Noise and Gain Performance of spiral antenna coupled HEB Mixers at 0.7 THz and 2.5 THz.

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Abstract

Noise and gain performance of hot electron bolometer (HEB) mixers based on ultrathin superconducting NbN films integrated with a spiral antenna was studied. The noise temperature measurements for two samples with different active area of 3 μm x 0.24 μm and 1.3 μm x 0.12 μm were performed at frequencies 0.7 THz and 2.5 THz. The best receiver noise temperatures 370 K and 1600 K, respectively, have been found at these frequencies. The influence of contact resistance between the superconductor and the antenna terminals on the noise temperature of HEB is discussed. The noise and gain bandwidth of 5GHz and 4.2 GHz, respectively, are demonstrated for similar HEB mixer at 0.75 THz.

Introduction

The radioastronomic observations require heterodyne receivers that are able to register weak emission lines associated with rotation and vibration transitions in the molecules of the far galaxies. Available local oscillators (LO) at frequencies above 1 THz are not tunable enough and have low output power. Therefore, a heterodyne detector designed for these frequencies should have wide intermediate frequency (IF) band and should require small LO power. The most suitable receiver for the frequencies above 1 THz is the receiver based on NbN phonon cooled HEB mixer. The IF gain bandwidth of such a mixer achieves 5 GHz [1,2]. At the 2.5 THz LO frequency, the best measured value of the double side band (DSB) noise temperature is 1100 K at T=2 K and 1400 K at T=4.2 K [2]. Authors of the Ref. 2 used 3.5 nm thick NbN films deposited on MgO substrate. This material is not stable enough for radioastronomic applications. The purpose of this paper is to measure the noise and gain characteristics within one batch of mixers based on superconducting 3.5 nm thick NbN films grown on Si substrate with MgO buffer layer. Such films show much better superconducting properties than NbN films grown on either Si or MgO substrates. In this paper we present the results of the noise temperature and gain bandwidth measurements of NbN HEB mixer at the LO frequencies 0.7 THz and 2.5 THz.. We also discuss the effect of the mixer dimensions on its noise temperature.

Device design and fabrication.

The HEB mixers were manufactured from superconducting NbN film on Si substrates with MgO buffer layer. MgO buffer layer 200 nm thick was deposited by e-beam evaporation from MgO pellet. The substrate temperature during the MgO deposition process was about 400 °C.

Ultrathin NbN films have been deposited by reactive dc magnetron sputtering in the Ar + N_2 gas mixture. The maximum values of the critical film parameters (T_c and j_c) are reached at the Ar partial pressure of $5x10^{-3}$ mbar, the N_2 partial pressure of $9x10^{-5}$ mbar, the discharge current value of 300 mA, the discharge voltage of 300 V and the substrate temperature 800 °C. The deposition rate was 0.5 nm/s. It was defined as ratio of the film thickness, measured with a Talystep profilometer-profilograph, and its deposition time. The film thickness was 3.5 nm and determined by deposition rate. The quasioptical mixer was made by lift-off e-beam lithography and photolithography. The 0.12 µm and 0.24 µm long bolometers were formed by lift-off e-beam lithography across the gap between two Ti-Au (Ti ~ 3 nm, Au ~ 30 nm) small contact pads. The width of bolometers, 1.3 µm and 3.0 µm, respectively, was formed by SiO mask (SiO~ 70 nm) made by one more e-beam lift-off process. The central part of self-complementary spiral antenna was formed using lift-off e-beam lithography based on Cr-Au metallization (Cr~ 5 nm, Au ~70 nm). SEM images of the central part of the devices are shown in Fig. 1. The next process was the fabrication of the outer part of the mixer by lift-off photolithography based on Ti-Au metallization (Ti ~ 5 nm, Au ~ 200 nm). The last process was the removing of the NbN layer by ion milling in Ar atmosphere from the whole surface of the substrate except the central part of spiral antenna which was protected by SiO mask.

Typically, mixers based on 3.5 nm thick NbN films on silicon substrates with MgO buffer layer have a superconducting transition temperature between 10 K and 11 K.

Experimental setup

Experimental setup for noise temperature measurements at 0.7 THz and 2.5 THz is presented in Fig. 2.The hyper-hemispherical lens fabricated from high-resistivity silicon with a HEB positioned on the flat side of the lens were mounted on a copper holder which in its turn was tightly bolted to the 4.2 K cold plate of an Infrared Labs HD-3 LHe cryostat. The cryostat has a wedged 1.5 mm thick TPX pressure window. A 1.2 mm thick quartz window with an antireflection coating was mounted on the 77 K shield. This filter has a cut-off frequency exceeding 6 THz. The intermediate frequency (IF) signal was guided out of the HEB via a 50 Ω coplanar line, which was soldered to SMA connector. A bias tee followed by an isolator was used to feed the bias to the mixer and to transmit the IF signal to a low noise (<3 K) 1.2-1.8 GHz HEMT amplifier (36 dB gain at 1.5 GHz). The bias tee, the isolator and the amplifier were also mounted on the cold plate of the cryostat. The output of the amplifier was filtered at 1.5 GHz with a bandwidth of 75 MHz, further amplified and finally rectified with a crystal detector. The measurements at 0.7 THz and 2.5 THz were performed using an optically pumped FIR ring laser [**3**]. The ring laser design prevents back-reflection of CO_2 pump radiation from the FIR cavity into the CO_2 laser cavity resulting in a stable output power of the FIR laser. Out-coupling of FIR radiation was performed through a 3 mm diameter hole in one of laser mirrors.

The LO radiation was focused onto the HEB mixer by two high-density polyethylene lenses. In order to monitor the LO output power a wire grid in the LO beam path reflected a miner fraction of the LO radiation into a pyroelectric detector. A second, rotating wire grid served for attenuation of the LO power delivered to the HEB. The signal and the LO beam were superimposed by a 6 μm thick Mylar beamsplitter.

DSB receiver noise temperatures were determined by the Y-factor method. Ecosorb was used as the hot and cold load. The temperature of the hot and cold load was 293K and 77K, respectively. The stability of the laser systems was good enough to measure the noise temperature by putting alternately the hot load and the cold load in the signal path behind the beamsplitter. The optical path from the load to the pressure window of the cryostat was about 25 cm long. The hot and cold reading was averaged by a computer and the Y-factor as well as the noise temperature were calculated. The noise temperature was also measured by chopping (frequency 15 Hz) between the hot and cold load using lock-in technique. It was verified at the other frequencies that the direct technique and chopping technique yield the same result.

For bandwidth measurements we used an The gain and noise temperature bandwidths were measured by experimental setup similar to the one shown in Fig. 2. A backward wave oscillator OB-39 served as a local oscillator at 0.75 THz. LO radiation was focussed by Teflon lens, near infrared background radiation was filtered by 350 μm thick Zitex foil. In the IF bands 1.3 - 1.7 GHz and 4.4 – 5.2 GHz, IF signal can be amplified by two HEMT amplifiers did not noticeably contribute in the receiver noise temperature. Outside these bands, the measured receiver noise temperature was corrected for amplifier noise.

Experimental results and discussion

Below we discuss results obtained for two devices. The mixer L310(#5) had the planar dimensions (length x width) 0.24 μm x 3 μm wide and showed the best noise temperatures of 370 K and 1600 K at LO frequencies of 0.7 and 2.5 THz, respectively. The device L391(#23) with the dimensions 0.12 μm x 1.3 μm had the noise temperature 2200 K at 2.5 THz. We should admit that the noise temperature of the device L310(#5) - 370 K at 0.7 THz - was measured with the silicon lens whose antireflection coating was optimized for 2.5 THz. Thus, the noise temperature can be further decreased using the antireflection coating with appropriate thickness. We should admit that the improvement of the noise temperature with the increase of the bolometer width was found for all batches of mixers that we have studied. The essential difference between the noise temperature values can be understood taking into account additional to the bolometer itself contact resistance contributed by contact areas between the gold antenna and the thin NbN bolometer (Fig.3). Contact resistance between NbN film and metallization is most likely due to residue of photolack used in the lift-off process and/or to oxidization of the NbN film between film and contact deposition. In order to clean the surface of the NbN film right before the contact deposition, we use plasma etching in O_2. Among other cleaning methods, this one results in the lowest contact resistance. of the structure. However, this process can increase oxidization depth of the NbN film.

In comparison to gold metallization, the 3.5 nm thick NbN is a bad conductor for high-frequency (RF) current. Therefore, when gold is present on the top of the NbN film, RF current flows mostly through gold. This current enters the bolometer within contact areas having the length d (see Fig. 3). The dimensions of this contact areas determine the magnitude of the additional resistance. Both the contact resistance itself and the resistance of two additional portions of the NbN film forming the contact area dissipate part of the RF current and thus decrease radiation coupling. This impacts the noise temperature.

Our results show that the additional resistance contributed by the contact areas decreases when the width of the bolometer increases. Such tendency was found by analyzing several batches of devices with different width. In order to keep the bolometer inpedance and the IF match unchanged it is also necessary to increase the bolometer length. Thus, the noise temperature of a HEB mixer can be improved by increasing the size of the bolometer size. However, the increase of the mixer dimensions cause the increase of the required LO power. Since output power of multiplied solid-state radiation sources drops with frequency, it may be not sufficient to optimally pump a large device. That is why the general way to improve the noise performance of the mixer is to decrease the contact resistance between the metal antenna and the bolometer without increasing its dimensions. The most prospective process of ohmic contact formation is in situ gold deposition. However, there are difficulties in removing gold from the bolometer. We consider that the difference of the mixer noise temperature over the batch is first of all determined by the spread in values of additional resistance. Moreeover, because of film non-uniformities at the submicron scale, submicron bolometers that nominally have the same dimensions may not have the same resistance. This also causes spread in the noise characteristics within the batch.

We also measured the noise and gain bandwidths of the mixer L310(#7) at the LO frequency of 0.75 THz. The mixer showed the noise temperature of 840 K at the intermediate frequency about 1 GHz. To measure the noise temperature of this mixer we used two HEMT amplifiers that brought the negligible contribution to the noise characteristics of the receiver in the IF ranges of 1.3-1.7 GHz and 4.4-5.2 GHz. Outside these bands the noise of the receiver was effected by amplifier noise. To obtain complete IF frequency dependence of the mixer noise temperature we carried out the measurements in a wider frequency range and corrected the result for frequency dependent noise temperature of the amplifier and their effect on the system noise temperature. The corrected mixer noise temperature dependence is shown in Fig. 4. The noise temperature bandwidth of the mixer was about 5 GHz. The gain bandwidth of the mixer (Fig. 5) was about 4.2 GHz that was the typical value for the mixers based on the 3.5 nm thick NbN film.

Conclusion

The contact resistance appearing at the boundary between the superconducting bolometer film and contact metallization impacts the noise temperature of HEB mixers. One possibility to decrease the contact resistance and improve noise performance of the receiver is an enlargement of the mixer working area that is the bolometer itself. The enlargement of the working area from 1.5x0.12 μm^2 up to 3x0.24 μm^2 cause a decrease of the noise temperature from 2200 to 1600 K at LO frequency of 2.5 THz. However the required LO power is also increased along with enlargement of the mixer working area, that is unacceptable for wide range of the applications because available power from multiplied solid state sources decreases at the terahertz frequencies. At frequencies above 2 THz, antenna geometry also limits dimensions of the bolometer. Further improvement of HEB mixers is connected with development of the technology which would allows us to decrease the impact of contact resistance between the superconductor and contact metallization.

Acknowledgment

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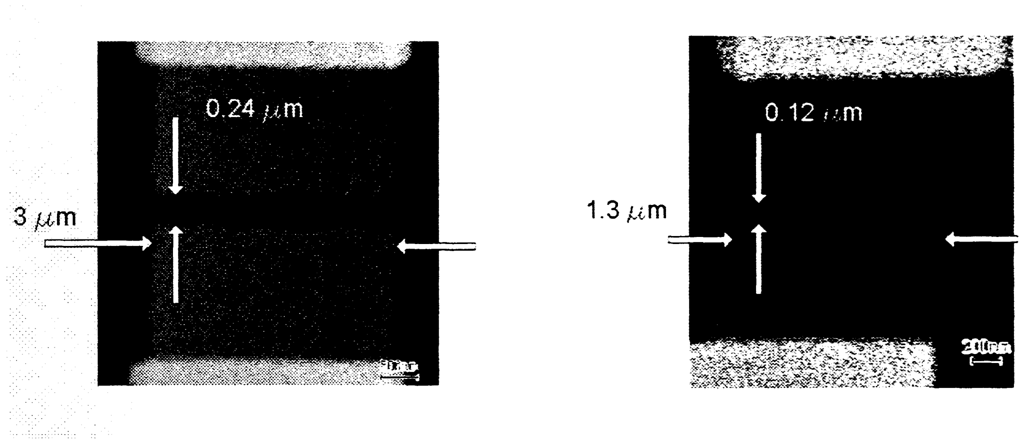

Fig. 1 SEM image of the central part of the spiral antenna.

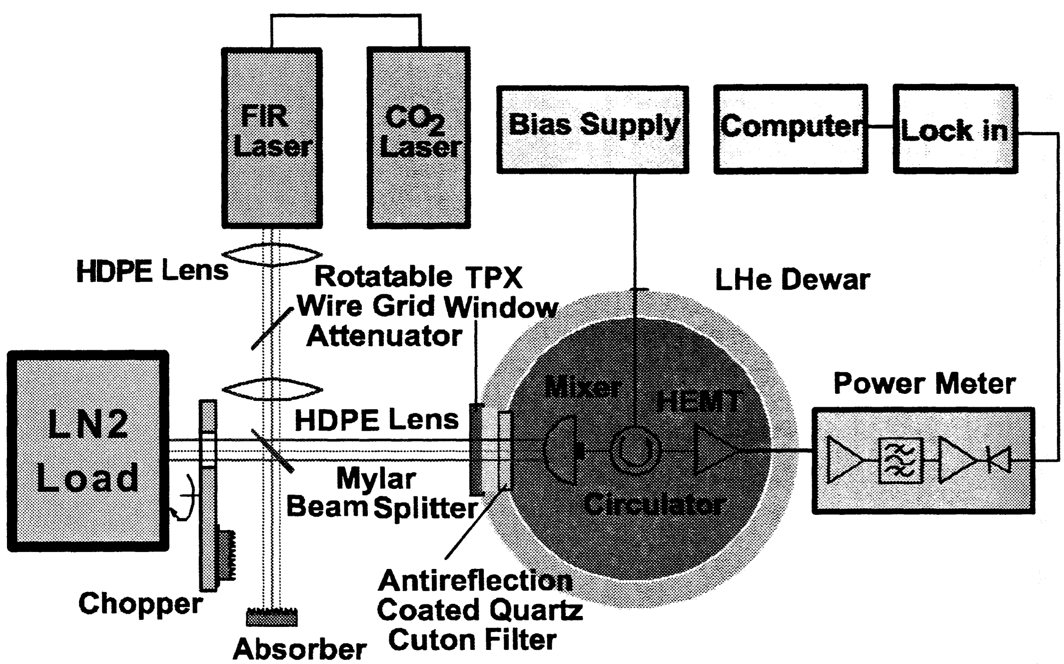

Fig. 2 Schematics of the experimental setup used for noise temperature measurements.

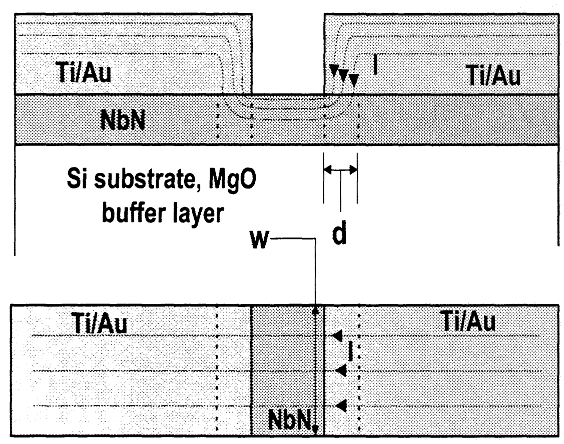

Fig. 3 Location of contact areas between the bolometer and antenna terminals. Shown is the current redistribution resulting in the excess contact resistance.

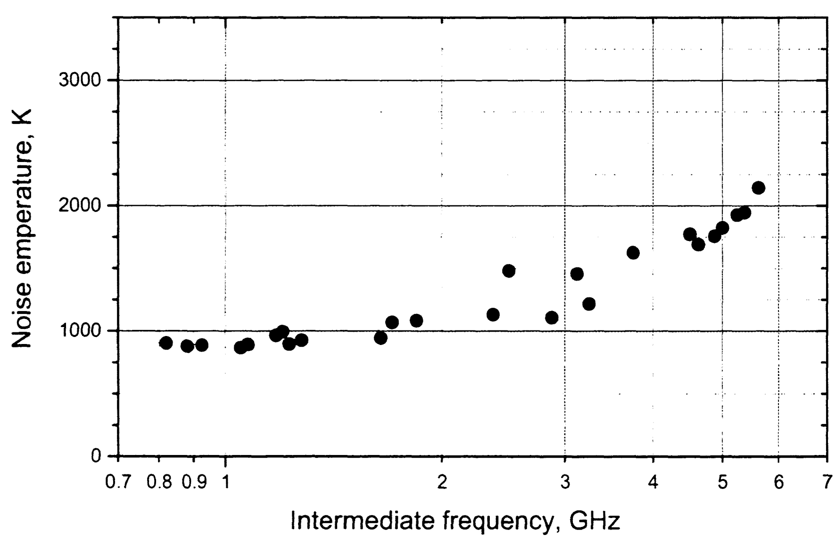

Fig. 4 Noise temperature vs. intermediate frequency for device L310(#7).

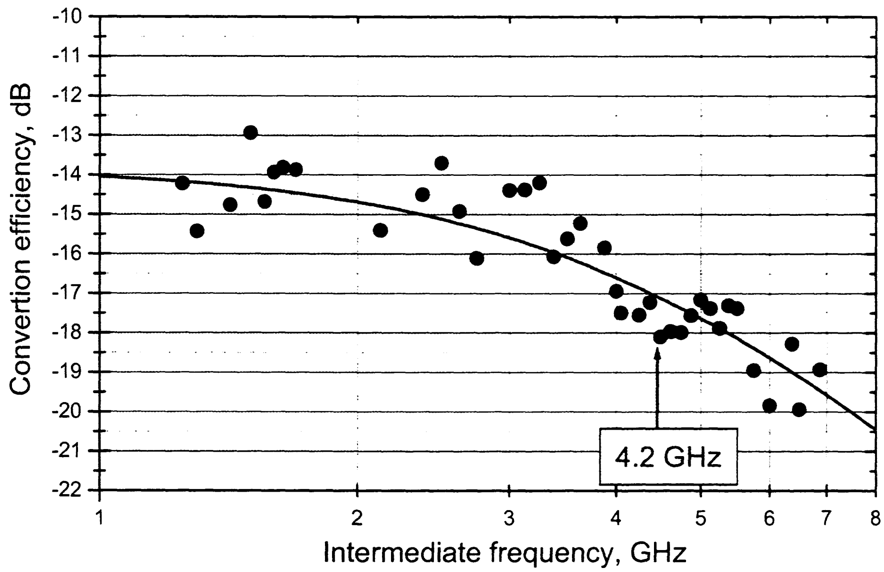

Fig. 5 Gain vs. intermediate frequency for device L310(#7).