THz Spectrometer Based on a Josephson Oscillator
and
a Cold-Electron Bolometer

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We have demonstrated a low temperature spectrometer operating in a wide range of frequencies from 100 GHz to 1.8 THz. The spectrometer has utilized unique properties of high-T_c superconducting Josephson junctions and wideband response of sensitive Cold-Electron Bolometers (CEB). The voltage response of the CEB integrated with log-periodic and double-dipole antennas, has been measured using an oscillator consisting of high-T_c Josephson junction integrated on separate substrate with a log-periodic antenna. The response of the bolometer with a double dipole antenna has resonance shape with maximum corresponding to the designed central frequency of 300 GHz. A voltage response of the bolometer up to $4\cdot 10^8$ V/W corresponds to a technical noise equivalent power of the bolometer of $1.2\cdot 10^{-17}$ W/Hz$^{1/2}$ including bolometer and amplifier sources of noise. A high-T_c Josephson junction operated at temperatures below 2 K shows advantages of high I_cR_n product that enhances the oscillation frequency to over 1.8 THz. The resolution of the spectrometer is determined by the linewidth of Josephson oscillations and for this temperature is of the order of 1 GHz.

Introduction: samples, layout and fabrication

For sensitive spectroscopy studies at THz frequencies one needs a simple, cheap, light, tunable, narrow linewidth THz source and a sensitive detector. The detector may need to be cooled to sub-Kelvin temperature in order to obtain a low enough noise level. It is an advantage if the generator can be at a substantially higher temperature if samples are placed at low temperature.

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. The first step of sample fabrication was thermal evaporation of 60 nm Au for fabrication of the normal metal traps and contact pads. The pattern for the traps and the pads were formed using photolithography. 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.

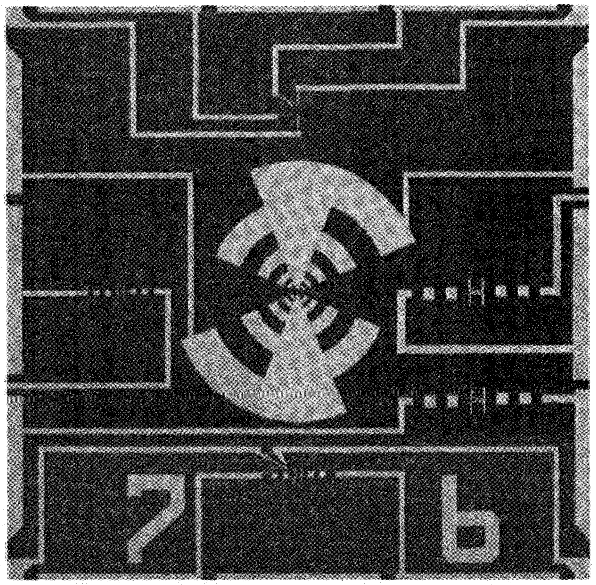

Figure 1. A bolometer chip layout. A wideband log-periodic antenna at the center, a 600 GHz double-dipole antenna to the left and two 300 GHz double-dipole antennas to the right.

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°. Films 250 nm thick were deposited by pulsed laser ablation on tilted sapphire bicrystal substrates 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 demonstrated a characteristic voltage I_cR_n of over 4 mV at a temperature of 4.2 K. Junctions were integrated with log-periodic antennas designed for frequency range 200-2000 GHz (see Fig. 2).

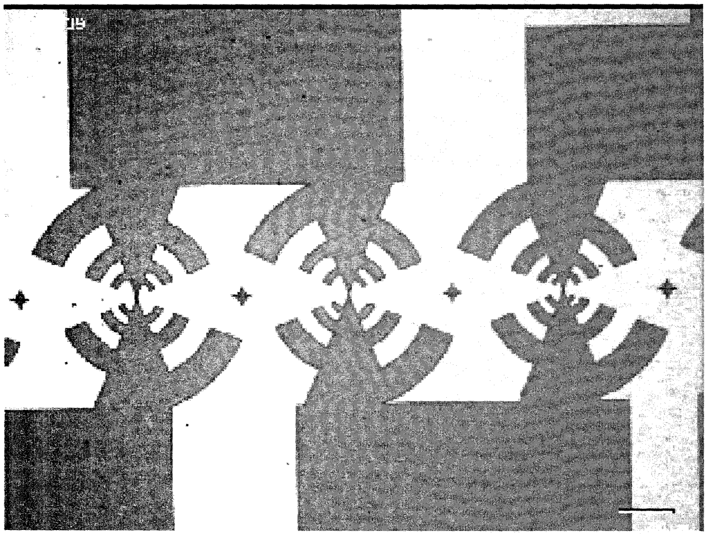

Figure 2. Central part of a Josephson oscillator chip

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. 3. 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).

$$NEP=I_n/S_i \text{ or } NEP=V_n/S_v \qquad (1)$$

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 amplifier-limited technical noise equivalent power TNEP value

$$TNEP=0.75\cdot 10^{-17}\ W/Hz^{1/2}$$

Using measured values of the temperature response and the power response one can also obtain the thermal conductivity of the bolometer.

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

Now we can calculate the thermodynamic NEP arising from the electron-phonon interaction $NEP_{ep}^2=4kT^2G$ in which thermal conductivity $G=5\Sigma vT^4=10^{-11}$ W/K, v is the absorber volume. This brings a thermodynamical noise equivalent power $NEP_{TD}=6\cdot 10^{-18}$ W/Hz$^{1/2}$, and if we compare with the thermal conductivity in the voltage bias mode it corresponds to a $NEP_V=1.3\cdot 10^{-18}$ W/Hz$^{1/2}$.

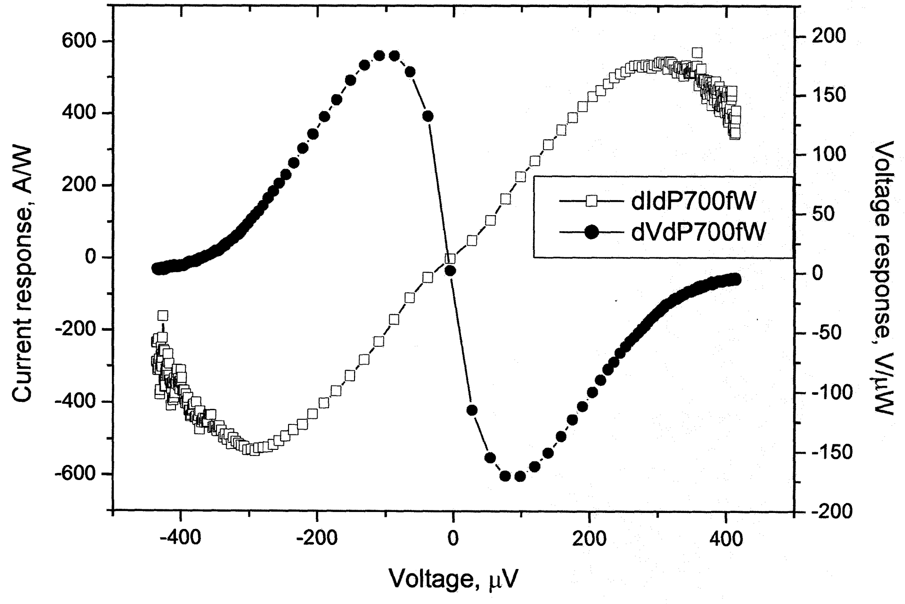

Fig. 3. Current and voltage responses for a 10 kΩ SIN junctions on the applied power at 260 mK.

Measurements of the response with a Josephson junction as a radiation source 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 4). 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. 1,2 central part) are designed for frequencies 100-2000 GHz.

The measured dependencies of the bolometer voltage response are presented in Fig. 5. 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.

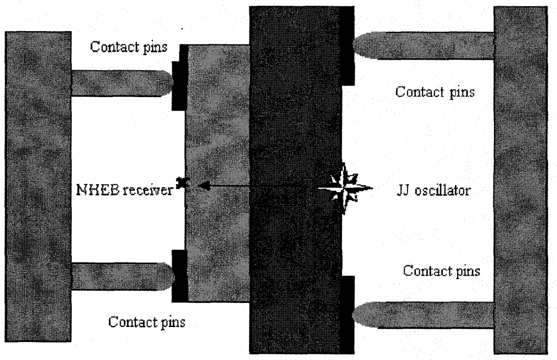

Figure 4. Schematic view for experimental setup at 260 mK in back-to-back configuration

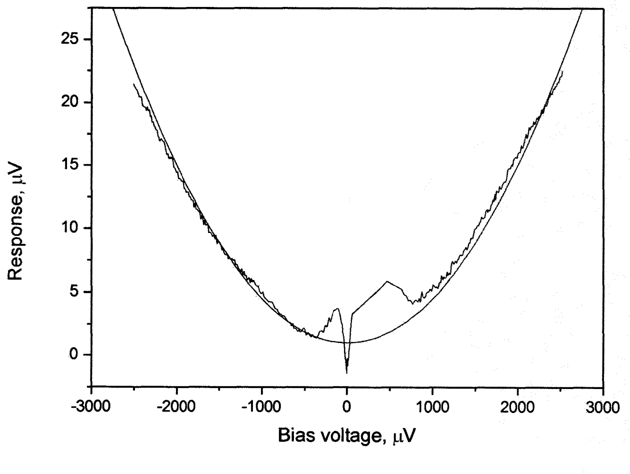

Figure 5. Bolometer response measured with a Josephson junction radiation source at 260 mK. The solid parabola is a fit for Joule heating.

For Josephson oscillators we can estimate the maximum available power as $P_{osc}=0.1 \cdot I_cV_c=2 \cdot 10^{-9}$ 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

$$T_m = \sqrt{T_b^2 + 3\left(\frac{eV}{2\pi k}\right)^2} \qquad (6)$$

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

$$P_r = \frac{hf}{e^{\frac{hf}{kT}} - 1} 0.3f \qquad (7)$$

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

$$P_{rad} = \frac{0.6}{4\pi^2} \cdot \frac{e^2V^2}{h} \qquad (8)$$

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. 6. 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 such oscillators can in principle operate at frequencies over 2.5 THz. Experimental curve in Fig.7 measured by bolometers integrated with log-periodic antennas, reveals that there is a 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

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

It is proportional to frequency, and corresponding losses

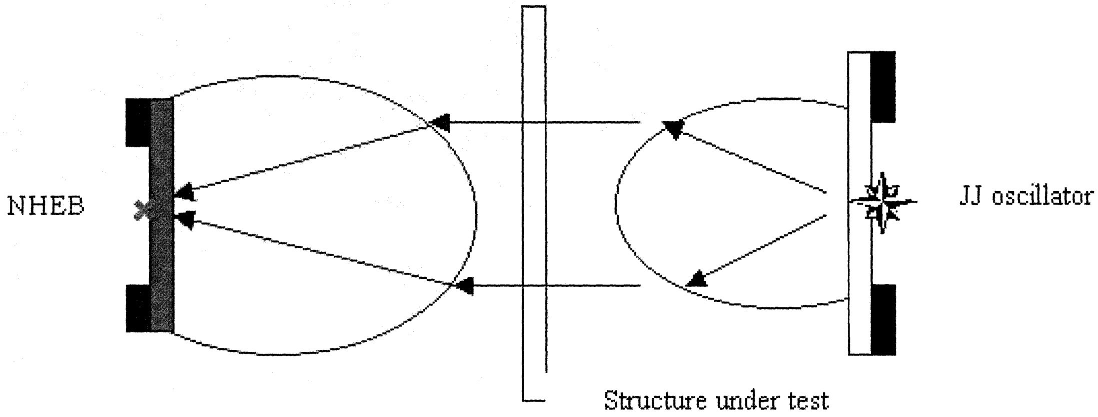

Fig. 7. Schematic view for quasioptical setup with NHEB lens-antenna unit at 260 mK and Josephson junction oscillator lens-antenna unit at 1.8 K.

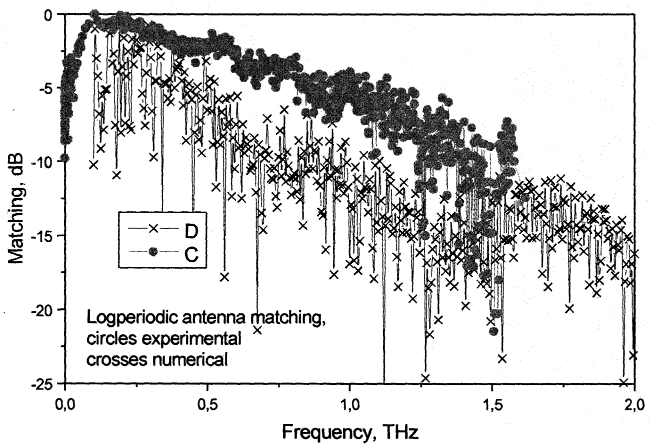

Figure 8. Experimental and calculated response by LPA.

In Fig. 8 signal is measured with a double-dipole antenna and demonstrate a clear maximum at the design frequency 300 GHz. We observed that suppressing the critical current by a magnetic field reduces the output power of the Josephson oscillator. The highest maximum corresponds to an oscillation frequency of 1.75 THz.

Discussion

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

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

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

$$P_{Ph-e} = \Sigma v T_{Ph}^5 = 0.5 pW$$

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

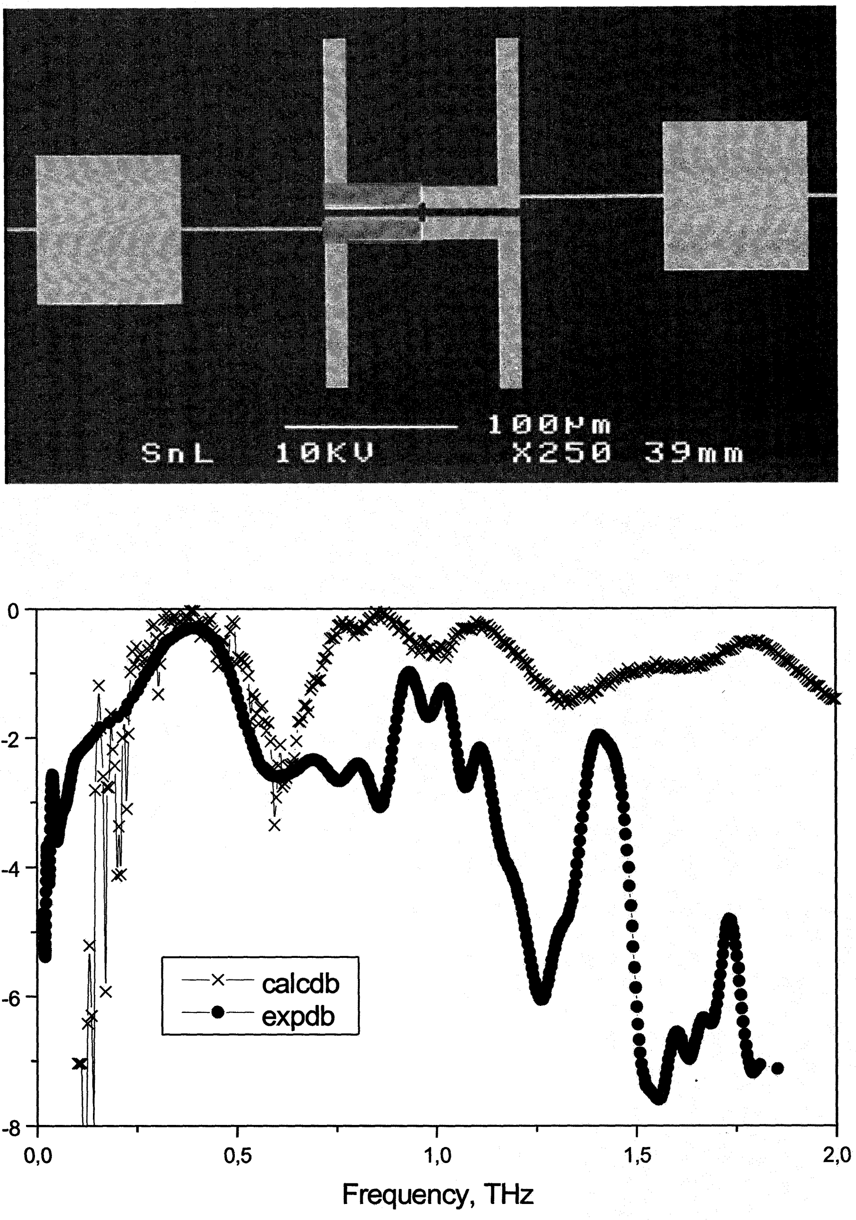

Figure 9. SEM view of the bolometer integrated with a double-dipole antenna in top panel and its experimental response (circles) and numerical modeling (crosses) in bottom panel.

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

This cooling current is associated with a shot noise. If we take the theoretical value for the current response $S_I = e/2k_bT = 6 \cdot 10^4$ A/W for electron temperature 100 mK it brings the shot noise impact $NEP_{sh} = 1.2 \cdot 10^{-18}$ W/Hz$^{1/2}$.

For phonon impact

$$NEP_I = \sqrt{4 k_b T_e \Sigma v T_{Ph}^5} = 1.6 \cdot 10^{-18} \text{ W/Hz}^{1/2}$$

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. For comparison below is presented a table with main characteristics of two cryogenic spectrometers: with cyclotron emission from 2DEG composite bolometer (see [7]) and our Josephson-CEB spectrometer

Main Characteristics	Cyclotron emission from 2DEG - composite bolometer*)	Josephson - CEB
Spectral range	0.1 – 2 THz	0.1 – 1.7 THz, Josephson - up to 4 THz CEB – up to 50 THz
Spectral resolution	200 GHz	1 GHz
Emitted power Received power Bolometer sensitivity	1 mW 50 pW 0.5 $\text{pW/Hz}^{1/2}$	1 nW 1 pW 10^{-17} $\text{W/Hz}^{1/2}$
Sweep	Magnetic feild	Voltage
Modulation frequency	Few Hz	up to several GHz for Josephson oscillator

Conclusion

We demonstrated the first experimental response of a normal metal cold electron bolometer at frequencies up to 1.8 THz. A voltage response of the bolometer is $4 \cdot 10^8$ V/W and experimental noise equivalent power of the bolometer is $1.3 \cdot 10^{-17}$ $\text{W/Hz}^{1/2}$. We were first to 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 any cryogenic detector, quasioptical submm wave grid filter, neutral density filter, absorber, 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 appreciate help by S.Shitov for numerical modeling of antennas spectral response and acknowledge support from VR, STINT, INTAS-01-686.

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