Terahertz Spectroscopy by Josephson Oscillator and Cold-Electron Bolometer

M.Tarasov, L.Kuzmin, E.Stepantsov, I.Agulo, T.Claeson

Chalmers University of Technology, Gothenburg SE 41296 Sweden
Email: Mikhail.Tarasov@mc2.chalmers.se

ABSTRACT

For sensitive wideband spectroscopy at THz frequencies with performance better than for Fourier Transform Spectrometer, one needs a wide-range electrically tunable, narrow linewidth THz source, and a sensitive broadband detector. To obtain a low noise level of sensor we use a superconducting normal metal cold electron bolometer (CEB). A voltage response of the bolometer is $4 \cdot 10^{8}$ V/W and an amplifier-limited technical noise equivalent power of the bolometer is $1.25 \cdot 10^{-17}$ W/Hz$^{1/2}$. The wide band electrically tuned terahertz band cryogenic oscillator is a Josephson junction. Contrary to conventional Josephson junctions based on niobium, and naturally limited in frequency by energy gap of about 700 GHz, the high critical temperature YBaCuO junctions can extend this limit by an order of magnitude. At 4 K such oscillators can radiate at frequencies exceeding 2 THz. Signals received by bolometers integrated with double-dipole and log-periodic antennas and irradiated by the Josephson oscillator show in our experiments the high frequency response corresponding to an oscillation frequency of up to 1.75 THz. Such cryogenic terahertz network analyzer is suitable for low-signal spectral evaluation of cryogenic detectors, quasioptical sub-mm cryogenic filters, planar antennas with planar microwave filters, integrated structures comprising such elements, and arrays of cryogenic receivers.

INTRODUCTION: SAMPLES, LAYOUT AND FABRICATION

A cold electron bolometer with capacitive coupling (CCNHEB) was proposed in [1] and experimentally demonstrated in [2]. Responsivity and noise equivalent power (NEP) of the bolometer are mainly determined by its electron temperature. To improve CCNHEB performance we suggest using direct electron cooling of the absorber by a superconductor-insulator-normal metal (SIN) tunnel junction [3]. The effect of electron cooling was demonstrated in [4] and further developed in [5]. General view on NHEB chip is presented in Fig. 1. A SEM view of the bolometer is presented in Fig. 2. The first step of sample fabrication was thermal evaporation of 60 nm Au for fabrication of the normal metal traps and contact pads. The next step was the fabrication of the tunnel junctions and the absorber. The structures were patterned by e-beam lithography and the metals were thermally evaporated using the shadow evaporation technique. The Al (superconductor) was evaporated at an angle of about 60° up to a thickness of 65 nm and oxidized at a pressure of 10^{-1} mbar for 2 minutes. A Cr/Cu (1:1) absorber of a total thickness of 75 nm was then evaporated directly perpendicular to the substrate. The cooling junctions have a normal state resistance R_N equal to 0.86 kΩ, while the two inner junctions have R_N equal to 5.3 kΩ. The inner junctions have a simple cross geometry, where a section of the normal metal absorber overlaps the thin Al electrodes. The area of overlap, which makes to the area of each of the tunnel junction, is equal to 0.2 x 0.3 μm^2. The structure of the outer junctions is such that the ends of the normal metal absorber overlap with a corner of each of the Al electrodes, which have a much larger area, compared to the middle Al electrode. The area of each of these junctions is 0.55 x 0.82 μm^2. The purpose of the larger area Al electrode is to give more space for quasiparticle diffusion compared to the middle Al electrode with simple cross geometry. In the described structure, the two outer and inner junctions have the R_N equal to 0.85 kΩ and 5.4 kΩ, respectively. The volume of the absorber was 0.18 μm^3.

A bias cooling current is applied through the outer junctions and the absorber. These tunnel junctions act as the cooling junctions, and therefore serve to decrease the electron temperature of the absorber. To determine the electron temperature, the voltage across the inner junctions is measured. A small current bias is applied to these junctions. The bias has to be optimal to obtain the maximum linear voltage response on temperature, and yet not too large so as to disturb the cooling process in the absorber.

High critical temperature Josephson junctions on tilted bicrystal sapphire substrates were fabricated in YBaCuO epitaxial films with c-axis inclined in <100> direction by angle 14°+14°. Junctions were integrated with log-periodic antennas (see Fig. 3). Films 250 nm thick were deposited by pulsed laser ablation on tilted sapphire bicrystal substrates

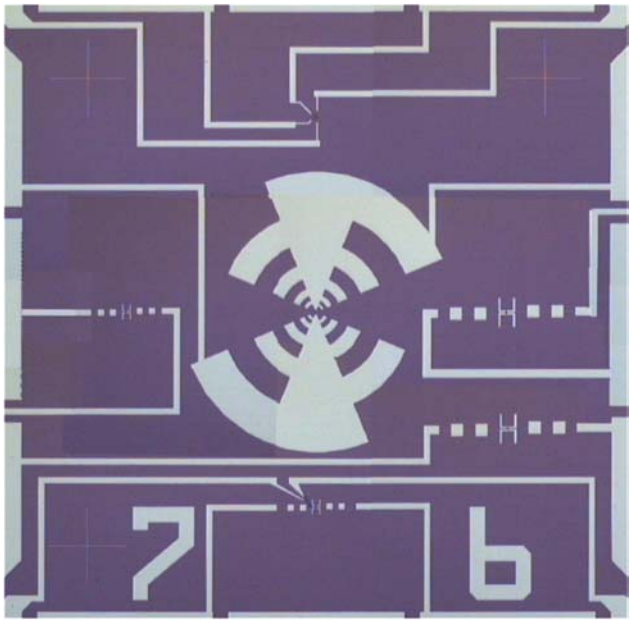

Fig. 1. A bolometer chip layout. A wideband log-periodic antenna at the center, a 600 GHz double-dipole antenna to the left and two 300 GHz double-dipole antennas to the right.

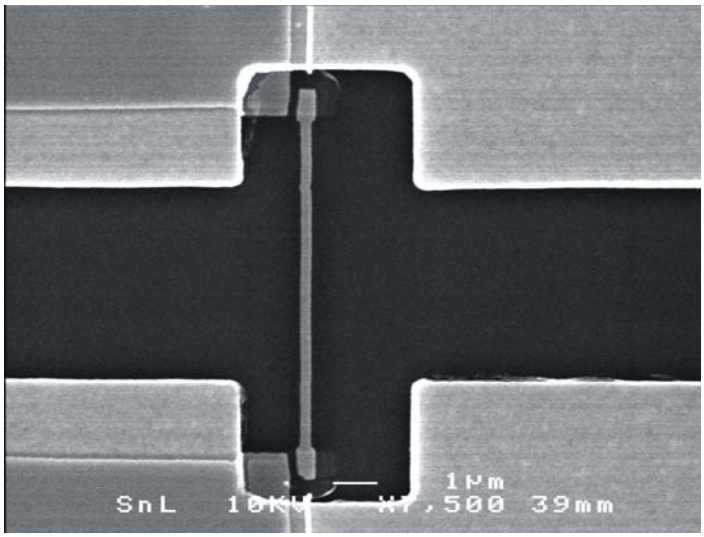

Fig. 2. A SEM view of the central part of a double-dipole antenna with bolometer.

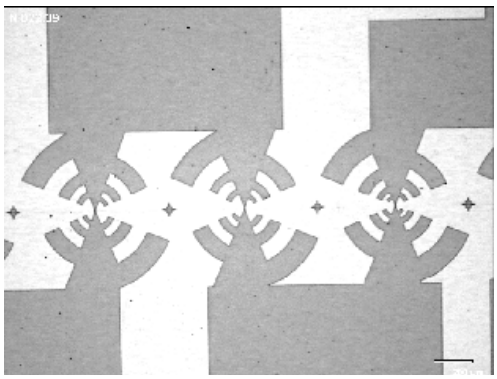

Fig. 3. Central part of a Josephson oscillator chip

covered by a CeO_2 buffer layer. The critical temperature of the film was T_c=89 K and ΔT_c=1.5 K. Bicrystal Josephson junctions of width from 1.5 to 6 μm at a temperature of 4.2 K demonstrated a characteristic voltage $V_c=I_cR_n$ of over 4 mV that corresponds to the oscillation frequency 2 THz.. This makes them promising candidates as oscillators for Terahertz frequency band applications.

POWER AND TEMPERATURE RESPONSES OF THE BOLOMETER

We measured the temperature response of the bolometers at the lowest temperature of about 260 mK that is available in our He3 sorption cooler cryostat. The dc response was measured at upper and lower structures with four SIN junctions. Two external junctions were used as thermometers and two internal as heaters. The highest value of voltage response to temperature variations is over 1.6 mV/K and the largest current response about 37 nA/K for a 10 kΩ junction and 55 nA/K for a 6 kΩ junction.

It was possible to apply a dc power to the central pair of junctions and measure the response of the outer pair of SIN junctions for these samples with four SIN junctions. Results of current and voltage responses on dc power are presented in Fig. 4. We observed the largest voltage response of 400 V/μW for a 70 kΩ junction and 550 A/W for a 10 kΩ junction. The obtained values of current and voltage responses can be converted to the natural figure of merit for the sensitivity of the bolometer in terms of a Noise Equivalent Power (NEP)

$$NEP=I_n/S_i \text{ or } NEP=V_n/S_v \tag{1}$$

in which I_n is the current noise, V_n is the voltage noise, S_i=dI/dP is the current response, S_v=dV/dP is the voltage response of the bolometer. Taking the voltage noise of a room-temperature preamplifier about 3 nV/Hz$^{1/2}$ one can obtain the technical TNEP value TNEP=$1.25\cdot10^{-17}$ W/Hz$^{1/2}$. Using measured values of the temperature response and the power response one can also obtain the thermal conductivity of the bolometer.

$$G_V = \frac{\partial P}{\partial T} = \frac{\partial V / \partial T}{\partial V / \partial P} = 0.8 \cdot 10^{-11} W / K \tag{2}$$

Now we can calculate the thermodynamic NEP arising from the electron-phonon interaction $NEP_{ep}^2=4kT^2G$ in which thermal conductivity $G=5\Sigma\nu T^4=10^{-11}$ W/K, ν is the absorber volume. This brings a thermodynamical noise equivalent power $NEP_{TD}=1.4\cdot10^{-18}$ W/Hz$^{1/2}$, and if we compare with the thermal conductivity in the voltage bias mode it corresponds to a $NEP_V=1.3\cdot10^{-18}$ W/Hz$^{1/2}$.

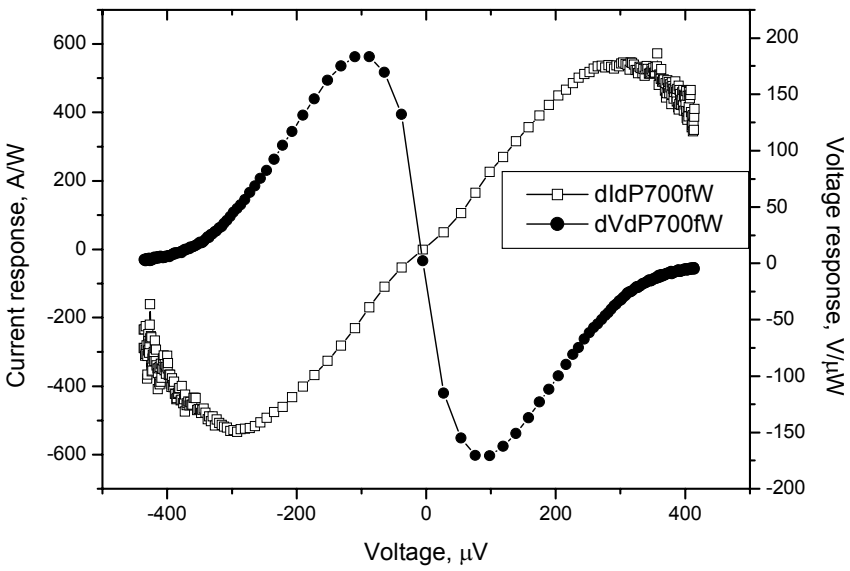

Fig. 4. Current and voltage responses for a 10 kΩ SIN junctions on the applied power at 260 mK.

MEASUREMENTS OF THE RESPONSE WITH A JOSEPHSON JUNCTION AT 260 MK

In the experiment we use a direct connection of the substrate with the Josephson oscillator to the substrate with the receiver (see Fig 5). When a planar antenna is placed on a dielectric substrate with a high refraction index, the main lobe of the beam-pattern is directed into the substrate. In this case most of the radiation from the Josephson oscillator is directed to the antenna with the bolometer. The log-periodic antennas used in both oscillator and receiver chips (see Fig. 1,3) are designed for frequencies 100-2000 GHz and 200-2000 GHz.

The measured dependencies of the bolometer voltage response are presented in Fig. 6. We choose a Josephson junction with rather low critical current about 20 μA to avoid overheating of both Josephson oscillator and attached bolometer. Applying a magnetic field one can suppress the critical current of Josephson junction, which leads to a decrease of the output power of Josephson oscillations and the frequency range according to the Josephson equations. When the critical current is suppressed below 2 μA the response voltage is clear proportional to the square of the JJ bias current and is no more affected by magnetic field. It means that we completely suppressed Josephson radiation and the residual radiation is just a thermal radiation by overheated normal resistance of the Josephson junction matched to the broadband antenna. This brings clear evidence that we can separate the Josephson radiation at frequencies below 1 THz and the thermal radiation of overheated matched load for bias voltages over 1 mV.

For Josephson oscillators we can estimate the maximum available power as $P_{osc}=0.1 \cdot I_c V_c=2 \cdot 10^{-9}$ W. Misalignment of antennas, mismatch of beam-patterns, material losses, mismatch of impedances can bring the total attenuation of the maximum power up to 30 dB that corresponds to an available power at the bolometer of about 10^{-12} W. The estimated above bolometer responsivity is $S=1.1 \cdot 10^{8}$ V/W that brings the maximum voltage response to this power about $1.1 \cdot 10^{-4}$ V. In our experiments we measured the voltage response up to 10 μV. The order of magnitude difference in response can be explained due to a non-ideal IV characteristic of the Josephson junction (excess current) and overheating that reduces the output power.

If we take as an approximation a model of overheating in a Josephson junction by [6] for a variable thickness microbridge

$$T_m = \sqrt{T_b^2 + 3\left(\frac{eV}{2\pi k}\right)^2} \tag{3}$$

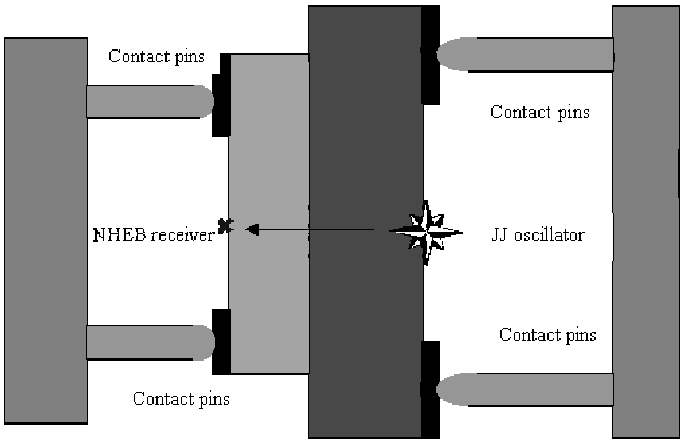

Fig. 5. Schematic view for experimental setup at 260 mK in back-to-back configuration

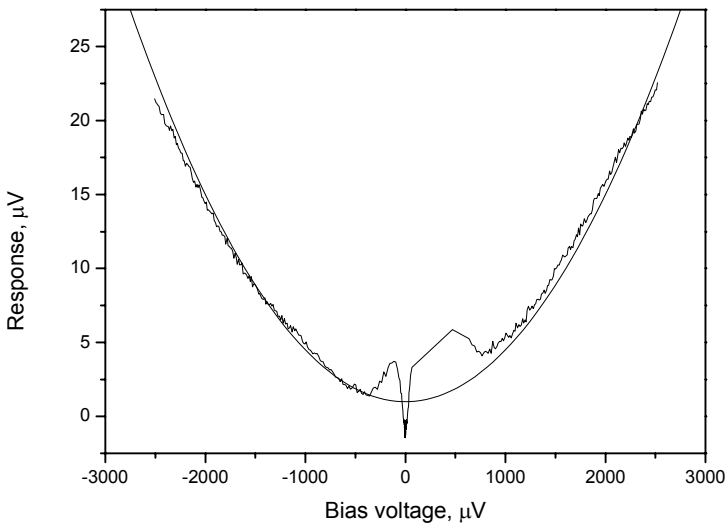

Figure 6. Bolometer response measured with a Josephson junction radiation source at 260 mK. The solid parabola is a fit for Joule heating.

in which T_b is bath temperature, V is a dc voltage bias; it brings the equivalent electron temperature at 1 mV bias of about 3 K. Taking into account that IR radiation is spread in a 4π solid angle and the bolometer is at a distance of over 1 mm, the dielectric can absorb a small part of this radiation, the measured increase in received temperature of 5 mK looks reasonable. Now we should take into account that this power is radiated and then received. It means that Plank's radiation law should be applied

$$P_r = \frac{hf}{e^{\frac{hf}{kT}} - 1} 0.3 f \tag{4}$$

for which the maximum of radiation is obtained at hf≈kT. If we apply the Plank's formula to equation (1) neglecting the phonon temperature

$$P_{rad} = \frac{0.6}{4\pi^2} \cdot \frac{e^2 V^2}{h} \tag{5}$$

it brings the square-law voltage dependence, as observed in the experiment.

IRRADIATION OF THE BOLOMETER BY A DISTANT JOSEPHSON JUNCTION AT 1.8 K.

To increase the output microwave power from the Josephson junction, the characteristic voltage I_cR_n , and oscillation frequency, it is necessary to increase the critical current of the Josephson junction from 20 μa as above, to over 500 μA. Placing the Josephson junction separately on the He4 stage prevents the bolometer from overheating by the relatively high power absorbed by the Josephson junction. Schematic view on experimental quasioptical setup is presented in Fig. 7. As the example if we take a junction with 10 Ωnormal resistances and oscillation frequency 300 GHz, it brings the absorbed power over 0.2 μW. At 1 THz it is already 2.5 μW. Such power is acceptable for He4 stage, but is rather high for millikelvin stage.

The layout of the Josephson sample was the same as in the 260 mK experiments with similar log-periodic antennas, but the critical current was over 500 μA at 2 K. As a result the I_cR_n product exceeds 5 mV for non-hysteretic junctions and

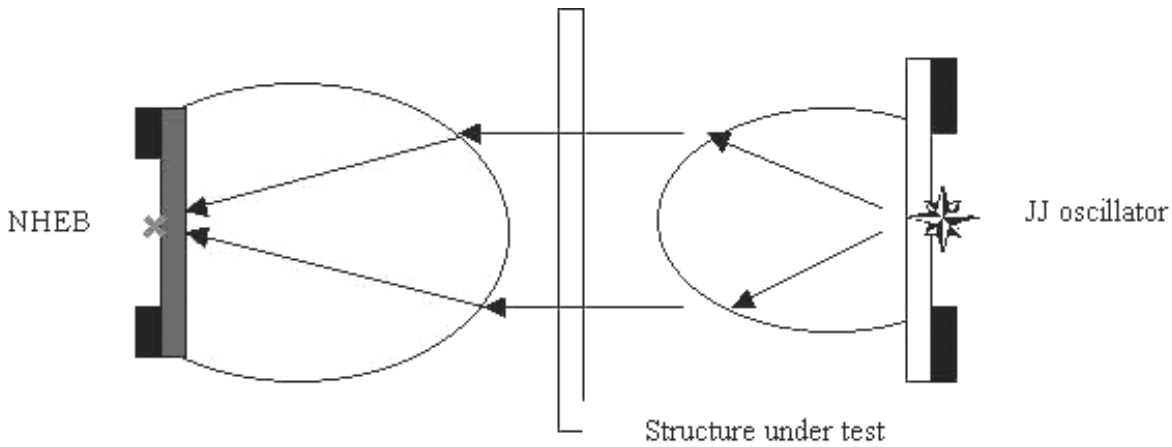

Fig. 7. Schematic view for quasioptical setup with NHEB lens-antenna unit at 260 mK and Josephson junction oscillator lens-antenna unit at 1.8 K.

such oscillators can in principle operate at frequencies over 2.5 THz. Experimental curves in Fig.8 measured by bolometers integrated with double-dipole and log-periodic antennas, reveals that there is clear maximum at the design frequency 300 GHz for DDA and smooth spectrum for LPA. Smooth reduction of signal received by log-periodic antenna can be easy explained by the increase of the beampattern width. In the simplest case of Gaussian telescope the output beam waist that is located at the focal distance L_f from the lens can be estimated as

$$w_{out} = \frac{\lambda L_f}{\pi w_{in}} \tag{6}$$

It is proportional to frequency, and corresponding losses

If signal is measured for two different values of I_c for oscillator, one can see that suppressing the critical current by a magnetic field reduces the output power of the Josephson oscillator. The response at higher bias voltages for Josephson oscillator is presented in Fig. 9. The highest frequency maximum corresponds to an oscillation frequency of 1.75 THz.

In general the Josephson junction oscillations spectrum contains not only the first harmonic at frequency $f_1=(2e/h)V$, but also harmonics at $f_n=nf_1$. According to [7] the amplitude of these harmonics is largest for the first one, it is equal to V_c, and decrease with the number as $V_n=V/(I/I_c+V/V_c)^n$. This dependence is rather weak for voltages below the V_c and can be roughly approximated as $(V_{c1}/V_{c0})^{n-1}$ for bias voltages above the characteristic voltage. If we suppress the critical current so that V_c is below the bias voltage, it will bring strong suppression of higher harmonics and their impact will be negligible.

DISCUSSION

A simple analytic analysis of the voltage response gives a rough relation for the practically achievable power response:

$$S_V^{\max} = \frac{2k_b}{e\Sigma\upsilon T_e^4} = 100 \text{ V/}\mu\text{W} \tag{7}$$

We can roughly estimate the characteristics for voltage bias mode with electron cooling. The main power stream from phonons to electrons is

$$P_{Ph-e} = \Sigma\nu T_{Ph}^5 = 0.5pW \tag{8}$$

To remove such a power from the electron system it is necessary to apply a cooling current

$$I_c = \frac{eP_{Ph-e}}{k_b T} = 2.2\cdot 10^{-8} A \tag{9}$$

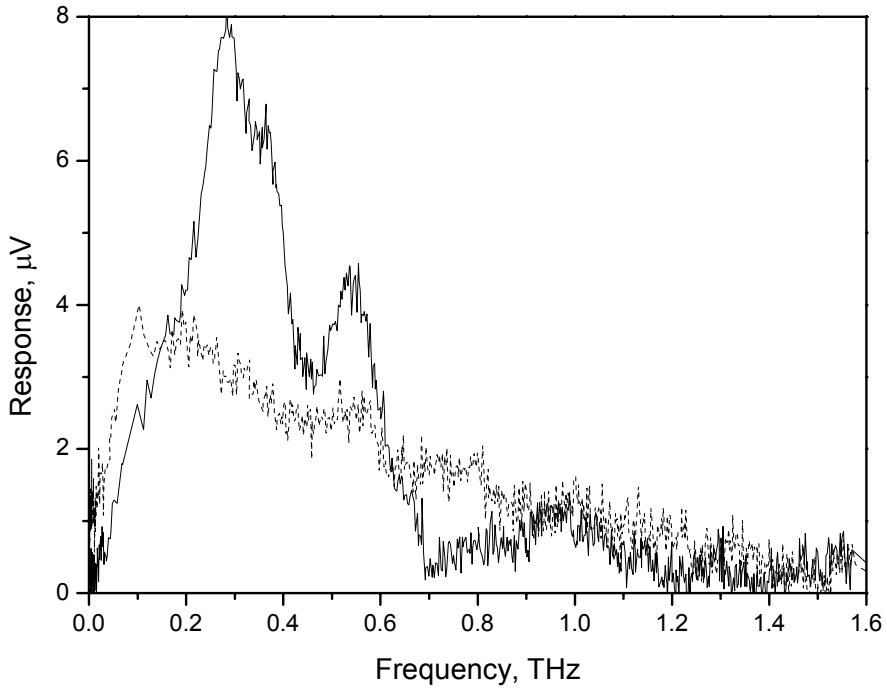

Fig. 8. Response measured by a double-dipole antenna (straight line), and a log-periodic antenna (dashed line) for the same Josephson radiation source.

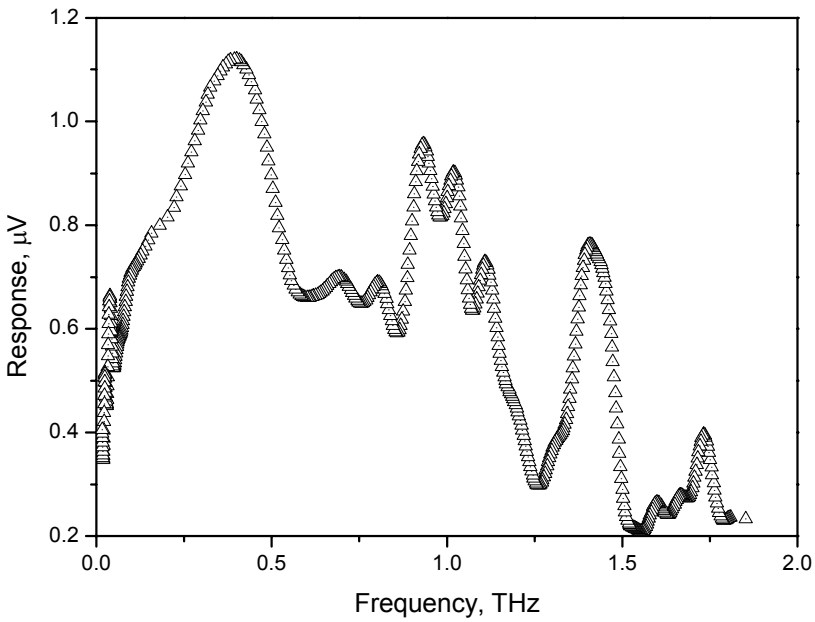

Fig. 9. Response measured for high bias voltages of the Josephson junction. Last maximum corresponds to oscillation frequency 1.75 THz.

This cooling current is associated with a shot noise. If we take the theoretical value for the current response $S_I=e/2k_bT=6\cdot10^3$ A/W it brings the

$$NEP_I = \sqrt{4k_b T_e \Sigma \nu T_{Ph}^5} = 1.3\cdot10^{-17}\ \mathrm{W/Hz^{1/2}} \tag{10}$$

From the two dependencies above one can also obtain the required noise equivalent power for a voltage bias mode of operation. It is determined by the thermal conductivity of the SIN junction.

CONCLUSION

We demonstrated the first experimental response of a normal metal cold electron bolometer at frequencies up to 1.7 THz. A voltage response of the bolometer is $4\cdot10^8$ V/W and an amplifier-limited technical noise equivalent power of the bolometer is $1.3\cdot10^{-17}$ W/Hz$^{1/2}$. We use electrically tunable high critical temperature Josephson quasioptical oscillator as a source of radiation in the range 0.2-2 THz. A high critical temperature Josephson junction operated at temperature about 2 K shows a I_cR_n product over 4.5 mV that enables an oscillation frequency over 2 THz. Combination of a Terahertz-band Josephson junction and a high-sensitive hot electron bolometer brings a possibility to develop a quasioptical cryogenic compact spectrometer with a resolution of about 1 GHz. Such cryogenic spectrometer can be used for low-temperature spectral evaluation of cryogenic detectors, quasioptical submm wave grid filters, neutral density filters, absorbers, etc. Cold electron bolometer detected that a Josephson junction is overheated by a transport current even when it is placed on millikelvin stage.

ACKNOWLEDGEMENTS

Authors acknowledge support from VR, STINT, INTAS-01-686.

REFERENCES

[1] L. Kuzmin, "On the Concept of a Hot-Electron Microbolometer with Capacitive Coupling to the Antenna", *Physica B: Condensed Matter*, vol. 2129, pp. 284-288, 2000.

[2] M. Tarasov, M. Fominsky, A. Kalabukhov, and L. Kuzmin, "Experimental study of a bolometer on hot electrons in normal metal with capacitive coupling", *JETP Letters*, vol. 76, № 8, pp 507-510, 2002.

[3] L. Kuzmin, I. Devyatov, and D. Golubev, "Cold-electron" bolometer with electronic microrefrigeration and the general noise analysis". *Proceedings of SPIE*, vol. 3465, pp. 193-199, July 1998.

[4] M. Nahum, T.M. Eiles, and J. M. Martinis, "Electronic microrefrigerator based on a normal-insulator-superconductor tunnel junction", *Appl. Phys. Lett.*, vol. 65, N 24, pp. 3123-3125, 1994.

[5] M. Leivo, J. Pecola, and D. Averin, "Efficient Peltier refrigeration by a pair of normal metal/insulator/superconductor junctions", *Appl. Phys. Lett.*, vol. 68 (14), pp. 1996-1998, 1996.

[6] M. Tinkham, M Octavio, and W.J. Scocpol, "Heating effects in high-frequency metallic Josephson devices: voltage limit, bolometric mixing and noise", *J. Appl. Phys.* vol. 48, N 3, pp. 1311-1320, 1977.

[7] K. Likharev, *Dynamics of Josephson junctions and circuits*, Gordon and Breach Publ., Amsterdam, 1986.