Submillimeter-wave Josephson spectroscopy

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A Josephson high-temperature superconducting (HTSC) submillimeter-wave spectrometer is designed, built, and experimentally investigated. The integrated detection structure of the spectrometer includes a YBCO Josephson junction on a bicrystalline boundary, a double-slot or log-periodic antenna, and a low-inductance resistive shunt. The selective detector response and the response at an intermediate frequency of 1.4 GHz are measured under the action of a signal in the frequency range 350–1250 GHz. Three methods of spectroscopy are investigated using this setup: 1) a method of Hilbert spectroscopy with processing of the detector response is implemented; 2) it is found that for a wide Josephson line at intermediate frequency (IF) the response has the same form as the detector response, making it possible to obtain a spectrum and the width of the generation line from IF response measurements; 3) for a narrow Josephson line the IF response corresponds to the regime of conversion with self-pumping. A new method is proposed for calculating the emission spectrum. The method consists of simple shift, summation, and subtraction operations. The advantages of the method are simplicity, high sensitivity, and high resolution. © *1999 American Institute of Physics.* [S0021-3640(99)00517-4]

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Millimeter and submillimeter wave spectrometers based on high-temperature superconducting (HTSC) Josephson junctions can operate in the temperature range 4–77 K.

Josephson mixers can have a noise temperature two to three times lower than that of spectrometers using Schottky diodes.[1,2] The method of Hilbert spectroscopy,[3] employed for processing the selective detector response of a Josephson junction, has been widely used to the present day. Another possible method of spectroscopy with a Josephson junction could be to employ a mixer mode with an external pump or with self-pumping.

In the mixer with self-pumping, the input signal at frequency f_s is mixed with the characteristic Josephson oscillations. If the input signal is monochromatic, then the linewidth of the converted signal at the intermediate frequency (IF) will correspond to the Josephson line width Δf_J, which is a natural measure of the spectral resolution of such a spectrometer. Shunting of the junction with a low-inductance resistive shunt can be used to improve the resolution of such a spectral instrument. According to theoretical estimates, the minimal two-band noise temperature of a Josephson mixer with self-pumping[1,2] corresponds to the physical temperature T for $f < 0.2 f_c$ and decreases as $8(f/f_c)^2$ as the frequency increases above f_c. A low-inductance shunt improves the noise temperature of the mixer with an external heterodyne and the resolution of a mixer with self-pumping.

The integrated detecting structure included a YBaCuO Josephson junction, formed by a bicrystalline MgO or sapphire substrate, and a gold complementary log-periodic or double-slot antenna. An 80–100 nm thick YBaCuO film was deposited by laser ablation. Two-micron wide junctions at 4.2 K possessed a 10 Ω normal resistance and a 300 μA critical current. The current–voltage characteristics (IVCs) of the experimental junctions possessed a low excess-current fraction, a Fraunhofer dependence of the critical current on the magnetic field, and oscillatory dependences of the Shapiro steps and critical current on the microwave power. Either integrated shunts, deposited on one substrate with a junction, or loops consisting of 5 mm in diameter and 50 μm thick gold wire, welded by ultrasonic welding to the contact pads, were used for the shunting junctions. Such shunts had a resistance of less than 0.1 Ω at 4.2 K and did not shunt substantially at the intermediate frequency 1.4 GHz.

The substrate with the detecting structure was placed on a flat surface of an elongate hyperhemispherical MgO lens, placed on the cold plate of a helium cryostat with an optical window. Backward-wave tubes (BWTs) for the ranges 350–650 and 880–1250 GHz were used as signal sources. Radiation from cold (77 K) and warm (300 K) loads was used as the source of the wide-band signal. A polyethylene beam splitter was used to mix the wide-band signal with the BWT radiation. Black polyethylene and Fluorogold filters were used to eliminate any influence of IR overheating of the sample at the 77 K and 4 K steps. The IF signal was fed through a matching circuit to an amplifier, cooled to 4.2 K, with a cold circulator at the entrance.

The curves of the selective detector response and IF signal under the action of external radiation at frequencies up to 1250 GHz were measured (Fig. 1). It was found that the curves of the IF signal, just as the detector response, can be used to determine the width of the generation line and the frequency of the perturbing signal (Fig. 1b), since the maxima and minima of the detector response and the IF response coincide if the width of the Josephson line is greater than the intermediate frequency. The calculation of the signal spectrum from the modified detector response by the Hilbert transform method is known as Hilbert spectroscopy,[3] and the proposed IF response method can be regarded as a modification of the Hilbert method, making it possible to simplify the measurement

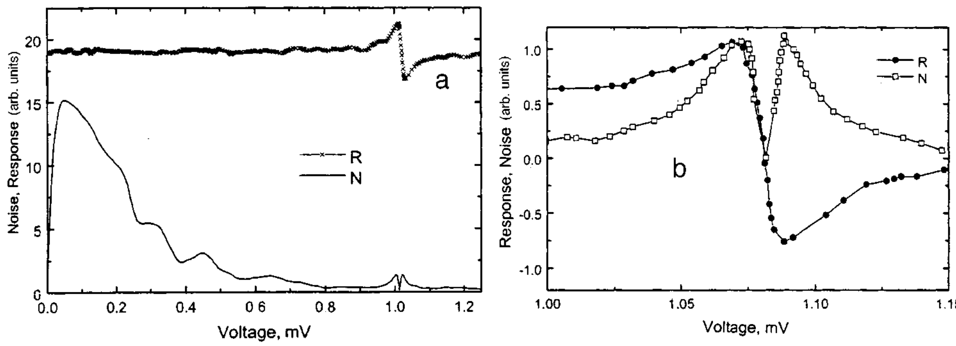

FIG. 1. a) Noise (Np,Na) and IVC (I), measured under the action of 0.5 THz irradiation (Np) and without irradiation (Na). b) Selective detector response R and noise DN, the latter after subtracting out the autonomous noise and extracting a square root. The generation linewidth is greater than the IF.

technique and to improve the sensitivity and frequency resolution. At 1000 GHz and temperature 4.2 K the generation linewidth was 34 GHz for a 20 Ω junction, 28 GHz for a 4 Ω junction, and 4.5 GHz for a junction with a 0.7 Ω resistive shunt. These values are six to eight times greater than the simple estimates from calculations based on the resistive model of a Josephson junction with thermal shunts as the main source of fluctuations $\Delta f[\mathrm{MHz}]=40(R_d^2/R_n)T[\mathrm{K}]$ (see Refs. 1 and 2).

A reconstructed spectrum, obtained by the Hilbert transform method from the detector response, with irradiation at 0.5 THz is presented in Fig. 2. The rf response curves measured for a wide intrinsic generation band ($\Delta f_J > f_{IF}$) have maxima and minima at the same values of the bias voltage as the detector response. For this case, the values of the generation linewidth and the signal frequency can be obtained just as in the case of a synchronous detector. If the IF is greater than the Josephson linewidth, $\Delta f_{IF} > f_J$, the positions of the maxima of the IF signal correspond to the sum and difference of the voltages at the signal frequency $V_s = f_s\Phi_0$ and at the IF $V_{IF} = f_{IF}\Phi_0$. Such a conversion regime has been investigated in detail in Ref. 4. This case can be easily modeled numerically using analytical relations. Figure 3 shows the computed dependences of the con-

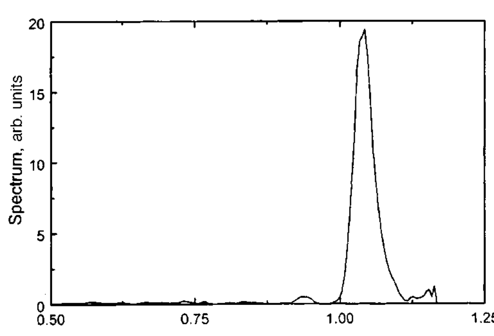

FIG. 2. Spectrum obtained from the detector response using a Hilbert transform.

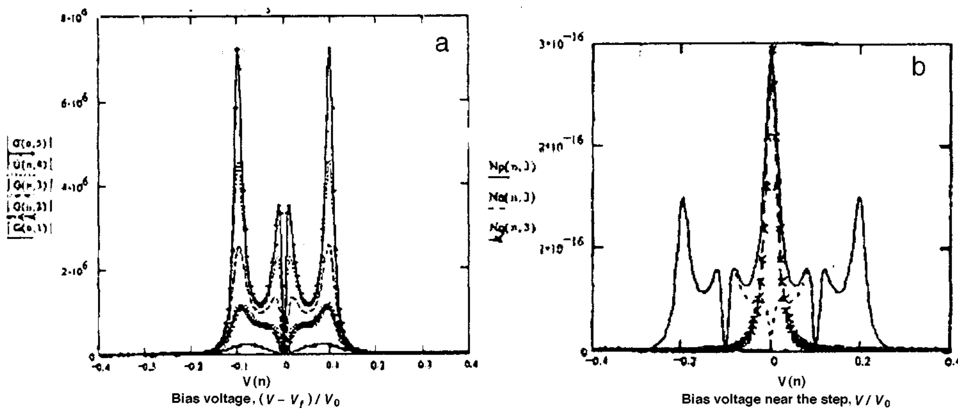

FIG. 3. a) Calculation of the conversion gain G near a Shapiro step. The maximum near the voltage step ($V=0$) corresponds the maximum of R_d, while the maxima located farther away correspond to a shift by the intermediate-frequency voltage $|V-V_f|=V_{IF}=0.1V_0$. b) Sum of Np and difference Nn of the shifted dependences and the reconstructed spectrum Nq.

version gain on the bias voltage for different values of the Q. Qualitatively, these dependences correspond to the measured values in Fig. 1.

We propose a simple numerical processing method to extract a spectrum from these dependences. The method includes subtraction of the autonomous value $Na(v)$ of the noise without the signal from the values $Np(v)$ obtained by feeding the signal, for the same values of the constant bias (see Fig. 4),

$$Ne(v)=Np(v)-Na(v). \tag{1}$$

Next, these dependences are shifted with respect to bias voltage by $+v_{if}$ and $-v_{if}$, where $v_{if}=f_{iv}\Phi_0$,

$$Ne(v+v_{if}) \quad \text{and} \quad Ne(v-v_{if}). \tag{2}$$

The sum and differences of these dependences are obtained:

$$Ns(v)=Ne(v+v_{if})+Ne(v-v_{if}), \tag{3}$$

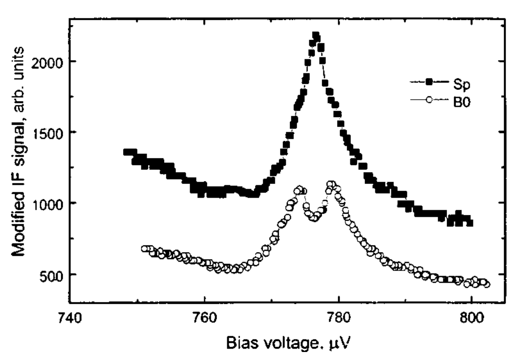

FIG. 4. Experimental curve of the output IF signal (squares) and the reconstructed spectrum (circles).

$$Nd(\nu)=Ne(\nu+\nu_{if})-Ne(\nu-\nu_{if}). \tag{4}$$

The desired spectrum is obtained from the last two functions as

$$S(\nu)=Ns(\nu)-|Nd(\nu)|. \tag{5}$$

Examples of such a calculation are presented in Fig. 3 for a model theoretical curve and in Fig. 4 for an experimental dependence.

The positions of the maxima of the detector response can be obtained from the analytical expression for the IVC of a Josephson junction near Shapiro steps in the presence of thermal noise of a normal resistance R_0. The blurring of the steps is characterized by the dimensionless parameter

$$\gamma=2ekT/\hbar I_{st}, \tag{6}$$

where I_{st} is the half-width of a step in the absence of noise. Exact analytical calculations are quite laborious, but simplified relations can be derived for practical estimates:

$$\Delta V\cong 1.92R_0\sqrt{2ekTI_{st}/h} \quad \text{for } \gamma\leqslant 1, \tag{7a}$$

$$\Delta V\cong 4\sqrt{3}kTR_0/h \quad \text{for } \gamma\geqslant 1, \tag{7b}$$

$$\Delta V=2f_{if}h/2e \quad \text{for} \quad I_{st}\cong 0. \tag{7c}$$

It is evident from these relations that when the Josephson linewidth is greater than the intermediate frequency, the positions of the maxima of the detector response and the IF response are the same. For the opposite case, the position of the detector response remains near the maximum of R_d, and the maxima of the IF response lie in the region of the side bands of the self-pumped mixer, i.e., at the voltages $V_{\max}=(f_J\pm f_{if})\Phi_0$. The sensitivity of these methods is determined, to a first approximation, by the sensitivity of the amplifiers. For a low-frequency detector response, the sensitivity is limited by noise with a $1/f$ spectrum and the amplifier noise can be estimated as $V_N=5$ nV/Hz$^{1/2}$. The noise temperature of the cooled amplifier at the IF can be less than 10 K. With a 0–10 dB conversion gain of the self-pumped mixer and a measured noise temperature of the order of $T_N\approx 1000$ K, and taking the sensitivity of the detector to be $\eta=10^6$ V/W,[5] the spectral density of the noise for detector and mixer spectrometers can be estimated as

$$S_{\text{det}}=V_N/\eta=5\times 10^{-9}/10^6=5\times 10^{-15}\ \text{W/Hz}^{1/2}, \tag{8}$$

$$S_{\text{spm}}=k\cdot T_N=1.4\times 10^{-23}\times 1000=1.4\times 10^{-20}\ \text{W/Hz}^{1/2}. \tag{9}$$

The frequency resolution of both methods corresponds to the Josephson linewidth, which can be greatly improved by using a low-inductance shunt. Such shunting something will not change the IF response much, but it will greatly decrease the selective detector signal; this indicates that the rf response method is preferable for improving the resolution and sensitivity of the spectrometer. Another advantage of the rf method is its insensitivity to the step size, making it possible to increase substantially the dynamic range of the apparatus.

In summary, a submillimeter-range HTSC Josephson spectrometer has been developed, built, and experimentally investigated. A new method of spectroscopy based on a self-pumped mixer mode was proposed and a method for extracting the spectrum of the experimental signal from the measured rf response was proposed. The spectroscopy method proposed using a Josephson self-pumped mixer at a high intermediate frequency makes it possible to improve substantially the sensitivity, spectral resolution, and dynamic range of the Josephson spectrometer.

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