Development of 0.8 THz and 1.5 THz Waveguide NbTiN HEB Mixers

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Abstract— **In this paper, we present results on the noise performance of the waveguide Niobium Titanium Nitride (NbTiN) superconducting hot electron bolometer (HEB) mixers, cryogenically cooled by a 4-K close-cycled refrigerator. The NbTiN superconducting HEB mixer is fabricated on a crystalline quartz substrate, and is mounted in a waveguide mixer block for RF and LO coupling. At 0.81 THz, the uncorrected DSB receiver noise temperature is measured to be 500 K and the noise bandwidth is 1.4 GHz. The same mixer shows the DSB receiver noise temperature of 640 K at 0.65 THz. We also investigate the DC performance of superconducting NbTiN HEB mixer designed for 1.5 THz.**

I. Introduction

Astronomy in the submillimeter-wave to far infrared region is very attractive. In this wavelength region, there exist various spectral lines of fundamental atoms and molecules, which provide us with rich information on physical conditions and chemical compositions of interstellar clouds and circumstellar envelopes [1]. With this in mind, we are developing the superconducting HEB mixer, which is demonstrated as the most sensitive detector above 1 THz. Currently, state-of-the-art phonon-cooled HEB mixers are usually made of Niobium Nitride (NbN) [2, 3, 4]. However, the Niobium Titanium Nitride (NbTiN) HEB mixer is promising as well in the THz region, because physical and chemical properties of the NbTiN and NbN thin films are closely related to and quite similar to each other. Since the NbTiN film can readily be fabricated on a quartz substrate, the waveguide coupling, which gives a well defined beam pattern, is possible for the NbTiN HEB mixer. This is an important merit for astronomical applications. In fact, the NbTiN HEB mixer receiver has been successfully installed to the APEX telescope to observe the CO *J*=13-12 emission line [5]. We here report the performance of the waveguide NbTiN HEB mixer fabricated in our laboratory.

II. Device Fabrication

The NbTiN thin film is deposited at the room temperature on a Z-cut crystalline quartz substrate by the RF plasma assisted sputtering system using an NbTi (weight ratio of Nb:Ti = 4:1) alloy target in the Ar and N_2 buffer gas. The film thickness is measured to be about 12 nm, where the deposition rate of the NbTiN superconducting thin film is about 6 nm per minute. We found that the N_2 mass flow sensitively affects the critical temperature T_c of the NbTiN superconducting thin film. The optimized N_2 mass flow is 0.94 sccm and the total chamber pressure is 0.42 Pa. When the N_2 flow is changed by 5 %, T_c significantly degrades. The film has a normal state sheet resistance of approximately 250 Ω per square. The NbTiN and Ti/Au layers are successively deposited on the crystalline quartz substrate without breaking vacuum in order to ensure a good contact between the two layers without suffering from natural oxidation of the NbTiN film surface.

The active area of the HEB mixer is defined by electron beam lithography and ICP (inductively coupled plasma) RIE (reactive ion etching) system to form a microbridge structure whose length and width are about 0.2 μm and 2 μm, respectively. The fabricated HEB mixer has a room temperature resistance of 25 Ω and a critical current of higher

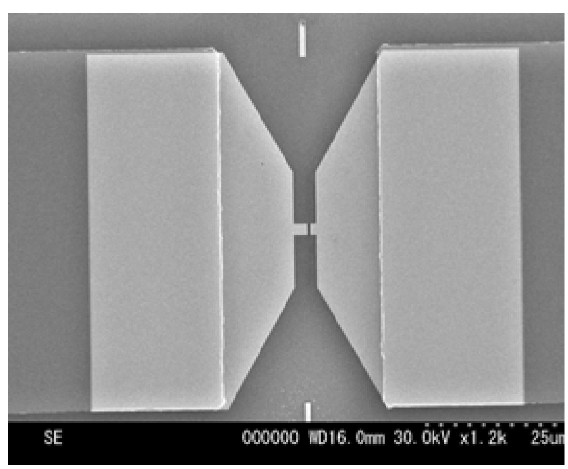


Fig. 1 SEM micrograph of a waveguide NbTiN HEB mixer.

than 500 μA at 4.2 K. We are unable to obtain exact critical current value due to the amplitude limit of our bias supply. Fig. 1 shows a SEM micrograph of an example of our HEB mixers.

In our past experiments, the structure of the HEB elements including choke filter, device thickness and width is simply taken from the design of the SIS mixers except for the microbridge part. This old design is found to have serious mismatching between the waveguide embedding impedance and the HEB mixer impedance. Therefore, the choke filter of the waveguide circuit is optimized so as to minimize the reflection loss between the RF circuit and the NbTiN superconducting HEB mixer.

III. Measurement Setup

Fig. 2 shows a schematic view of the measurement setup. The waveguide NbTiN superconducting HEB mixer chip is housed in a waveguide mixer block mounted on the cold plate of a GM two-stage 4-K close-cycled refrigerator. A Gunn oscillator, operating at 90 GHz, followed by two solid state frequency triplers, provides local oscillator (LO) power at a frequency of 810 GHz. The blackbody radiation from a slab of Eccosorb at 295 K (hot load) and 77 K (cold load) is used as an RF signal. The LO signal is collimated with a parabolic mirror, and is further combined with the RF signal by a beamsplitter. The combined signal passes through a parabolic mirror, a 7.5 μm thick Kapton vacuum window, and two Zitex G106 infrared filters mounted on the 50 K shield, and is finally directed into the diagonal horn of the mixer block by a parabolic mirror mounted on the cold plate of the cryostat.

The IF output signal of the HEB mixer with the frequency range 0.9-1.3 GHz goes through a bias-tee and an isolator to the cryogenic amplifier, and it is further amplified by a room-temperature amplifier chain. The latter consists of two amplifiers and a band pass filter. The IF power is finally measured by a square-law detector. The band pass filter has a bandwidth of 200 MHz at the center frequency of 1.1 GHz. The entire IF chain has a gain of 87 dB and a noise temperature of 9.5 K.

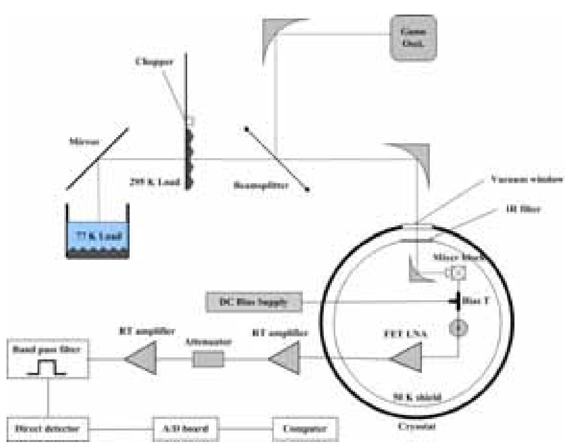


Fig.2 Schematic of measurement setup.

IV. Measurement Results

We used the conventional Y-factor method to measure the noise performance of the waveguide NbTiN superconducting HEB mixer, taking the ratio of the receiver output power corresponding to the hot and cold loads. The current-voltage curves of the HEB for different absorbed LO power levels are shown in Fig. 3.

Fig. 4 shows the measured IF output power corresponding to the hot and cold loads respectively, as a function of the bias voltage at optimum LO pumping level. The measured minimum receiver noise temperature is 500 K, where the bias voltage and current are 0.8 mV and 93 μA, respectively. This is a comparatively low noise performance when it is compared with results published previously [6], even though we use relatively thick NbTiN film of 12 nm. It should be noted that the flat region of IF output power around zero bias voltage is caused by residual series resistance of 3 Ω.

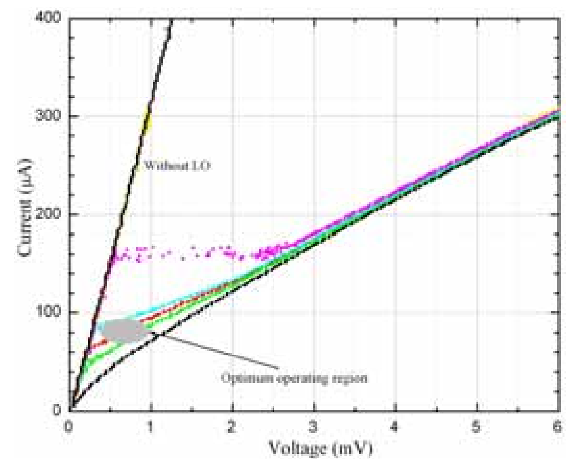


Fig. 3 Current-voltage curves of the waveguide superconducting NbTiN HEB mixer for different LO pumping levels. The optimum working region is 0.4-1 mV and 70-95 μA with the absorbed LO power is about 290 μW.

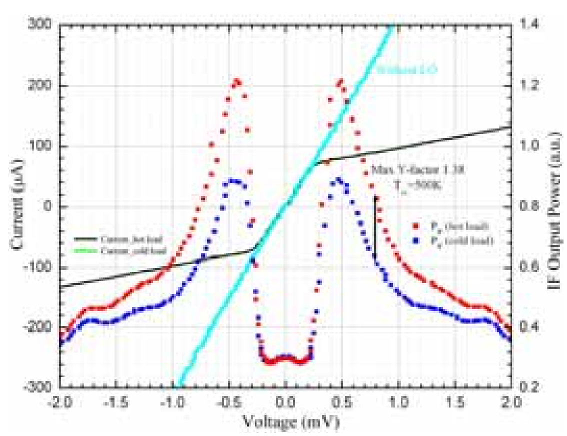


Fig. 4 Current-voltage curves of HEB mixer with and without LO at 0.81 THz, and receiver IF output power corresponding to the hot (295 K) and cold (77 K) loads as a function of bias voltage at optimum LO pumping level. The maximum Y-factor determined by the ratio of the IF output power levels corresponding to the hot and cold loads is 1.38.

We also measured the DSB receiver conversion gain of the waveguide NbTiN superconducting HEB mixer using a U-factor technique [7], as shown in Fig. 5. The HEB mixer gain is obtained after correcting the losses in the quasi-optical path and the IF amplifier chain. Since the bandwidth of IF amplifier chain is 0.9-1.3 GHz, the accurate receiver and mixer gains can't be obtained below 0.9 GHz. The IF gain bandwidth of the superconducting NbTiN HEB mixer is supposed to be around 1.2 GHz. The measured receiver noise bandwidth of superconducting HEB mixer is about 1.4 GHz.

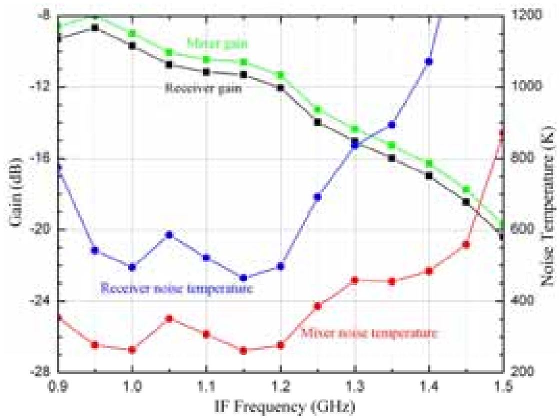
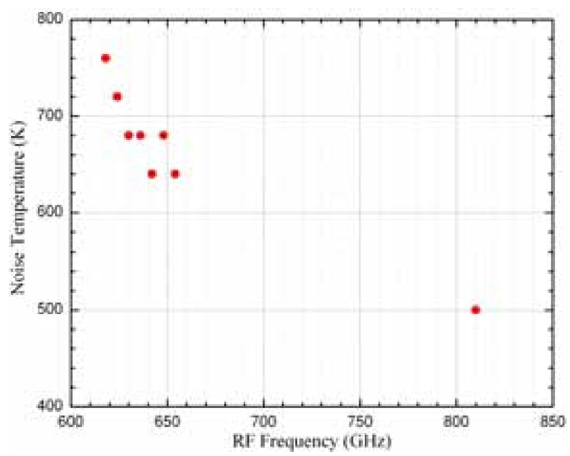
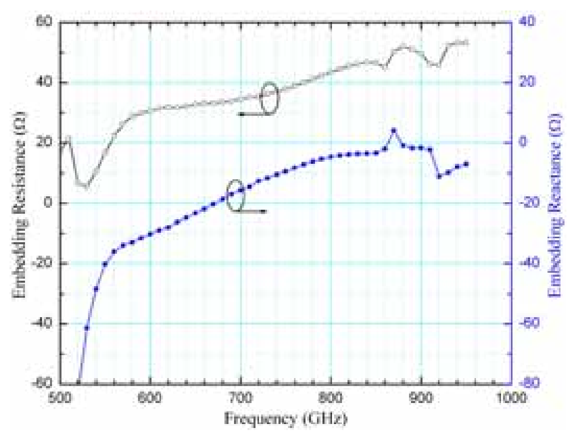


Fig. 5 Measured receiver noise temperature and conversion gain. The mixer noise temperature and gain are obtained after correcting the losses of the quasi-optical path and the IF amplifier chain.



(a)



(b)

Fig. 6 Measured DSB receiver noise temperature at 0.62-0.65 and 0.81 THz for the same HEB device (a) and simulated embedding impedance with HFSS in the frequency range of 0.5-1 THz (b).

Our NbTiN HEB mixer designed for 0.81 THz is found to be still sensitive at 0.62 THz. The receiver noise temperature is measured to be 640 K at 0.65 THz and 760 K at 0.62 THz, as shown in Fig. 6 (a). Fig. 6 (b) shows that the degradation of the receiver noise temperature at 0.62 THz partly results from the impedance mismatching between the superconducting HEB microbridge and the waveguide embedding circuit. The calculated coupling efficiency between the HEB mixer and the waveguide embedding circuit reduces from 92 % at 0.81 THz to 80 % at 0.62 THz.

The structure of the superconducting HEB mixer for the 1.5 THz region is designed with the HFSS simulator, and is fabricated by the same process as the 0.81 THz HEB mixer element. The thickness of the quartz substrate is 30 μm, the microbridge width 1.5-4 μm, and the length 0.2-0.6 μm. The HEB chip is housed into a waveguide of 180 μm wide and 70 μm high. Current-voltage curves of 1.5 THz superconducting NbTiN HEB mixers with different chip volumes are measured by a liquid-helium dip test, as shown in Fig. 7. The measurement of the RF performance of the NbTiN HEB mixer at 1.5 THz is ongoing.

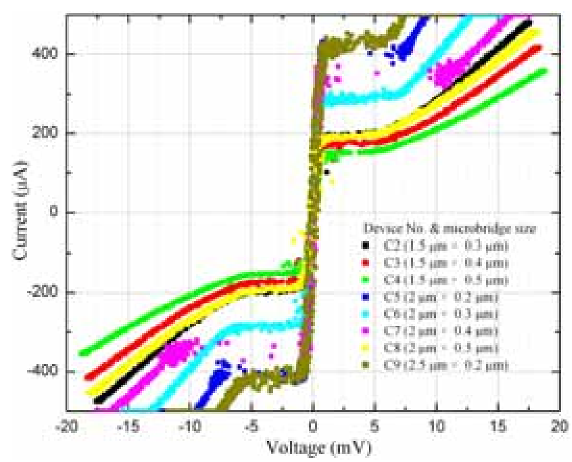


Fig. 7 Current-voltage curves of 1.5 THz superconducting NbTiN HEB mixers without LO pumping power for different element sizes.

V. Conclusions

In conclusion, we successfully fabricated the waveguide superconducting NbTiN HEB mixer, and characterized its DSB receiver noise temperature and conversion gain at 0.81 THz. A uncorrected DSB receiver noise temperature is measured to be 500 K at 0.81 THz, and the calibrated mixer noise temperature is 260 K after the correction of the losses of quasi-optical path and IF amplifier chain. The measured noise bandwidth is about 1.4 GHz, and the IF gain bandwidth is about 1.2 GHz. Although our mixer employs a relatively thick NbTiN film (12 nm), the performance obtained is comparable to those reported previously. The superconducting NbTiN HEB mixer designed for 0.81 THz still has high sensitivity even down to 0.65 THz, where the measured DSB receiver noise temperature is 640 K. In addition, we obtained good DC characteristics of superconducting NbTiN HEB mixers at 1.5 THz, and their RF performance tests are in progress.

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