A Concept of Cold Electron Bolometer Mixer

Mikhail A. Tarasov and Leonid S. Kuzmin

***Abstract*— A novel type of phase-sensitive Terahertz heterodyne detector with Cold Electron Bolometer (CEB) sensor is proposed. In CEB mixer a normal metal absorber of sub-micrometer size is terminated to planar antenna via superconductor-insulator-normal metal (SIN) junctions. Such mixer combines advantages of Hot Electron Bolometer (HEB) mixer such as high signal frequency and low LO power, and advantages of SIS mixer such as low noise, high IF and immunity to small temperature variations. At the same time it avoids drawbacks of HEB and SIS such as sensitivity to magnetic field interference, additional noise due to Josephson effect and superconducting transition.**

***Index Terms*—cold electron bolometers, hot electron bolometers, terahertz mixers, power mixers.**

I. Introduction

At present there are two main types of most sensitive superconducting mixers in submm-wave or THz frequency range. First is SIS mixer approaching a noise temperature about 100 K that is of a few quantum limits T_n^q=hf/k at frequencies up to about 1 THz [1]. Above the energy gap frequency 700 GHz of Nb with transition temperature 9 K or twice as high for NbN with T_c=15 K, the noise temperature increase greatly above frequency 0.7 or 1.4 THz. Hot electron bolometer-mixer HEBM [2] is alternative type of mixers that can operate well above 1 THz with noise temperature about 1000 K that can be approximated as T_n~10hf/k [3]. The mechanism of operation for HEBM is much different from a conventional switching mixer in which conductance is modulated by LO frequency. In HEBM resistance can not be modulated with so high frequency, bolometer is too slow to follow THz frequency. Instead it detects the average of interference signal, similar to what happens in Fourier Transform Spectrometer with Michelson interferometer and Goley cell as a sensor. The HEB mixer performance is limited by intrinsic losses in superconductor-normal metal interface due to proximity effect, excess noise in the region of hot spot, overheating of bolometer by dc and RF biases.

In this paper we present a concept of novel device that can overcome limitations of both types of superconducting mixers. A Cold Electron Bolometer-Mixer (CEBM), see Fig. 1, combines elements of SIS and HEB, it consists of a normal metal (or weak superconductor) strip of absorber terminated to electrodes by superconducting tunnel junctions of SIN type as in conventional cold electron bolometer [4]. Contrary to conventional operation of CEB as a direct bolometer in millikelvin temperature range, in the case of CEBM it operates at liquid helium temperature that increase the response frequency from 10-100 MHz to about 1 GHz that is acceptable as IF. In this paper we compare operation of cold electron bolometer in coherent and noncoherent operation modes and show the difference of conventional switching mixer and power mixer.

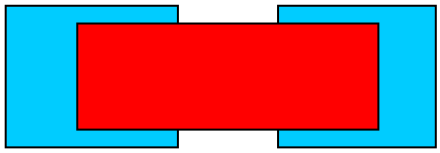

Fig. 1. Schematic view of SINIS for CEB mixer. Electrodes are superconducting, absorber (in the center) is normal metal. Gap between electrodes is 1 μm, size of overlap (tunnel junctions) is 1x1 μm^2.

II. Coherent and Incoherent Detection at MM and SUBMM Waves

There are two basic methods to detect radiation: coherent one that is arranged by mixers and incoherent that utilizes direct detectors and bolometers.

There are two basic types of incoherent detectors, in first one incoming photons generate single or multiple charge carriers, in second one incoming radiation is converted to heat. First class is presented by photoconductors and discharge tubes, in which an incoming photon excites a carrier into a semiconductor's conduction band, or in vacuum between cathode and anode. In bolometers the incoming radiation elevates the temperature of a sensitive thermometer. The characteristic of absorption determines the frequency range and usually absorber and thermometer are separated in so-called composite bolometers. Microwave radiation directly accelerates electrons in hot electron bolometers, heating the electron gas into a range where the electron mobility is energy dependent. Thermodynamic temperature of the electron gas T_e is higher than the lattice temperature, and changes in current are proportional to the electron mobility $\Delta i \sim V/\Delta r \sim V/(ne\mu(E))$.

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In coherent receiver the input signal frequency is converted by mixing with monochromatic local oscillator in a nonlinear element. The receiver is phase coherent because the phase relation of incoming signal to LO is preserved in the output signal. Mixers can be divided into two different classes. The first one can respond to the signal and LO frequencies separately, it is so-called switching mixer. Schottky diodes and SIS tunnel junctions are most popular mixers of this type. The second type is class of power mixers, which responds to the total power. These mixers do not respond separately to the individual fields, but measure the interference, which brings the difference frequency in the total power. Hot electron bolometers and photoconductors fall into this class. Classical heterodyne mixers, or switching mixer, generate output signals at sums and differences of input frequencies and their harmonics. In quantum detector the shape of IV curve is irrelevant, they produce one charge carrier per incident phonon.

Phase coherent methods preserve the phase information of the incoming signal, but at the cost of imprecision in the intensity (number of phonons) in the incoming radiation. Phase incoherent methods are capable of counting photons, but consequently destroy the phase information in the signal. The reason for this is a wave-particle duality of electromagnetic radiation. The Heisenberg uncertainty principle can be expressed as

$$\Delta E \cdot \Delta t \geq \hbar / 2 \qquad (1)$$

The intensity can be rewritten in terms of number of photons N, and time in terms of phase φ, so $\Delta E = hf \cdot \Delta N$ and

$$\Delta t = \frac{\Delta\varphi}{\omega} = \frac{\Delta\varphi}{2\pi f}$$

which brings the relation $\Delta E \cdot \Delta t = hf \cdot \Delta N \frac{\Delta\varphi}{2\pi \cdot f} \geq \frac{\hbar}{2}$, that shows simple relations of amplitude and phase uncertainty

$$\Delta N \cdot \Delta\varphi \geq \frac{1}{2} \qquad (2)$$

It means that it is generally impossible to simultaneously determine both the phase and number of photons to arbitrary high precision. Another important consequence is that, in principle, incoherent detection is more sensitive than coherent, because sensitivity is ΔN and $\Delta N > \frac{1}{2\Delta\varphi}$

III. CONVENTIONAL HETERODYNE MIXERS

A classical switching mixer generates output signals at frequencies equal to the sum and difference of input frequencies. Usually the difference frequency between the LO and the signal is of main interest. The LO is a large signal that shifts the mixer's bias point on a nonlinear IV curve as a function of time. The signal amplitude is small and does not affect the bias point, but interacts with the mixer as with a passive nonlinear element with resistance depending on LO frequency. The shift by LO of bias point changes the resistance that can be presented as a Fourier series at LO harmonics, the main component is

$G(t)=G_0+G_1(A,\omega_{LO})Cos(\omega_{LO}t)$

The signal voltage will produce the output current

$I(t)=G(t)V_sCos\omega_st=G_0V_sCos\omega_st+0.5G_1V_s[Cos(\omega_s+\omega_0)t+Cos(\omega_s-\omega_0)t]$

in which the down-converted signal is

$$I_{if}=0.5G_1V_sCos(\omega_s-\omega_0)t \qquad (3)$$

Numerical example see in Fig. 2. To calculate the output power one should take into account the mismatch of source and input impedances

$K=4R_sR_l/(R_s+R_l)^2$

The last relation shows the fundamental limit on conversion efficiency in any resistive mixer: in the optimal case the source power is shared in equal parts by source and load impedances that bring the maximal conversion efficiency of –3 dB.

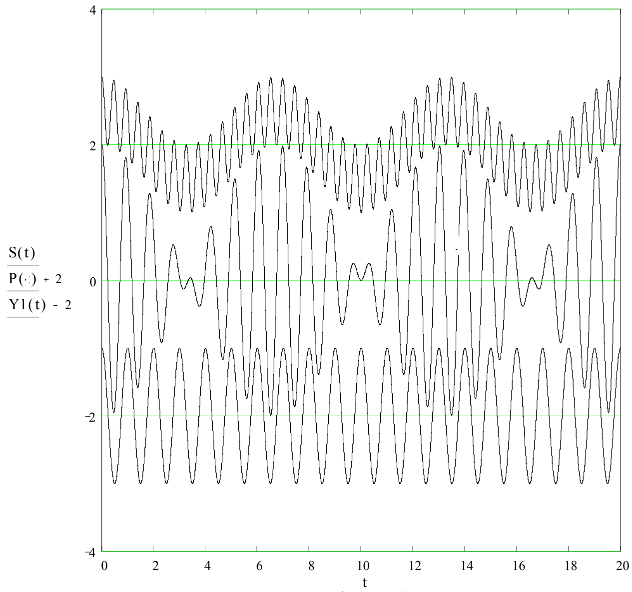

Fig. 2. Conversion process for switching and power mixer. Lower trace Y=Cos(f1·t) is initial signal, middle S=Y1+Y2 is a sum of two cosin terms in the power mixing, and upper trace P=Y1·Y2 is a product of multiplying of two cosin terms in switching mixer

IV. POWER MIXERS

The power mixer can be viewed as a combination of power detector and interferometer in which signal and local oscillator fields interfere to form the interference pattern with rapidly varying interfered component. The general case, when LO power is much greater the signal power, the analysis can be reduced to a simple one when both amplitudes are equal

$E(t)/E_{LO}=Cos\,\omega t+\alpha Cos(\omega+\delta)t=(1-\alpha)Cos\omega t+\alpha[Cos\omega t+Cos(\omega+\delta)t]= E1+E2$

The last term E2 brings the interference pattern that can be converted to natural form:

$$E2 = Cos\omega t + Cos(\omega+\delta)t = 2 \cdot Cos\frac{2\omega+\delta}{2}t \cdot Cos\frac{\delta}{2}t \qquad (4)$$

These two components E1 and E2 of combined fields independently heat our slow bolometer and produce power

$$P = \frac{\overline{E_1^2}}{R} + \frac{\overline{E_2^2}}{R} = \frac{\overline{(1-\alpha)^2}}{R}Cos^2\omega t + \frac{\overline{4\alpha^2}}{R}Cos^2\left(\frac{2\omega+\delta}{2}t\right) \cdot Cos^2\frac{\delta}{2}t =$$

$$= \frac{(1-\alpha)^2}{R}\left(\frac{1-Cos2\omega t}{2}\right) + \frac{4\alpha^2}{R}\left(\frac{1-Cos(2\omega+\delta)t}{2}\right)\left(\frac{1-Cos\delta t}{2}\right)$$

which brings after averaging in the signal frequency time scale the IF power

$$P(t) = \frac{(1-\alpha)^2}{2R} + \frac{\alpha^2}{R} - \frac{\alpha^2}{R} Cos\delta t \qquad (5)$$

which can be clearly explained for equal levels of power α=1

$$P(t)=(E^2/R)(1-Cos\delta t) \qquad (6)$$

It means that output power varies from zero to maximum, and its average is

$$P=E^2/2R+E^2/2R=E^2/R$$

that is the sum of equal initial powers. If LO power is larger, the interference term automatically will interact only with the equal amplitude. It means that required power for detection of low signal is equally low. If it is required to have a large dynamic range, then the amplitude of available at bolometer-mixer input should be equal to the maximum amplitude of the expected input signal. The HEBM operation can be explained with the above model, and our proposed CEBM can also be viewed as a power mixer that is too slow to follow the LO frequency, but fast enough to detect IF response at difference frequency. Numerical illustration to these equations is given in Fig. 2 and Fig. 3.

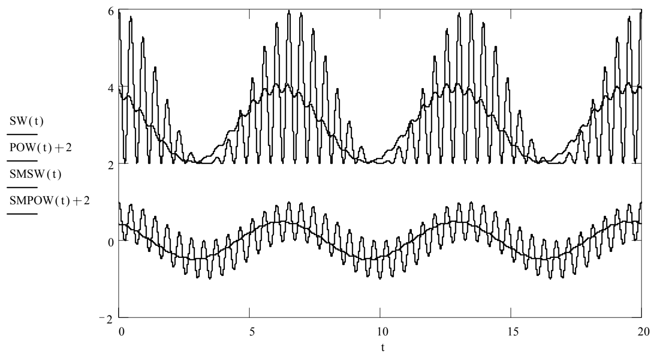

Fig. 3. Power and switching mixing after squaring. Integration of both signals brings the same down-converted frequency. Upper dependencies were calculated for power mixing after squaring and after averaging. Lower dependencies – for switching mixer.

V. COLD ELECTRON BOLOMETER AS MIXER

When operate at millikelvin temperatures CEB demonstrate rather slow response in a megahertz range due to reduced electron-phonon interaction and slow cooling of the overheated electrons. With increase of temperature the e-p interaction power increases as $P_{ep}=\Sigma\nu(T_e^5-T_{ph}^5)$ in which is Σ material constant, ν is volume, T_{ph} is phonon temperature, T_e is electron temperature.

An effective thermal time constant without electrothermal feedback (electron cooling) can be estimate from the simple relation

$\tau_0=C_v/G_{ep}$, $\tau=\tau_0/(L+1)$

in which $C_v=\nu\gamma T_e$ is heat capacity of the absorber, $G_{ep}=5\Sigma\nu Te^4$ is electron-phonon thermal conductance, $L=G_{cool}/G_{ep}$ is ETF gain. The estimated values of effective time constant are10 μs at 100 mK and 150 ps at 4.2 K. With ETF they can be reduced by a factor of 10 to 1000. These values are in the range of commercial cooled RF amplifiers with the noise temperature below 10K.

The conversion efficiency can be estimated from the basic principles of electron cooling: if we have incoming heating power P_{sig} it will be completely compensated by electron cooling to have the same electron temperature. One electron of current roughly removing the energy of kT, and it means, that $P_{cool}=P_{sig}=kT\cdot\Delta I/e$, or $\Delta I=eP_{sig}/kT$. Power absorbed in the IF load can be estimated from simple Joule heating by IF current at bias voltage close to the gap voltage. That is for two junctions in series $P_{IF}=2V_\Delta\cdot\Delta I=2eV_\Delta\cdot P_{sig}/(kT)$, Finally the power gain $G=P_{IF}/Psig=2eV_\Delta/kT=eV_{2\Delta}/kT$ and it means that contrary to classical mixer with 3 db conversion losses as the best, for CEBM we can have a moderate power gain.

Noise performance in first approximation can be deduced from the shot noise of SIN junction at the output port (input assume as noiseless, it is just real resistance of metal strip). Current shot noise at the output is $I_n^2=2eI\cdot\Delta f$ and it can be recalculated into power as $P_n\approx 2eIR\cdot\Delta f\approx 2eV_\Delta\cdot\Delta f=kT_n\cdot\Delta f$ from which we can obtain the output noise temperature $T_n^{out}=eV_{2\Delta}/k$ that is about 30 K in the case of Nb. If we can also take into account the above estimated conversion gain $G=eV_{2\Delta}/kT$ one can obtain a very optimistic estimation of noise temperature referred to the input T_n=T.

Power matching to the input signal is much easier compared to SIS mixer, in CEBM or SINIS we do not need to compensate the intrinsic capacitance of tunnel junction, its impedance is rather low and we have mainly real resistance of metal absorber (normal metal film) that is terminated to the planar antenna. In this case it is very easy to achieve perfect impedance matching, even in the wide frequency range.

For IF matching the problem is essentially the same as for SIS mixer, and it can be solved for SINIS in the same way. For estimations of resistances and capacitances we can take characteristics of regular SIS junctions with AlOx barrier [5] that are characterized by the R_nA product (A is an area, R_n is normal resistance of the junction) in the range 25-30 $\Omega\cdot\mu m^2$, that corresponds to the current density of 7-8 kA/cm^2, and specific capacitance 70 $fF/\mu m^2$. For the junction of 1 μm^2 area the resistance can be about 30 Ω and capacitance 70 fF.

At IF=1.5 GHz it brings capacitive impedance of about 1500 Ω and dynamic resistance about R_n=30 Ω, while the absorber should be about 70 Ω to match THz signal to complementary planar antenna. Finally at IF we need to match 130 Ω of SINIS to 50 Ω of amplifier that can be done by a coplanar matching transformer. Losses at the IF port in the case of 70 Ω absorber will be about 3 dB. If we apply the advanced technology of AlN tunnel barrier [6], that allows to obtain the RnA product down to 1 $\Omega\cdot\mu m^2$, in this case the problem of IF matching is easy solved. The IF impedance will be equal to normal resistance of absorber that is chosen to be 70 Ω for matching to complementary planar antenna at signal frequency.

VI. Design and Studies of CEB

We designed and fabricated CEB sensors in a simple technology of angle evaporation through suspended mask. Normal metal absorber was made of Cu film and superconducting electrodes are made of Al. Bolometers were integrated with log-periodic and double-dipole antennas. The view of the SINIS sample with log-periodic antenna is presented in Fig. 4. Absorber in this sample is relatively long, about 10 μm. Samples were measured at temperature 280 mK that is below transition temperature of Al. The estimated time constant for such samples at this temperature is about 1 MHz. Reducing the length of bolometer down to 1 μm and replacing Al with Nb or NbN will allow to increase temperature over 4.2 K and increase response frequency over 1 GHz. According to our estimations it is possible to achieve IF in CEBM up to 10 GHz.

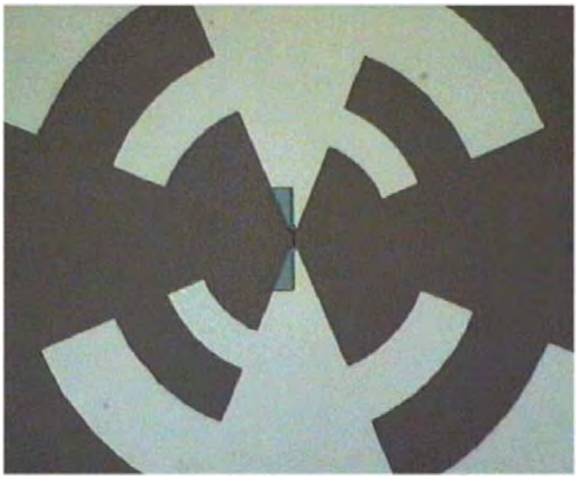

Fig. 4. CEB integrated with log-periodic antenna.

Voltage and current responses of CEB are presented in Fig. 5, and frequency response in Fig. 6. For details of these measurements and sample layout see also [7]. These dependences illustrate capability of SINIS sensor to detect submm-wave radiation at frequencies around 2 THz that is much above the gap frequency of of Al and with Noise Equivalent Power (NEP) below $2 \cdot 10^{-17}$ W/Hz$^{1/2}$. The electron-phonon relaxation time for the sample with Cu absorber at temperature 300 mK can be estimated as

$\tau_{ep}=20/T^3$ ns=1 μs ,

which is reduced to 0.36 ns at 4.2 K. By changing absorber material and thickness this value can be reduced further in the same way as in HEB mixers.

To summarize, earlier it was demonstrated that SINIS sensor can be used as incoherent detector. High sensitivity was achieved at millikelvin temperatures using ^{3}He sorption cooler. Now we propose to use the same SINIS as coherent detector for spectroscopy in Terahertz frequency range. With Nb or NbN junctions, AlN barrier and reduced length of absorber it is possible to increase intermediate frequency up to few gigahertz at ambient temperature 4.2 K.

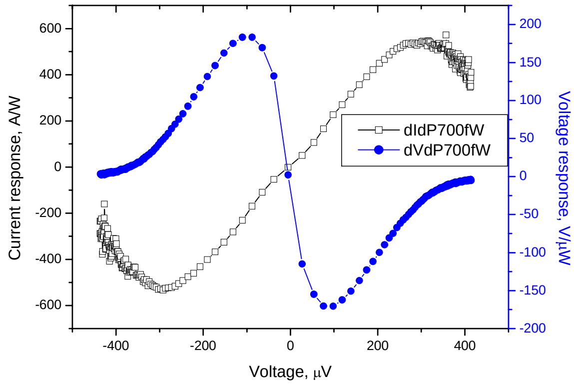

Fig. 5 Current and voltage response of CEB on applied power.

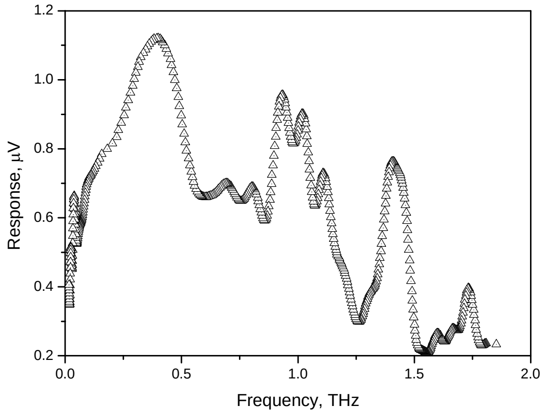

Fig. 6 Spectrum response of CEB in bolometer mode.

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