ORAL SESSION n°5

« HEB »

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Chaired by :

Dr. Boris Karasik & Dr. Edward Tong

Spiral antenna coupled and directly coupled NbN HEB mixers in the frequency range from 1 to 70 THz

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***Abstract*—We investigate both antenna coupled and directly coupled HEB mixers at several LO frequencies within the range of 2.5 THz to 70 THz. H_2O (2.5÷10.7 THz), and CO_2 (30 THz) gas discharge lasers are used as the local oscillators. The noise temperature of antenna coupled mixers is measured at LO frequencies of 2.5 THz, 3.8 THz, and 30 THz. The results for both antenna coupled and directly coupled mixer types are compared. The devices with in–plane dimensions of 5×5 μm^2 are pumped by LO radiation at 10.7 THz. The directly coupled HEB demonstrates nearly flat dependence of responsivity on frequency in the range of 25÷64 THz.**

***Index Terms*—Superconducting radiation detectors, Hot carriers, Bolometers, Mixers.**

I. Introduction

The performance of antenna coupled NbN HEB mixers is mostly investigated at the frequencies below 5 THz [1], [2]. There are only two other types of the mixers, except for HEB mixer, which are being developed for terahertz range – Schottky and SIS mixers, but at frequencies above 1.25 THz SIS mixer is not applicable yet [3] and Schottky one demonstrates much worse sensitivity, not sufficient for most applications [4]. Although antenna coupled NbN HEB mixer significantly outperforms Schottky or SIS one in the sensitivity at frequencies over 1.2 THz, its own noise performance becomes essentially worse when LO frequency exceeds 4 THz. It is believed that this is caused by smaller size of planar antenna at higher frequencies and accordingly smaller area of the contacts between the sensitive NbN bridge and Au antenna. As a result the contact resistance increases as well as RF losses [5].

It has been suggested to use the structures coupled to the radiation directly i.e. without any additional Au planar antenna patterned on the mixer chip [6]. In this case the sensitive bridge itself is appeared to be an absorber, and the contacts, being in the IF circuit, are appeared to be excluded from RF circuit at all.

This article is devoted to the work aimed at the realization of the idea of directly coupled mixer which can improve NbN HEB mixers performance at higher terahertz LO frequencies and also make them applicable in the middle IR.

II. Antenna coupled mixer at 2.5 and 3.8 THz

Let us consider our results achieved for antenna coupled NbN HEB mixers at LO frequencies below 4 THz. The DSB noise temperature of our NbN HEB mixers at 2.5 THz is reported to be about 1300 K, while at 3.8 THz the noise temperature value is increased up to 3100 K [7]. Both the values are still more than one order of magnitude higher than the quantum limit at corresponding frequencies and amount to $11\frac{hf_{LO}}{k}$ and to $17\frac{hf_{LO}}{k}$, respectively. In these expressions f_{LO} is the LO frequency. Such an increase of antenna coupled mixer noise temperature can not be explained by taking into account the quantum noise only. The most probable explanation is the raise of RF losses partly due to contact resistance which increases with the LO frequency. This contacts resistance mostly affect RF current because at the LO frequency the sheet resistance of NbN layer ($\sim 500\frac{\Omega}{\square}$) is 3 orders of magnitude higher than that of covering Au layer ($\sim 0.8\frac{\Omega}{\square}$). Due to this fact the RF current flows into active NbN film only in the small area near the edges of the antenna (fig. 1). The characteristic antenna size may depend on RF frequency in a manner that if frequency is increased a smaller antenna should be chosen for integration with the sensitive bridge. As a result, at higher frequencies the areas where RF current flows become smaller and smaller, the effective contact resistance is increased, and consequently, noise temperature becomes worse.

III. Directly coupled mixer at 30 THz

The NbN HEB mixer designed for the frequency of 30 THz do not have an additional planar antenna integrated with its sensitive bridge. It utilizes an ability of electron subsystem of disordered NbN film to absorb incident radiation directly. For preliminary experiments we have chosen the most simple configuration of the sensitive bridge. Active area of NbN film between Au IF contacts was patterned in a form of a rectangle with dimensions close to 30×20 μm^2 (fig. 2). If the wave front of LO beam is flat the LO radiation is focused on the film in a spot with the diameter limited by diffraction. At the

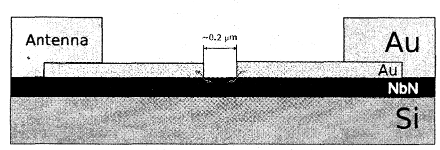

Fig. 1. RF current in the contacts between sensitive NbN bridge and Au antenna. The small area where RF current flows is denoted by the arrows.

LO frequency of 30 THz the diameter of the diffraction limited LO spot is about 5 μm that is less than the dimension of the sensitive area side (fig. 3), so it can be stated that all the absorption of incident radiation only occurs inside the NbN bridge contour.

The form of the LO wave front affects the pumping of directly coupled HEB mixer. If LO spot is smaller than the superconducting bridge (fig. 3, left graph) superconducting DC current may flow around it. Corresponding IV – curve is marked as "diffraction limited LO spot" in fig. 4. In the case of defocused LO the whole NbN bridge is pumped to the resistive state (fig. 3, right graph) and corresponded IV–curve is marked as "slightly defocused LO spot". It should be noted that both the curves highlighted in fig. 4 correspond to the same LO power.

Another reason to defocus the LO spot follows from the fact

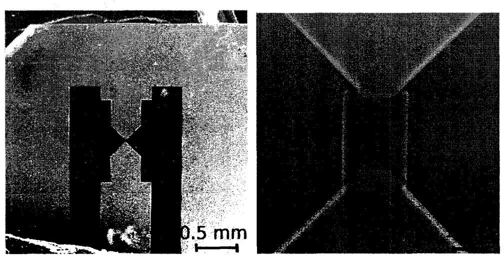

Fig. 2. SEM photos of directly lens coupled NbN HEB mixer.

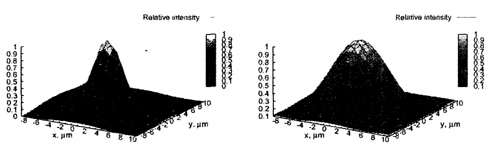

Fig. 3. Simulated intensity of LO spot on the NbN sensitive bridge at 30 THz. The left graph corresponds to the flat wave front, while the right graph corresponds to the situation when the LO spot is slightly defocused. The dimensions of x–y planes shown in the images are close to the in–plane dimensions of NbN sensitive bridge. The simulation are given for hemispherical Ge lens with the diameter of 12 mm and extension length of 1.96 mm.

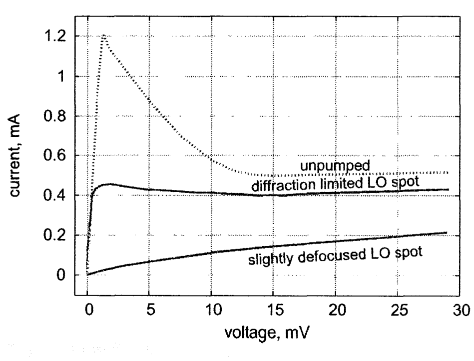

Fig. 4. IV – curves versus LO spot for directly coupled NbN HEB.

that down conversion of RF signal happens only in the area pumped by LO. In particular, in the noise temperature measurement the image of the hot/cold black body load overlap all the mixer's sensitive area. As LO spot may be smaller than the device area overlapped by the load image, not all parts of this area may be involved in the down conversion. In order to involve all the sensitive area into the down conversion it is sufficient to make the diameter of the LO spot to be close to the active area size. This can be achieved by a slight defocussing of the LO spot.

The optimal absorbed LO power for directly coupled NbN HEB was estimated by isothermal technique. Its value amounts to 20 μW [6]. It should be noted that this value is at least 20 times higher than that for antenna coupled mixers. At the same time, there is no lack of powerful radiation sources in the infrared region containing, in particular, the frequency of 30 THz at which the experiments on the noise temperature measurement were carried out. At lower frequencies (5÷10 THz) sufficient LO power can be obtained by use of recently introduced quantum cascade lasers.

The noise temperature at 30 THz for directly coupled NbN HEB mixers was measured by Y-factor technique using a CO_2 gas discharge laser as LO. Only two measurements were done – with 600 K and 1200 K hot black body loads. In both measurements a room temperature black body was used as a cold load. The *Callen & Welton noise temperature* was close to 2300 K, that was amounted to 3 times of the quantum limit [6].

The responsivity of the receiver was investigated in the detection mode using a chopped filament and a room temperature black body as the signal loads. In order to obtain a rough dependence of the receiver's responsivity versus frequency a set of bandpass dispersion filters was used (fig. 5). For certain filter the responsivity is expressed as:

$$s \simeq \frac{U_r}{\int_0^\infty \mathcal{T}(\nu)\left(\mathcal{D}_\nu(\nu, T_{bb}) - \mathcal{D}_\nu(\nu, T_r)\right) \mathrm{d}\nu} \qquad (1)$$

where $\mathcal{D}_\nu$ is the incident power per unit bandwidth, $\mathcal{T}(\nu)$ is the dependence of the filter transmission versus frequency, $T_r \simeq 296$ K and $T_{bb} \simeq 1200$ K are the room and filament temperatures, respectively, and U_r is the response voltage.

In the experiments, U_r was measured by a lock–in amplifier for each filter of the set, and then the responsivity was calculated using (1) (fig. 5).

It can be concluded that at the frequencies $\lesssim 25$ THz the device responsivity is cut by Ge input window of the cryostat and the lens, while at the frequencies $\gtrsim 25$ THz the responsivity is almost flat and close to 70 $\frac{V}{W}$.

The radiation pattern of the heterodyne receiver based on directly coupled NbN HEB mixer is narrower than that of log–spiral antenna coupled HEB and amounts to 0.6° [6]. This experimental result is in good agreement with simulation of Gaussian radiation pattern for the sensitive area with in–plane dimensions of 20×20 μm^2 (fig. 6).

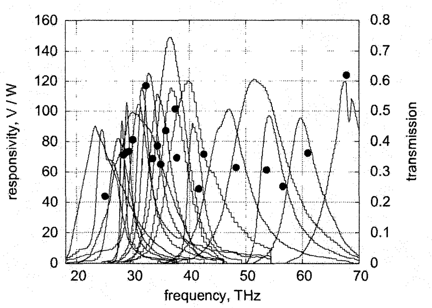

Fig. 5. The dependence of the receiver's responsivity versus frequency (filled circles) and the transmissions of the bandpass filters used in the experiment (lines).

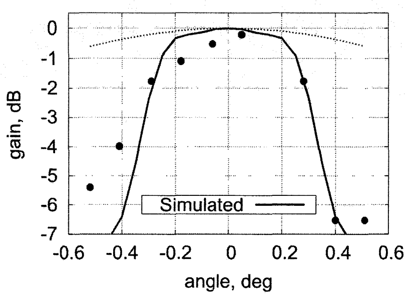

Fig. 6. Radiation pattern of directly coupled NbN HEB mixer based receiver at 30 THz (solid circles). Dotted line corresponds to the radiation pattern of the system consisting of Si lens, spiral antenna and a mixer at 2.5 THz [8]. Solid line corresponds to the simulation given for hemispherical Ge lens with the diameter of 12 mm and extension length of 1.96 mm. More detailed description of the receiver is given in [6].

IV. HEB MIXER FOR 10.7 THZ LO FREQUENCY

The H_2O gas discharge laser used for investigation of the noise temperature at 2.5 THz and 3.8 THz has also an emission line at 10.7 THz. However the intensity of this line is not enough to pump the directly coupled HEB mixers with the active area dimensions of $30 \times 20\ \mu\mathrm{m}^2 \times 4$ nm. Investigations at 10.7 THz were performed using HEB mixers with smaller, $5 \times 5\ \mu\mathrm{m}^2$, active area. The coupling of smaller mixer with LO radiation at 10.7 THz is strongly dependent on the orientation of the mixer relatively to the polarization of LO. More power is absorbed by the mixer if $\vec{E}$ is directed across the slot between the Au contacts (fig. 7). This can be explained if we consider this contacts as an antenna.

V. CONCLUSIONS

Planar antenna coupled NbN HEB mixers exhibit low noise temperature at the terahertz frequencies: from 0.7 to 2.5 THz it is close to $10\frac{hf_{LO}}{k}$ and at 3.8 THz it is about $17\frac{hf_{LO}}{k}$ (3100 K). At higher terahertz frequencies it goes up much steeper because of antenna and contacts losses. Preliminary investigations of directly coupled to radiation NbN HEB mixer demonstrate high sensitivity that can be obtained with this type of coupling: at 30 THz *Callen & Welton noise temperature* is about 2300 K that is close to $3\frac{hf_{LO}}{k}$.

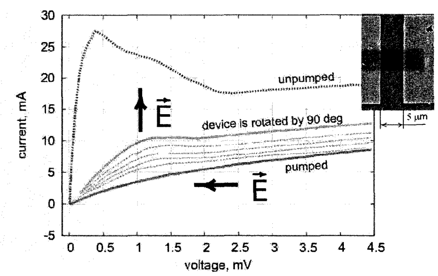

Fig. 7. LO pumped IV-curves for $5 \times 5\ \mu\mathrm{m}^2$ device at 10.7 THz.

For $30 \times 20\ \mu\mathrm{m}^2$ device the optimal absorbed LO power is about 20 μW. Responsivity of the device versus frequency is almost flat and amounts to 70 $\frac{\mathrm{V}}{\mathrm{W}}$ in the frequency range of 20÷70 THz. At 10.7 THz we pumped $5 \times 5\ \mu\mathrm{m}^2$ device that is smaller than the radiation spot and did not have enough LO power to pump $30 \times 20\ \mu\mathrm{m}^2$ device.

ACKNOWLEDGMENTS

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