Noise temperature measurements of NbN phonon-cooled Hot Electron Bolometer mixer at 2.5 and 3.8 THz.

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ABSTRACT

We present the results of noise temperature measurements of NbN phonon-cooled HEB mixers based on a 3.5 nm NbN film deposited on a high-resistivity Si substrate with a 200 nm - thick MgO buffer layer. The mixer element was integrated with a log-periodic spiral antenna. The noise temperature measurements were performed at 2.5 THz and at 3.8 THz local oscillator frequencies for the 3 μm x 0.2 μm active area devices. The best uncorrected receiver noise temperatures found for these frequencies are 1300 K and 3100 K, respectively. A water vapour discharge laser was used as the LO source. We also present the results of direct detection contribution to the measured Y-factor and of a possible error of noise temperature calculation. This error was more than 8% for the mixer with in-plane dimensions of 2.4 x 0.16 μm^2 at the optimal noise temperature point. The use of a mesh filter enabled us to avoid the effect of direct detection and decrease optical losses by 0.5 dB. The paper is concluded by the investigation results of the mixer polarization response. It was shown that the polarization can differ from the circular one at 3.8 THz by more than 2 dB.

1. INTRODUCTION

Today, many terahertz radio astronomy projects and research efforts are aimed at studying the atmosphere of the Earth. Generally, if such a project is directed to the measurements at frequencies over 1.2 THz then HEB mixers that have no competitive analogues for this frequency range are used. As a rule, astronomical and atmospheric missions require a receiver of linearly polarized radiation in a relatively narrow frequency band which matches the LO frequency. In this case the optimal solution is to use a mixer with a well-studied plane polarized twin slot antenna for which the band is centered to a given frequency. This is the direction of the research efforts of diverse scientific groups. In particular, such projects as TELIS [1] and HERSCHEL [2] in the terahertz frequency rang are oriented to building a heterodyne receiver which has a 1.8 THz channel and a heterodyne spectrometer which has two channels at 1.41-1.91 THz, respectively.

The measured noise temperature versus frequency dependence is well linearly approximated by 8-10$\hbar\omega/k$ for the frequencies less than 2.5 THz. However, the solution of a series of some scientific tasks is concerned to the fabrication of the mixers that are optimized to operate at higher frequencies (more than 2.5 THz) for which the performance of twin-slot antennas is poor. In fact, the only investigation of the HEB mixers at the frequencies over 2.5 THz is the one in which the noise temperature of the mixer was measured at frequencies up to 5.2 THz [3]. These measurements show that the sensitivity of the mixer drops and the noise temperature versus frequency dependence significantly differs from 10$\hbar\omega/k$. That is why further feasibility studies are needed to find out if the performance of heterodyne receivers directed to higher frequencies can be improved. In this work we investigated quasioptical mixers both at the well studied frequency of 2.5 THz and the frequency of 3.8 THz where very few measurements had been taken previously. In particular, we studied polarization properties of the mixers integrated with a spiral antenna at 3.8 THz. Besides, many similar problems are unsolved yet for both frequencies less than 2.5 THz and higher frequencies. One of them is the effect of direct detection, which causes an experimental error of Y – factor measurement in laboratory and real astronomical experiments. When mixer sizes are reduced, the effect of direct detections becomes more significant, hence the experimental error value of Y – factor measurement is increased. It can lead to a spectral line distortion in radioastronomical investigations.

2. HEB FABRICATION AND EXPERIMENTAL SETUP

HEB mixers were manufactured from a 3.5 nm thick superconducting NbN film on Si substrates with a MgO buffer layer. A 200 nm thick MgO buffer layer was deposited by e-beam evaporation from MgO pellet. Ultrathin NbN films have been deposited by reactive dc magnetron sputtering in the Ar + N_2 gas mixture. The quasioptical mixer was made by lift-off e-beam lithography and photolithography. A scanning electron microscope (SEM) image of the central part of one of the devices is shown in Fig.1. Typically, the mixers based on 3.5 nm thick NbN films on silicon substrates with an MgO buffer layer have a superconducting transition temperature between 10 K and 11 K.

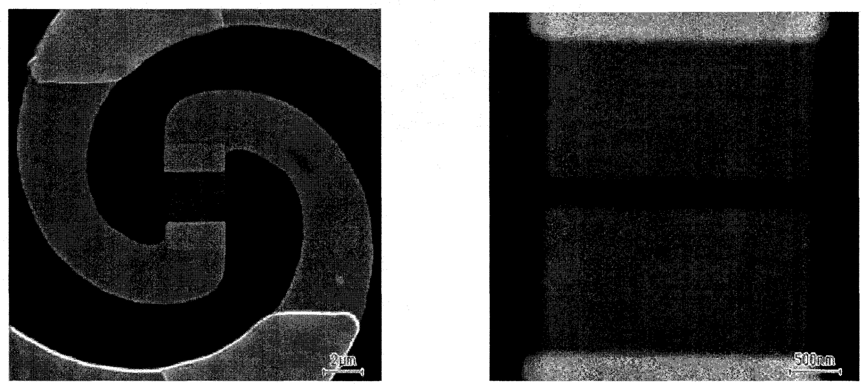

Figure 1. SEM micrograph of the spiral antenna (left) and central part of the spiral antenna with an NbN bridge (right).

The experimental setup for noise temperature measurements is presented in Fig2. 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 LHe cryostat. The cryostat has a wedged 0.5 mm thick high-density polyethylene window. A 0.35 mm thick black polyethylene IR filter was mounted on the 77 K shield. The intermediate frequency (IF) signal was guided out of the HEB via a 50 Ω coplanar line, which was soldered to an 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 (5 K) 1.2-1.8 GHz HEMT amplifier (30 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 40 MHz, further amplified and finally rectified with a crystal detector.

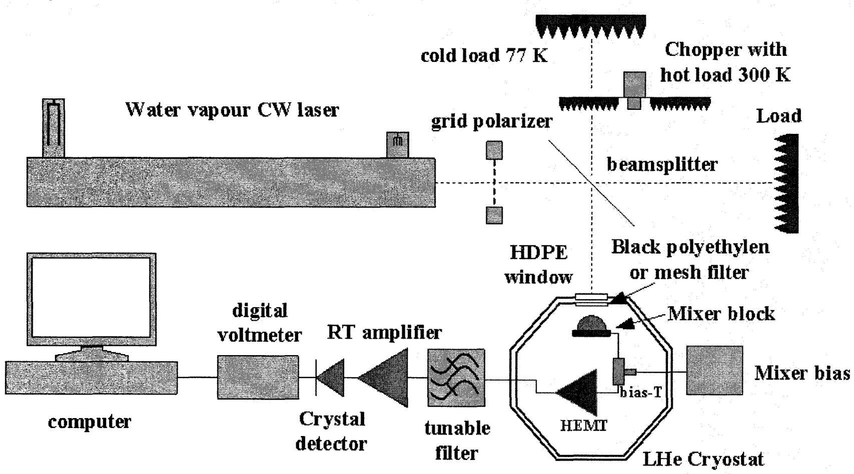

Figure 2. Experimental setup for noise temperature measurements.

The measurements were performed using the CW gas discharge water-vapor laser as a local oscillator. The laser operates on the terahertz transitions of 2.529 THz, 3.826 THz and 3.792 THz. The intensity of transition line at 3.792 THz is essentially weaker than one of the line at 3.826 THz, and the difference between the frequencies of these lines is about 34 GHz. That is why only the 3.826 THz transition line was used in the experiments. The laser was constructed from a straight quartz tube having two openings for the electrodes and for pumping and reflectors against its ends. One of the reflectors was a concave spherical mirror with a 6 meter curvature radius, driven longitudinally to the laser cavity for fine tuning by differential screw arrangement, and the other was a square nickel mesh of wires 10 μm thick, with centre-to-centre spacing of 30 μm (a transmission coefficient of 0.5-1% at 80-120 μm). The laser used a flowing mixture of water vapor and helium (1:2) at a total pressure near 1 Torr. It was excited at an applied voltage of about 2.5 kV. The axial discharge current might be changed over the range of

0.5-1.2 A by current stabilized power supply. High-density polyethylene was used to cover the mesh coupler. The measured diameter of the Gaussian laser beam at half maximum of the intensity profile obtained by scanning the Golay cell across the laser beam at a distance of 1m from the output mesh is 16 mm and 13 mm at 2.5 and 3.8 THz, respectively. The signal and the LO radiation were superimposed by a 10 μm thick Mylar beam splitter. DSB receiver noise temperatures were determined using the Y-factor technique. Ecosorb was used as a hot and cold load. The temperature of the hot and cold loads was 293K and 77K, respectively. The laser systems were stable enough to measure the noise temperature either by putting alternately the hot load and the cold load in the signal path behind the beam splitter or by chopping between the hot and cold loads using a lock-in technique.

3. RESULTS OF NOISE TEMPERATURE AND DIRECT DETECTION EFFECT MEASUREMENTS

Two types of planar antennas are widely used in quasioptical mixers at the moment: twin-slot and log-periodic spiral ones. The log-periodic spiral antenna is the most appropriate to operate at frequencies over 2 THz. This type of antenna has a rather wide input band. Besides, significant variation of spiral sizes leads only to an inconsiderable variation of the antenna bandwidth [4]. On the one hand, this fact enables us to perform noise temperature measurements at various frequencies in a rather wide range. For the best device 180#14 we measured 1300 K at 2.5 THz and 3100 K at 3.8 THz (see Fig. 3).

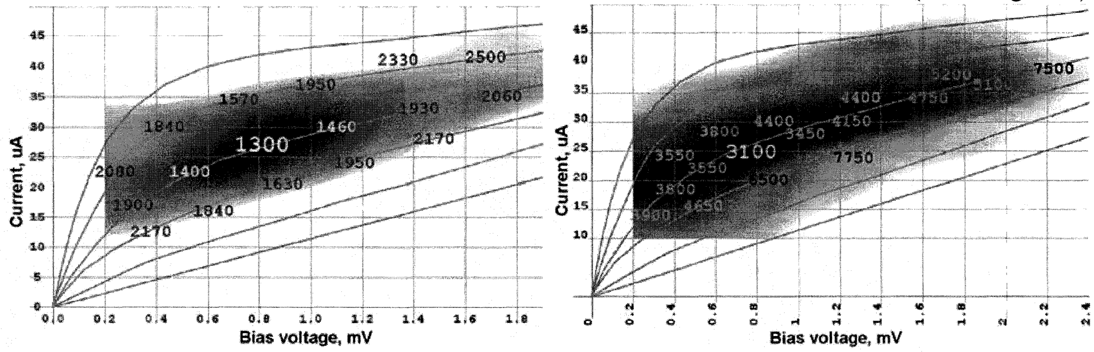

Figure 3. Pumped IV-curve and bias dependence of noise temperature at 2.5 THz (left) and 3.8 THz (right) for device 180#14.

These results are given for the silicon lens without antireflection coating. If the antireflection coatings [5] would be used for each frequency of 2.5 and 3.8 THz the noise temperature values would be about 1050 K and 2500 K respectively. On the other hand, it brings about an additional heating of the mixer electron subsystem and a noticeable variation of the mixer bias current when hot and cold loads are swapped in the signal path of the receiver.

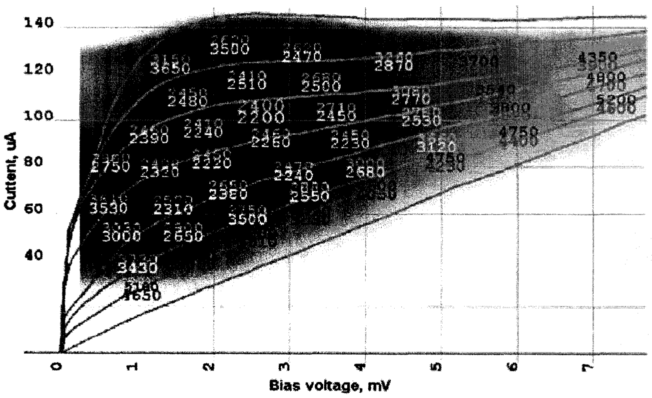

Figure 4. Pumped IV-curve and bias dependence of uncorrected receiver noise temperature at 2.5 THz with black polyethylene used as IR-filter (top) and corrected to direct detection one (bottom) for device 567/1#8.

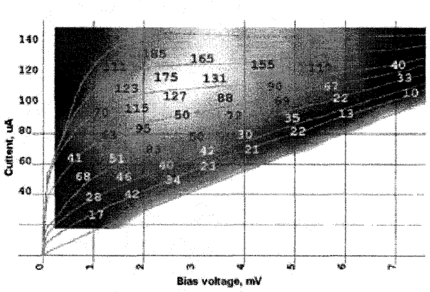

Figure 5. Pumped IV-curve, bias current variation due to the effect of direct detection [in nA] and output IF power P_{out} (shown by brightness) for device 567/1#8.

This effect is known as the effect of direct detection [6]. Since the output power of the mixer is dependent on bias operating point, it leads to a Y – factor measurement error. The error value can be derived from the measured bias current variance value (ΔI) and the derivative dP_{out}/dI taken at the operating point, where "P_{out}" is output IF power of the mixer and "I" is the bias current. The $P_{out}(I)$ dependence and dP_{out}/dI value can be obtained by varying the LO power. ΔI and Y – factor values are measured simultaneously by swapping cold and hot loads. If this experimental error is taken into account, the corrected Y – factor can be roughly expressed as $Y_{cor} = (P_{hot} \pm (dP_{out}/dI) * \Delta I) / P_{cold}$, where P_{hot} and P_{cold} are output power values measured when the hot and cold loads, respectively, are placed in the signal path of the receiver. The contribution of the direct detection effect to the measurement error of mixer noise temperature was studied for a typical mixer 567/1#8. The bias dependence of the noise temperature derived from the directly measured Y – factor is shown in Fig. 4 (above). The minimum value of the directly measured noise temperature is 2400 K. In order to estimate the contribution of direct detection effect, ΔI and P_{out} (Fig. 5) versus bias dependencies were obtained. The estimation of the noise temperature derived from corrected Y – factor is shown in Fig. 4. It is seen that the noise temperature is negatively corrected if the bias current is less than the one corresponding to the maximum of the output IF power. If bias current is more than that corresponding to the maximum of output IF power the noise temperature value is corrected positively. To avoid an error of Y –factor

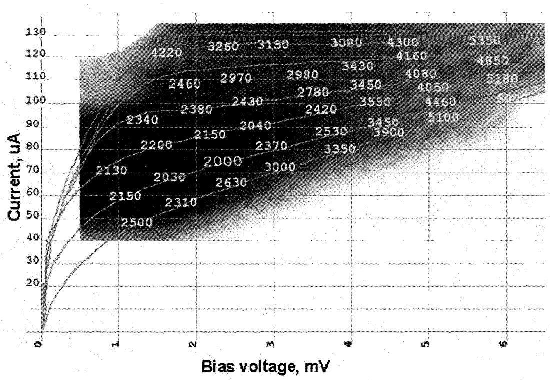

Figure 6. Pumped IV-curve and bias dependence of uncorrected receiver noise temperature at 2.5 THz with a cold input mesh filter.

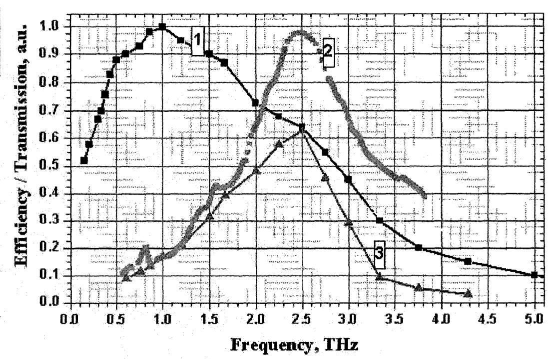

Figure 7. FTS spectra of log-spiral antenna (1), frequency dependence transmission coefficient of the mesh-filter (2) and product of multiplication of these two curves (3)

measurement, an additional input cold IR filter with the bandwidth significantly narrower than that of the spiral antenna can be used. Such a filter must also have low losses at the LO frequency. One of the most appropriate filters is a metal mesh. It is known that a mesh filter with square cells has its transmission versus frequency dependence of a bell curve form. The central frequency of the mesh filter is expressed by $f_{max} \sim 1.2$ d in which d is the period of the mesh. In our experiment a square nickel cell mesh filter with d = 100 μm and a filling factor of 0.15 was mounted on the helium shield of the cryostat instead of the traditionally used black polyethylene IR filter. The mentioned filling factor is the ratio of the wire diameter to the mesh period. The transmission vs. frequency dependence of the filter is shown in Fig. 7. When the mesh filter is used, ΔI is decreased until it is less than 10 nA at the optimal noise temperature point, and the error of the noise temperature measurement becomes negligible. Furthermore, the replacement of a black polyethylene IR filter by a mesh filter caused a noticeable decrease of the noise temperature of the receiver. The noise temperature versus bias dependence for the receiver with a cold input mesh filter is shown in Fig. 6. At the optimal operating point the directly measured noise temperature is about 2000 K which is even less than the noise temperature obtained by Y – factor correction for the same receiver with polyethylene input IR filter. Hence, the use of the cold input mesh filter not only enables us to avoid the effect of direct detection but also decreases optical losses.

4. POLARIZATION MEASUREMENTS

Polarization measurements of the mixer integrated with a spiral antenna were done using the experimental setup shown in Fig. 8. Linearly polarized radiation of FIR water vapor laser passed through the rotator of the polarization plane and applied to the mixer fixed on hyperhemispherical lens inside the helium cryostat. The rotator of the polarization plane used is based on a 3 – mirrors reflector. The rotation of the polarization plane was due to rotation of the reflector, as shown in Fig. 8. The laser output power was calibrated by the Golay cell.

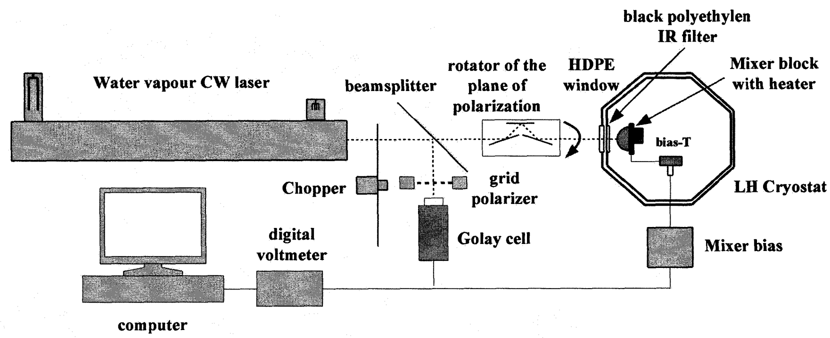

Figure 8. Experimental setup for polarization measurements.

The temperature of the mixer was maintained around the critical value by a heater. The laser radiation was chopped at a frequency of 20 Hz. The mixer was biased by a current source, and the amplitude of the mixer voltage oscillation at the chopping frequency was the measured signal value, which in its turn was reduced to

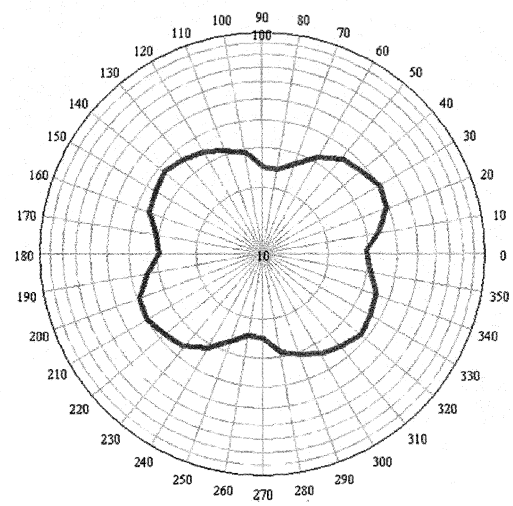

Figure 9. Polarization response of NbN HEB mixer integrated with log - periodic spiral antenna at 3.8 THz LO frequency.

the value of absorbed power. The results of the polarization measurements at 3.8 THz are presented in fig.9. As seen from the Figure, absorbed power can vary more than 2 dB when the polarization plane of the input radiation is rotated. Hence, the noise temperature of the receiver significantly depends on the polarization of the input radiation even if a spiral antenna - coupled mixer is used.

5. CONCLUSION

Direct detection contribution to the measured Y-factor leads to an error of noise temperature calculation of more than 8% for the mixer with in-plane dimensions of 2.4 x 0.16 μm^2.

Polarization of mixer integrated with log-periodic spiral antenna can differ slightly from the circular one at a frequency over 2.5 THz and is about 2 dB at 3.8 THz.

The measured receiver noise temperatures are 1300 K at 2.5 THz LO frequency and 3100 K at 3.8 THz. It should be stated that the obtained noise temperatures are based on the measurements with a lens without an antireflection coating and without regard to the contribution of direct detection. Taking into account the optical losses due to reflection on the silicon lens [6] the corrected receiver noise temperatures are 1050 K and 2500 K at 2.5 and 3.8 THz, respectively.

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