor of the microstripline was strongly affected by the effective penetration depth near the gap frequency. In fact, the calculated center frequency of the power coupling efficiency using the actual parameters including the microstrip size, the NbN gap, the current density, and the Al conductivity, was almost the same as the experimental result. This indicates that the properties of the NbN junction and the tuning circuits were well characterized in our design process, and that the parameters of the fabricated mixer were also well controlled.

4. Conclusion

We have designed, fabricated, and tested a quasi-optical NbN/AlN/NbN SIS mixer that has low-loss Al/SiO/NbN microstrip tuning circuits and is capable of operating at terahertz frequencies. A double sideband receiver noise temperature of 457 K has been achieved at 783 GHz (above the gap frequency of Nb). The frequency dependence of the receiver noise agreed well with the calculated frequency dependence. These results suggests that our well controlled NbN SIS mixer is capable of low-noise operation at frequencies below the NbN gap frequecy of about 1.4 THz. We are developing a process to fabricate NbN/AlN/NbN tunnel junctions with low-loss NbN tuning elements or self-tuned NbN SIS junctions with the hope of obtaining even better performance.

Acknowledgments

We thank Dr. C.E. Tong and Dr. R. Blundell of Harvard-Smithsonian Center for Astrophysics for valuable discussions on the tuning circuits. This work was supported in part by the Joint Research Fund of National Astronomical Observatory.

References

[1] J. R. Tucker, Appl. Phys. Lett. 36, 477 (1979).

[2] J. Carlstrom and J. Zmuidzinas, Review of Radio Science 1993-1996, edited by W. Ross Stone (The Oxford University Press, Oxford, 1996).

[3] J. Zmuidzinas, H.G. LeDuc, J.A. Stern, and S.R. Cypher, IEEE Trans. Microwave Theory Tech., 42, 698 (1995).

[4] Z. Wang, A. Kawakami, Y. Uzawa, and B. Komiyama, J. Appl. Phys., 79, 7837 (1996).

[5] Z. Wang, A. Kawakami, and Y. Uzawa, Appl. Phys. Lett., 70, 114 (1997).

[6] Y. Uzawa, Z. Wang, and A. Kawakami, IEEE Trans. Appl. Supercond., 7, 2574 (1997).

[7] Y. Uzawa, Z. Wang, and A. Kawakami, Eighth Intern. Symp. Space THz Technology, Boston, MA, 301 (1997).

[8] Y. Uzawa, Z. Wang, and A. Kawakami, IEICE Trans. Electron. E-79-C, 1237 (1996).

[9] Z. Wang, Y. Uzawa, and A. Kawakami, IEEE Trans. Appl. Supercond., 7, 2797 (1997).

[10] C. E. Tong, R. Blundell, S. Paine, D. C. Papa, J. Kawamura, X. Zhang, J. A. Stern, and H. G. LeDuc, IEEE Trans. Microwave Theory Tech., 44, 1548 (1996).

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

Table. 1 Parameters used in the design process.

NbN gap frequency:	1.27 THz
NbN film thickness:	200 nm
NbN conductivity at 20 K:	$1.5 \times 10^6\ \Omega^{-1}m^{-1}$
SiO film thickness:	250 nm
SiO dielectric constant:	5.5
Al film thickness:	120 nm
Al conductivity at 4.2 K:	$2.0 \times 10^8\ \Omega^{-1}m^{-1}$

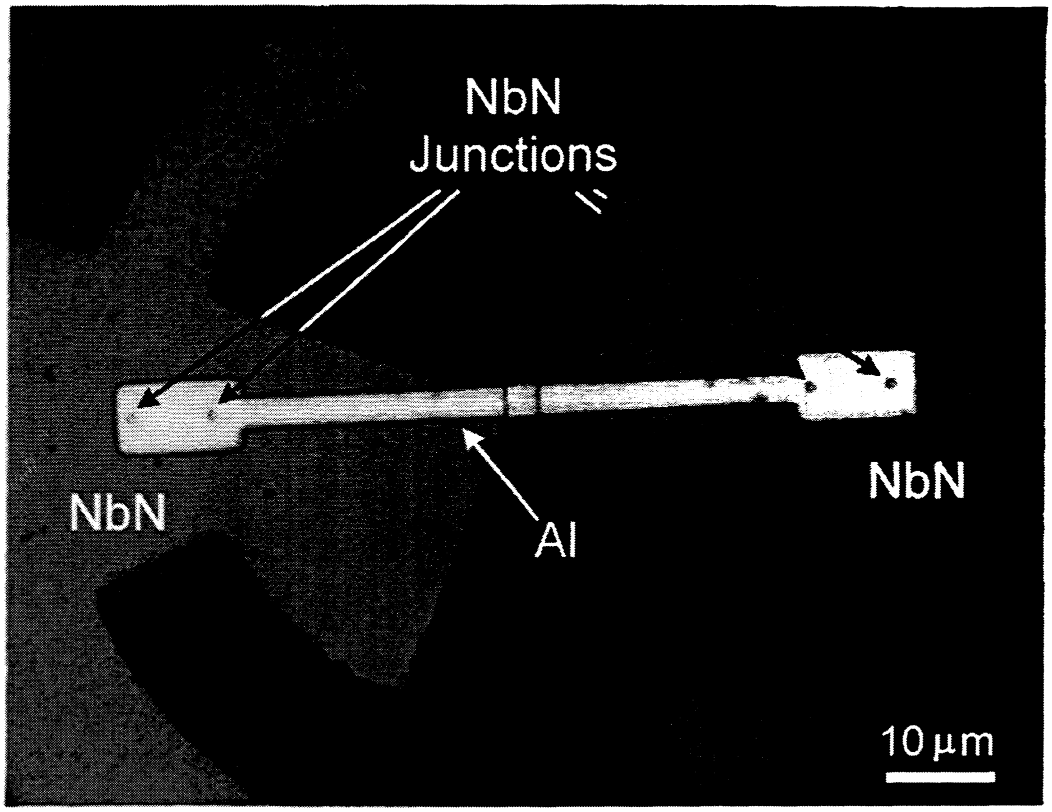

Fig. 1. An optical micrograph of the NbN/AlN/NbN mixer. NbN junctions with integrated Al/SiO/NbN microstrip tuning circuits are fabricated with a self-complementary log-periodic antenna as their ground plane. Each junction is approximately 0.9 µm in diameter.

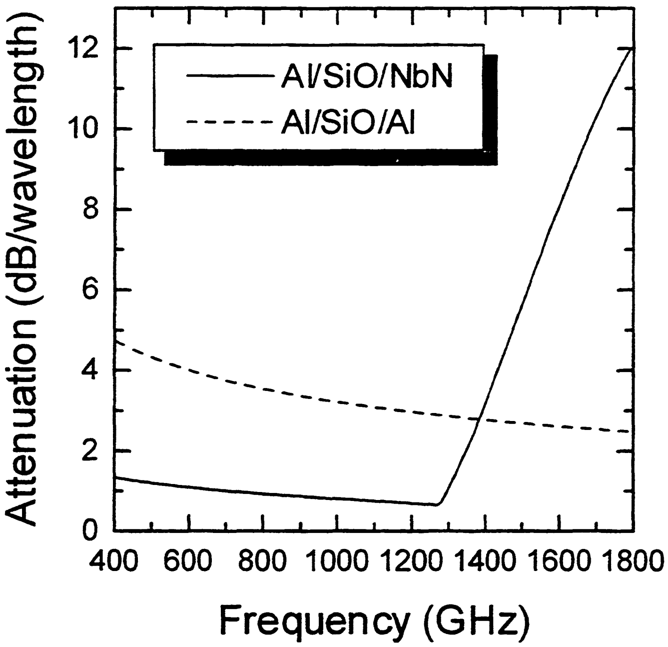

Fig. 2. The calculated frequency dependence of the loss per wavelength for the 3-μm-wide Al/SiO/NbN microstripline and the Al/SiO/Al microstripline.

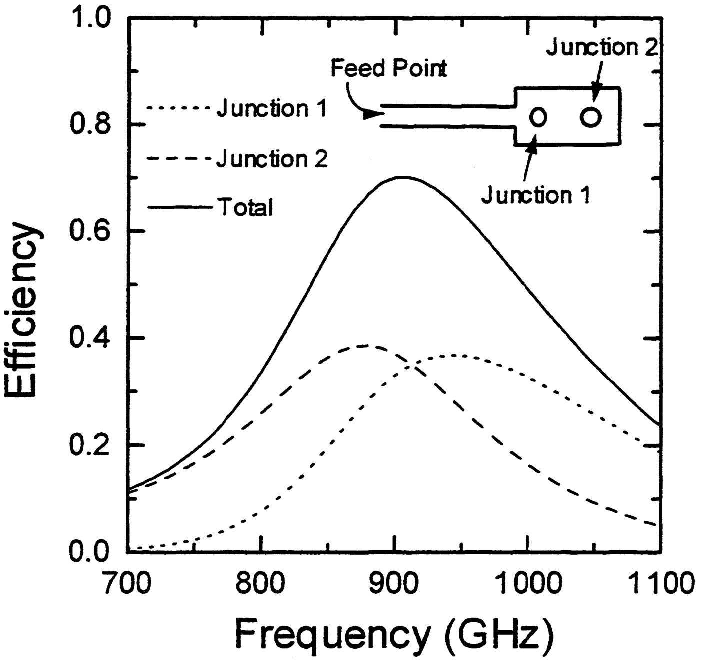

Fig. 3. The calculated power coupling efficiency from the feed point to the two-junction.

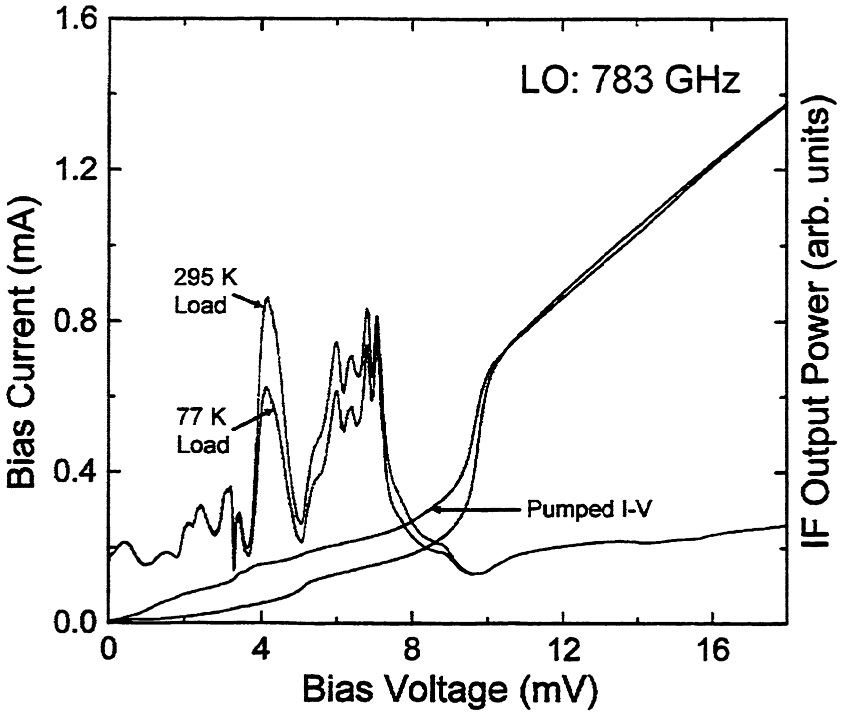

Fig.4 Heterodyne response of the receiver at 783 GHz. Shown are the I-V characteristics of the mixer device with and without LO power. Also shown is the IF power as a function of bias voltage for hot (295 K) and cold (77 K) loads.

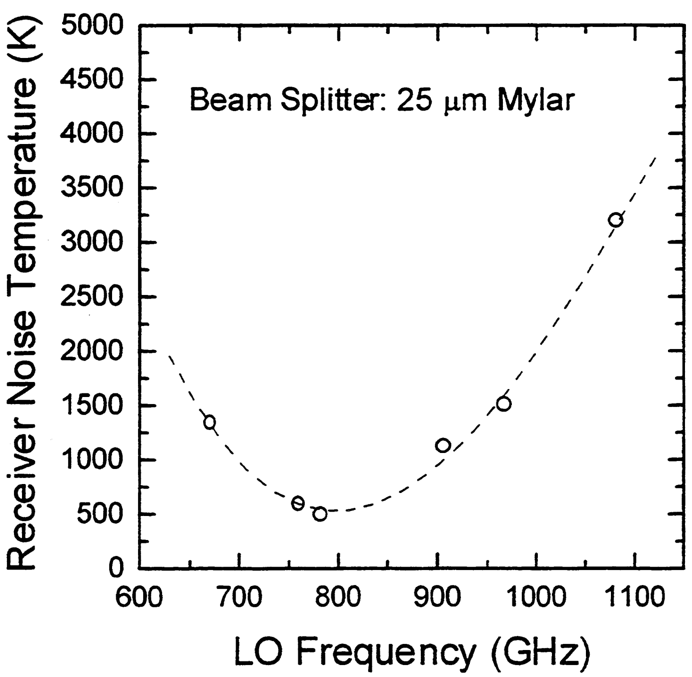

Fig. 5 DSB receiver noise temperature as a function of LO frequency.