DEVELOPMENTS OF THE 810-GHz SIS RECEIVER WITH Nb-BASED JUNCTIONS

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1 Abstract

We present the experimental and astronomical results of the tunerless waveguide 810-GHz SIS receiver. The Nb/AlO$_x$/Nb junctions associated with a broadband tuning circuit, namely parallel connected twin junctions, are fabricated at Nobeyama Radio Observatory. The tuning microstrip line is made of a Nb thin film. The lowest receiver noise temperature is 580 K (DSB) measured at 810 GHz, in which the noise contributions of the RF-input section alone and the IF-system account for about 4 % and 20 %, respectively. Note that the applied magnetic field with a permanent magnet to suppress the Josephson effect is 700 - 800 Gauss and the SIS mixer is cooled down to 3.9 K. The R_{sub}(2mV)/R_N is 16, which suggests relatively good quality of the junctions. This SIS mixer was installed on the receiver of the Mount Fuji submillimeter-wave telescope. We have detected the submillimeter-wave spectral lines of CI (^{3}P$_2$-^{3}P$_1$: 809.3432 GHz) and CO (J=7-6 : 806.651 GHz) in the Orion A molecular cloud.

2 Introduction

Radio astronomy at millimeter and submillimeter wavelengths has made rapid progress by using the heterodyne mixing with Superconductor-Insulator-Superconductor (SIS) tunnel junctions. The Nb-based SIS mixer associated with various types of integrated tuning structure has achieved the low receiver noise temperature of a few times the quantum limit (3 - $5\hbar\omega$/k). Recently, the sensitive THz SIS receiver has been required for space-borne astronomical and atmospherical observations. According to the Mattis-Bardeen theory [1], the loss of Nb-stripline increases remarkably due to the photon absorption (breaking Cooper-pairs) above the gap frequency of Nb ($2\Delta/h \approx$ 680 GHz. Δ is minimum energy of one quasiparticle excitation). Therefore, Nb-based SIS mixers using low-loss materials such as NbTiN [2, 3, 4], NbN [5, 6] and Al [7, 8, 9, 10] as a microstrip line circuits have been extensively studied theoretically and experimentally. However, Winkler et al. showed analytically that SIS mixer can be used up to twice the gap frequency ($4\Delta/h$) [11]. Lange et al. investigated the noise performance of a Nb-based SIS mixer at 600 - 1500 GHz and compared the results with the quantum mixing theory [12]. Honingh et al. accomplished the receiver noise temperature of less than 950 K at 780 - 820 GHz using fixed tuned SIS waveguide mixers [13].

We have developed the Nb-based 500-GHz waveguide SIS mixer associated with parallel connected twin junctions (PCTJ) [14, 15], which have been used for the receiver system of the Mount Fuji submillimeter-wave telescope [16, 17]. With this receiver system we have carried out the mapping observations of the CI ($^3P_1$-$^3P_0$: 492 GHz) line toward a number of molecular clouds. Since another transition of CI ($^3P_2$-$^3P_1$) lies at 810 GHz, immediate extension of the observing frequency up to 810 GHz is strongly required from astronomical reasons. On the basis of this motivation, we have developed the experimental 810-GHz mixer which is a scaled version of the 500-GHz SIS mixer. We have tested the mixer performance under various operating conditions at 810 GHz for future developments of a sensitive Nb-based SIS mixer with the PCTJ and the tuning stripline made of highly conductive normal metal like Al. A special attention has been paid for improvement of the RF-input section.

In this paper we present performance of the Nb-based SIS receiver at 810 GHz. First, the junction properties, the lay-out of the mixer and the experimental setup for performace evaluation are described. Next, we present the DC I-V curve characteristics and frequency response of the mixer measured by a Fourier transform spectrometer (FTS). Finally, the receiver noise temperature, the noise contribution and the astronomical results are presented.

3 Lay-out of the 810-GHz Waveguide Mixer

3.1 Junction properties

In the 810-GHz SIS mixer presented here Nb/AlO_x/Nb junctions and Nb-stripline are employed and they are fabricated at Nobeyama Radio Observatory (NRO). The dielectric layer of microstrip line used for impedance transformers is made of Nb_2O_5(1000 Å) /SiO_2(2700 Å) /Al_2O_3(900 Å). The tuning circuit consists of parallel connected twin junctions (PCTJ) associated with a superconducting tuning microstrip line with a width of 6.5 μm and a length of 10 μm. The PCTJ has advantages of a better RF and IF coupling and a larger tuning inductance than an end-loaded type [18]. In addition, it is also suggested that the structure of the PCTJ might be easier to suppress the Josephson effect. Other circuit elements include a waveguide-to microstrip transition with a DC/IF return path and an offset probe [19], a 75 Ω and a 45 Ω microstrip line and the RF choke filter which consists of a series of wide and narrow sections of microstrip line. The crystal substrate is polished down to 50 μm. The substrate width is 98 μm. These structure are shown in Figure 1. The size and normal-state resistance for a single junction are 1.25 μm$\times$1.25 μm and 22.1 Ω, respectively. Assumming $I_C R_N$ of 2.0 mV and the specific capacitance of 90 fF/μm^2, the critical current density and $\omega R_N C_j$ product are 9 kA/cm^2 and 11, respectively. The tuning bandwidth of the junctions, $\Delta f = f/\omega R_N C_j$, is about 80 GHz, since the Q-factor of the PCTJ is approximately equivalent to junctions' $\omega R_N C_j$ product [18]. The critical current density of 9 kA/cm^2 seems to be close to the upper limit for the Nb-junction with the high quality because of the fabrication process.

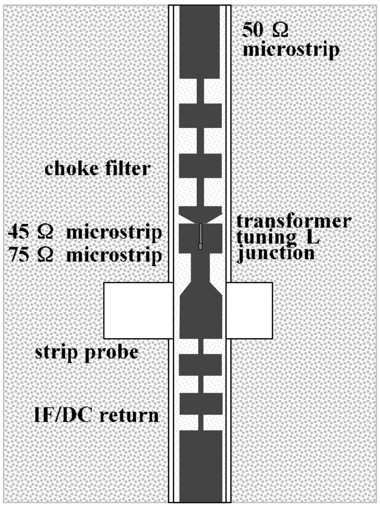

Figure 1: Structures of the 810-GHz SIS chip

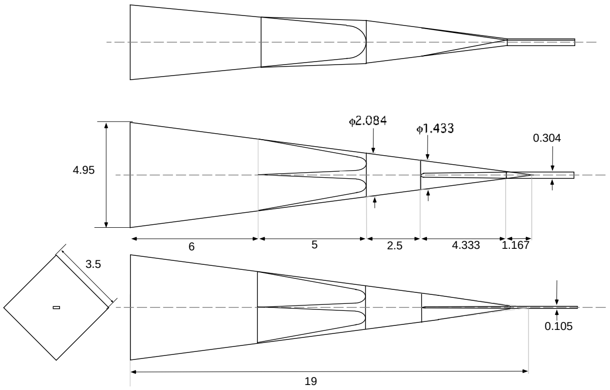

Figure 2: Diagonal horn of the 810-GHz mixer

3.2 Waveguide mixer

The 810-GHz SIS mixer is a scaled version of our 500-GHz waveguide SIS mixer. The mixer block is split into two blocks made of copper with electric gilding. The horn antenna and the channel for the SIS chip are included in one block, and the backshort cavity in the other block. This mixer does not employ any mechanical tuners for adjustment of the RF impedance of the mixer [20]. This fixed-tuned design is very important for a remote operation of this receiver on the Mount Fuji submillimeter-wave telescope. Dimensions of the waveguide and the IF-channel of the 810-GHz mixer are 304 μm $\times$105 μm and 105 μm $\times$ 105 μm, respectively. The substrate is shifted with 40 μm offset from the center of the waveguide. The IF/DC output port and 50 Ω microstrip line are connected with 10 μm Al wires. The slot of the ground port is filled with indium metal. A diagonal horn is adopted as the feed horn antenna because of the convenient fabrication. It has a good beam pattern and an efficient coupling to a Gaussian beam. The aperture and the length of the diagonal horn are 3.5 mm and 19.89 mm, respectively. The coupling efficiency of the fundamental mode of a diagonal horn is about 84 % if a field is transmitted smoothly from a horn to a waveguide [21]. The horn and the waveguide taper-transition are shown in Figure 2.

3.3 Measurement setup

An overview of the measurement syetem is shown in Figure 3. The frequency independent quasi-optical system based on the Gaussian beam propagation is installed at 4 K cold stage of a spare dewar for the Mount Fuji submillimeter-wave telescope [17]. The 4 K cold stage is covered by 40 K shield. The material of the dewer window and the IR filter are Kapton with thickness of 12.5 μm and Zitex (G106) with thickness of 150 μm, respectively. These thickness are decided from a standpoint of mechanical strength. The transmission of the IR filter was measured with the FTS at the room temperature, while that of the dewer window was estimated from the calculation. The transmission G and the equivalent noise temperature T_{eff} in the dewer are shown in table 1, where the effective temperature is expressed by $hf/\mathrm{k} \times \exp((hf/\mathrm{k}T_{amb}) - 1)^{-1}$. T_{amb} is the physical temperature. The RF and Local oscillator signal (LO) are combined by a wire grid polarlizer as a beam splitter. This polarlizer transmits most of the RF signal (95 %), while it reflects a small fraction of the LO power. These signals are focused to the horn by an ellipsoidal mirror. The LO signal at 809 GHz is produced by a combination of the W-band (90 GHz) Gunn diode and two triplers, which gives sufficient LO power for the mixing (230 μW). The intermediate frequency (IF) is amplified by an S-band low noise HEMT amplifier which is cooled on the 4 K cold stage. The return loss of the Bias T is larger than 25 dB in the frequency range from 1.8 to 2.7 GHz. The equivalent noise temperature and the gain of this amplifier associated with an isolator are about 7 K and 43 dB at 19 K, respectively. The DC SIS bias voltage and the IF line is combined by a Bias T. Finally, the DC I-V curve and the IF output power are measured by using an oscilloscope and a spectrum analyzer, respectively.

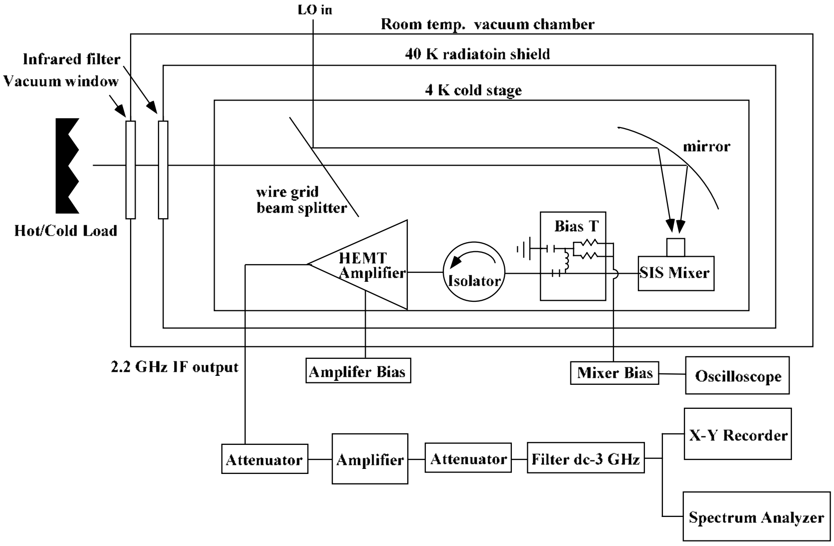

Figure 3: Measurement system.

Table 1. Materials and properties of the RF-input section.

	Dewar window	IR filter	Beam splitter
material	Kapton	Zitex (G106)	Wire Grid
transmission [%]	93 ± 1 (12.5 μm)	98 ± 1 (150 μm)	95
T_{eff}[K]	276	43	−−

4 Results and Discussion

4.1 DC I-V performance

The normal resistance R_N for a single junction is measured to be 22.6 Ω, which is well consistent with the expected value. The R_{sub}(2.0 mV)/R_N is about 16 at 4 K, where R_{sub} is a resistance at 2.0 mV. The subgap leakage current at 2.0 mV is less than 10 μA. As shown in the sample DC I-V curve (Figure 4), it was difficult to find out the resonace step (even varying the applied magnetic field strength), only seeing the step at the half of the gap voltage (~1.5 mV). The permanent magnets, giving a magnetic field of 830 Gauss at the position of junctions are attached at the both side of a mixer block to suppress the Josephson current. The magnetic coils are not used, because it can be a source of an unfavorable heat inflow. When we applied the magnetic field of 530 Gauss, the second Shapiro step, the knee strucure due to the proximity effect and the increase of gap voltage increased slightly. The field of 830 Gauss is 40 % of the upper critical magnetic field of Nb. Since the properties of magnets and the divergence of the magnetic field at a low temperature are not known accurately, the absolute value of the magnetic field might be overestimated.

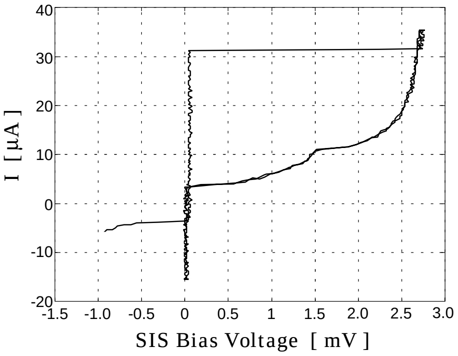

Figure 4: DC I-V curve of the 810-GHz SIS mixer below the gap frequency of Nb.

4.2 Frequency Response

The frequency response of the 810-GHz waveguide mixer coupled with the PCTJ was measured with the FTS. The frequency resolution was 3.6 GHz. The result is shown in Figure 5. The frequency cut-off of the waveguide can be seen around 600 GHz. In addition, the peak around 720 GHz should be neglected due to the direct absorption of a photon at the gap energy. The other subgap staructures in the response curve are due in part to the measurement system such as absorptions by H_2O vapor. Therefore, the basic response curve seems to have a peak around 820 GHz, which is 30 GHz lower than the designed value. This is relatively consistent with the designed value. From this result, the suitable SIS bias voltage is found to be from 2.0 to 2.2 mV.

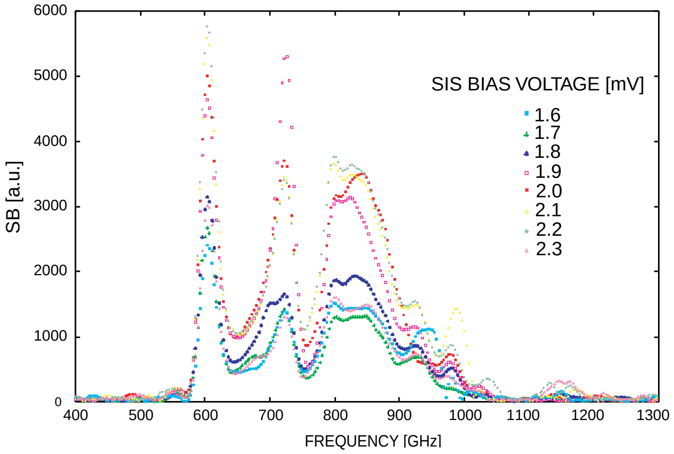

Figure 5: FTS measurement of 810-GHz SIS mixer at various SIS bias voltage.

4.3 Receiver noise temperature

Using the Y-Factor method with the hot load (295 K) and the cold load (77 K), the noise temperature of the 810-GHz waveguide SIS mixer has been measured by using a spectrum analyzer. The noise performance in the frequency range of 790 - 830 GHz is shown in Figure 6. The relatively narrow frequency range of measurements is due to limited frequency tunability of the LO source employed here. The frequency is measured by the Shapiro steps so that it has a typical uncertainty of 0.3 GHz. The lowest receiver noise tempetrature of 580 K (DSB) is obtained around 810 GHz at the SIS bias voltage 2.0 - 2.2 mV. These results are in good agreement with those expected from the FTS measurement. In addition, we measured the receiver noise temperature (T_{RX}) at diffrent temperatures. We controled the temperature by using an electric heater attached on the cold stage. Understanding the temperature dependence is useful, since the actual mixer installed into the telescope is not always cooled at 4 K due to various heat loads. As shown in Figure 7, the noise temperature is found to depend on the temperature substantially even around 4 K. Note that T_{RX} also depends on the magnetic field applied. The apparent difference in the best receiver noise temperature was not observed between the magnetic field of 530 Gauss and 830

Gauss. However, 0th - 3th Shapiro steps could be seen apparently in the case of 530 Gauss, and the IF output power is slightly unstable around the SIS bias voltage of 2.0 - 2.2 mV. A sample of the measured total IF output power superposed on the DC I-V curve is displayed in Figure 8. The IF output power in Figure 8 is averaged all over the frequency range of DC - 3 GHz, which includes the frequency range with the bad responsivility of the HEMT Amplifier.

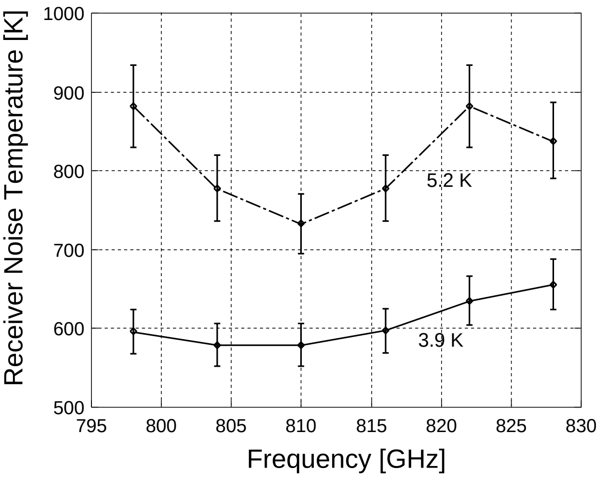

Figure 6: Receiver noise temperature (DSB) of 810-GHz mixer versus frequency

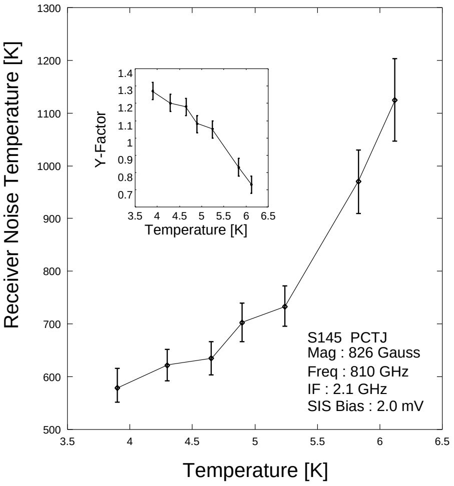

Figure 7: Receiver noise temperaure at different temperatures

4.4 Noise contribution

The measured receiver noise temperature consists of the noise contributions of the RF-input section, the mixer and the IF-chain, which is simply expressed by

$$T_{RX} = T_{RF} + \frac{T_{MIX}}{G_{RF}^{tot}} + \frac{T_{IF}}{G_{RF}^{tot} G_{MIX}}. \tag{1}$$

where T$_{RX}$,T$_{RF}$,T$_{MIX}$ and T$_{IF}$ are the equivalent noise temperature of the receiver, the RF-input section, the mixer, and the IF-chain, respectively. The G_{MIX} is the gain of the mixer. The G_{RF}^{tot} is expressed by $G_{RF}^{opt} \times G_{RF}^{tune}$, where G_{RF}^{opt} is a transmission of the RF-input section including the dewer window, the IR filter, the beam splitter and the horn and is evaluated to be about 0.73. The G_{RF}^{tune} is a gain of a tuning circuit and a microstrip line. In order to study the contribution of the components of each term of Eq.1 above gap frequency, we at first measured T$_{RF}$ by performing intersecting lines technique [22]. As the result, the equivalent noise temperature of 95 K at the intersection point was obtained from the Figure 9, which is much larger than that of 22 K calculated from the RF-input section alone. According to the Ke's discussion

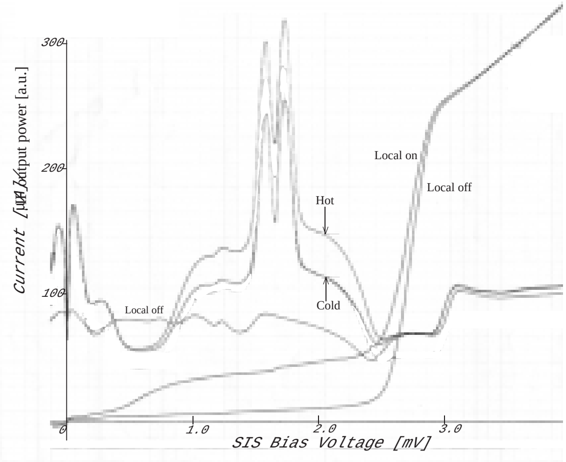

Figure 8: IF output power superimposed on the DC I-V curve versus SIS bias voltage.

[23], this equivalent noise temperature at the intersection point should be expressed by $T_{RF} + \sum \tau / G_{RF}^{tot}$. $\sum \tau$ is the sum of the quantum noise and the correction terms which are independent of G_{MIX} in case that the SIS mixer is not perfectly matched to the LO source. Therefore, the large residual of 73 K might result from these terms. Since $\sum \tau / G_{RF}^{tot}$ as well as T_{RX} is extremely influenced by the G_{RF}^{tune}above the gap frequency of Nb, it seems likely that the value at the intersection point is reduced by adopting the NbTiN, NbN, or normal metal such as Al as the microstrip line. Next, T_{IF} of about 6 K is obtained by using the linear relation in the shot noise region of IF output power [24, 25]. In addition, $T_{IF}/G_{RF}^{tot} G_{MIX}$ is obtained to be 115 K by comparing the total IF output power for the hot load with that of IF-chain alone at the gap voltage [15], where $G_{RF}^{tot} G_{MIX}$ is estimated to be 0.05.

From above simple estimations, the low noise tempereture of our mixer seems likely to be due in part to the low T_{RF}, the good performance of the tuning circuit of the PCTJ [18], and a comparatively high R_{sub}/R_N. Therefore, it might be exceedingly important to improve the high quality junction not only with a low loss material but also with a high current density, a low subgap current and a high coupling tuning circuit, as Dieleman et al. suggest [10].

4.5 Observation of CI($^3P_2$-$^3P_1$) and CO(J=7-6) line

We are conducting large mapping observations of CI ($^3P_1$-$^3P_0$: 492 GHz) toward various molecular clouds using Mount Fuji submillimeter-wave telescope. Comparison of the CI ($^3P_1$-$^3P_0$: 492 GHz) intensity with the CI ($^3P_2$-$^3P_1$: 809 GHz) intensity is essential to investigate the physical parameter such as the temperature and H_2 gas density in the region where CI exists. For this aim, we installed the 810-GHz SIS mixer

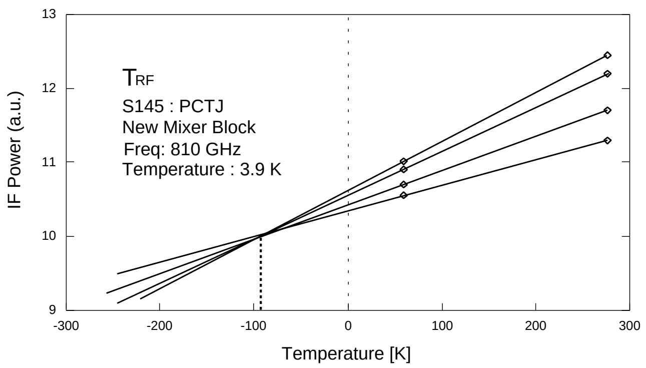

Figure 9: Equivalent noise temperature of the RF-input section measured by performing intersecting lines technique

into the dewer of Mount Fuji submillimeter-wave telescope and carried out the test observations toward the Orion A molecular cloud. As a result, we could detect the CI ($^3P_2$-$^3P_1$) and the CO (J=7-6) line as demonstrated in Figure 10. The system noise teperature including the loss of the atmosphere and the radome was 6500 K(DSB). This high system noise temperature mainly originates from high physical temperature of the mixer, a loss of bandpass filter, and an insufficient LO-power.

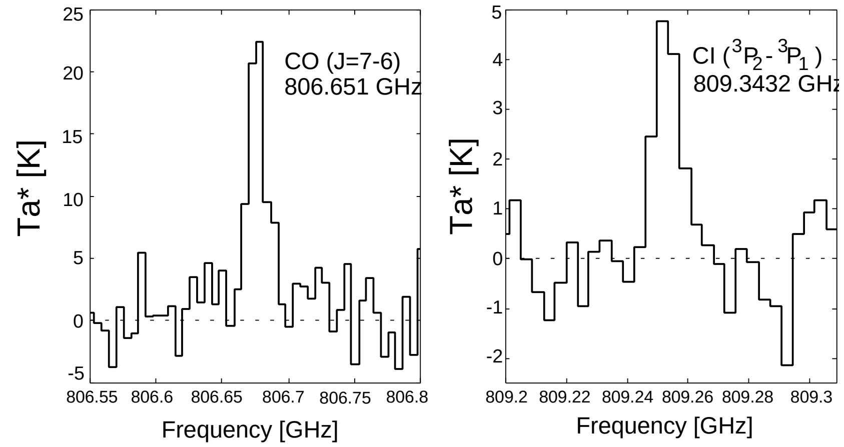

Figure 10: Samples of spectral lines toward Orion A molecular cloud

5 Summary

We have produced an experimental Nb-based waveguide 810-GHz SIS mixer. The good receiver noise temperature of about 600 K in the range of 790 - 830 GHz was obtained with the laboratory receiver setup. In the view point of the stability of the

IF output power, the optimized magnetic field and SIS bias voltage were 830 Gauss and 2.0 - 2.2 mV, respectively. These properties agree well with the result of the FTS measurement. It seems likely that this low noise performance of Nb-based mixer above the gap frequency is due to the low T_{RF}, the efficient couplings of the PCTJ, and relatively high R_{sub}/R_N. Although the 810-GHz mixer installed in Mount Fuji submillimeter-wave telescope was not used in the ideal condition, we observed the CI ($^3P_2$-$^3P_1$) and the CO (J=7-6) line toward Orion A molecular cloud.

Acknowledement

We are grateful especially to S. Saito for lending us a 800 GHz LO source. We are also grateful to the members of the Mount Fuji submillimeter-wave telescope project for the observations of the CI and the CO line. We would like to thank H. Matsuo and T. Matsunaga for the FTS measurement.

References

[1] D.C. Mattis and J. Bardeen, Phys. Rev., vol. 111, p. 412, July 1958.

[2] J.A. Stern, B. Bumble, H.G. LeDuc, W.J. Kooi, and J. Zmuidzinas, Proc. 9th Internat. Symp. on Space Terahertz Technology, CIT, PC, p. 305, Mar. 1997.

[3] B.D. Jackson, N.N. Iosad, B. Leone, J.R. Gao, T.M. Klapwijk, W.M. Laauwen, G. de Lange, and H. van de Stadt, Proc. 10th Internat. Symp. on Space Terahertz Technology, Charlottesville, p. 144, Mar. 1999.

[4] J.W. Kooi, J.A. Stern, G. Chattopadhyay, H.G. LeDuc, B. Bumble, and J. Zmuidzinas, Int. J. of IR and MM Waves, vol. 19, 1998.

[5] Y. Uzawa, Z. Wang, and A. Kawakami, Proc. 9th Internat. Symp. on Space Terahertz Technology, CIT, PC, p. 273, Mar. 1998.

[6] P. Dieleman, T.M. Klapwijk, H. van de Stadt, M. Schicke, B. Plathner, and K.H. Gundlach, Proc. 8th Internat. Symp. on Space Terahertz Technology, Boston, USA, pp. 291-300, Mar. 1997.

[7] H. van de Stadt, A. Baryshev, P. Dieleman, Th. de Graauw, T.M. Klapwijk, S. Kovtonyuk, G. de Lange, I. Lapitskaya, J. Mees, R.A. Panhuyzen, G. Prokopenko, and H. Schaeffer, Proc. 6th Internat. Symp. on Space Terahertz Technology, CIT, PC, p. 66, Mar. 1995.

[8] M. Bin, M.C. Gaidis, J. Zmuidzinas, T.G. Phillips, and H.G. LeDuc, Appl. Phys. Lett., vol. 68(12), p. 1714, Mar. 1996.

[9] G. de Lange, J.J. Kuipers, T.M. Klapwijk, R.A. Panhuysen, H. van de Stadt, and M.M.W.M. de Graauw, J. Appl. Phys., vol. 77, pp. 1795-1804, 1995.

[10] P. Dieleman, T.M. Klapwijk, J.R. Gao, and H. van de Stadt, IEEE Trans. Appl. Supercond, vol. 7, no. 2, p. 2566, June 1997.

[11] D. Winkler and T. Claeson, J. Appl. Phys.,vol. 62, pp. 4482-4498, 1987.

[12] G. de Lange, C.E. Honingh, J.J. Kuipers, H.H.A. Schaeffer, R.A. Panhuysen, T.M. Klapwijk, H. van de Stadt, and M.M.W.M. de Graauw, Appl. Phys. Lett,. vol. 64, pp. 3039-3041, 1994.

[13] C.E. Honingh, S. Haas, D. Hottgenroth, K. Jacobs and J. Stutzki, IEEE Trans. Appl. Supercond., vol. 7, no. 2, June. 1997.

[14] S.C. Shi, T. Noguchi, J. Inatani, Y. Irimajiri and T. Saito, Proc. 9th Internat. Symp. on Space Terahertz Technology, Pasadena, CA, Mar. 1998.

[15] S.C. Shi and T. Noguchi, IEEE Trans. Appl. Supercond., vol. 7, no. 2, pp. 2587-2590, June. 1997.

[16] H. Maezawa, M. Ikeda, T. Ito, G. Saito, Y. Sekimoto, S. Yamamoto, K. Tatematsu, Y. Arikawa, Y. Aso, T. Noguchi, S.C. Shi, K. Miyazawa, S. Saito, H. Ozeki, H. Fujiwara, M. Ohishi, and J. Inatani, 1999, ApJ, 524, L129.

[17] Y. Sekimoto, et al., 2000, Review of Scientific Instruments, accepted.

[18] S.C. Shi, and T. Noguchi, IEICE Trans. Electron., vol. E81-C, no. 10, pp. 1584-1594, Oct. 1998.

[19] S.C. Shi and J. Inatani, IEEE Trans. Microwave Theory Tech., vol. 45, no. 3, pp. 442-445, Mar. 1997.

[20] S.C. Shi, T. Noguchi, and J. Inatani, IEEE Trans. Appl. Supercond., vol. 7, no. 4, pp. 3850-3857, Dec. 1997.

[21] P.F. Goldsmith, in Infrared and Millimeter Waves, 6, ed. K.J. Button, New York, NY: Academic Press, 1982, 277.

[22] R. Blundell, R. E. Miller, and K. H. Gundlach, Int. J. of IR and MM Waves, vol. 13, no.1, pp. 3-14, Jan. 1992.

[23] Q. Ke and M. J. Feldman, IEEE Trans. Microwave Theory Tech., vol. MTT-42, no. 4, pp. 752-755, Apr. 1994.

[24] D.P. Woody, R.E. Miller, and M.J. Wengler, IEEE Trans. Microwave Theory Tech., vol. MTT-33, no. 2, pp. 90-95, Feb. 1985.

[25] N.B. Dubash, G. Pance, and M.J. Wengler, IEEE Trans. Microwave Theory Tech., vol. MTT-42, no. 4, Apr. 1994.