Terahertz Spectral Analysis by ac Josephson Effect in High-T_c Bicrystal Junctions

Yuri Divin, Oleg Volkov, Valery Pavlovskii, Ulrich Poppe, and Knut Urban

***Abstract*—A prototype of a terahertz Hilbert-transform spectrum analyzer based on a high-T_c Josephson junction integrated into a Stirling cooler has been developed. The detector response of $YBa_2Cu_3O_{7-x}$ Josephson grain-boundary junctions to monochromatic radiation with the frequency f in the range from 60 GHz to 5 THz has been studied. Odd-symmetric resonances near the voltages $V=hf/2e$ in the responses $\Delta I(V)$ of these junctions to radiation with different frequencies f have been observed in a decade of spectral range for any operating temperature between 30 to 85 K. Decreasing the junction temperature from 85 to 30 K by a Stirling cooler, the spectral analysis could be made in two decades of spectral range. A resolving power $\delta f/f \sim 10^{-3}$ has been shown in the terahertz spectral analysis with the low-resistive Josephson junctions. As an example of application of this analyzer, an optimization of the single-line operation of a far-infrared optically-pumped CH_3OH laser has been demonstrated.**

***Index Terms*—High-temperature superconductors, Josephson junctions, radiation detectors, spectral analysis.**

I. INTRODUCTION

DETECTORS of electromagnetic radiation, based on the ac Josephson effect, can give an information on the spectrum of incident radiation. A frequency-selective detection takes place in Josephson junctions due to an interaction of internal voltage-controlled Josephson oscillations and external signals. The corresponding detectors based on low-T_c Josephson junctions have been studied earlier [1-5], and the first evaluations of high-T_c Josephson junctions for this application have been carried out [6-8]. Recently, we have demonstrated a selective Josephson detection in a decade of the spectral range with the highest frequency of 3.1 THz [9].

Frequency-selective Josephson detection of electromagnetic radiation is the basic principle of Hilbert-transform spectral analysis [1]. Spectral measurements of millimeter- and submillimeter-wave radiation by Hilbert-transform technique have been carried out using both low-T_c and high-T_c Josephson junctions [1, 10-16]. Some laboratory prototypes of Hilbert-transform spectrometers and spectral analyzers cooled by cryogenic liquids have been developed [1,11,13,16]. A necessity to use cryogenic liquids for cooling is considered as a main obstacle on the way of superconducting electronics into the market, and a replacement of them by cryocoolers is required [17].

Here, we report on the terahertz characterization of a Hilbert-transform spectrum analyzer based on high-T_c Josephson detector integrated into a Stirling cooler.

II. THEORY

In the simple resistively shunted junction (RSJ) model [18], the response $\Delta I = I(V) - I_o(V)$ of a Josephson junction to weak monochromatic radiation with the frequency f is equal to [18]

$$\Delta I(V) = I_s^2\left(\frac{2e}{h}\right)\frac{I_c^2R_n^2}{8I_0V}\left[\frac{(f_j+f)}{(f_j+f)^2+\left(\frac{\delta f}{2}\right)^2}+\frac{(f_j-f)}{(f_j-f)^2+\left(\frac{\delta f}{2}\right)^2}\right], \qquad (1)$$

where I_c is the critical current of the junction, R_n is the normal-state resistance of the junction, I_s – is the amplitude of the radiation induced current $(I_s<<I_c)$, I_o is the dc current flowing through the junction, $V=R_n(I_o^2-I_c^2)^{1/2}$ is the voltage across the junction, $f_j=2eV/h$ is the voltage-controlled frequency of internal Josephson oscillations and δf is the linewidth of Josephson oscillations.

The response $\Delta I(V)$ (Eq. 1) is quadratic with the signal amplitude I_s. At low voltages $V<<hf/2e$ in the limit of small δf, the response $\Delta I(V)$ approaches the value

$$\Delta I_o = -(I_s^2R_n/2)(2e/h)(f_c/2f^2), \qquad (2)$$

where $f_c=(2e/h)I_cR_n$ – is a characteristic frequency of the Josephson junction. This low-voltage response is actually a suppression of the critical current of the junction by external radiation.

At the voltages V, where the Josephson frequencies f_j are close to the frequency f of the incident radiation, the response $\Delta I(V)$ shows an odd-symmetric resonance. The maximum amplitude ΔI_{max} of this resonance at

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$V=(h/2e)[f+(\delta f/2)]$ is inversely proportional to the Josephson linewidth δf:

$$\Delta I_{max} = (I_s^2 R_n/2)(2e/h)[f_c^2/4(f_c^2+f^2)^{1/2} f\delta f] \,. \quad (3)$$

For broadband thermal fluctuations with a noise temperature T and $kT<eV$, the Josephson linewidth is equal to [18]

$$\delta f = 4\pi(2e/h)^2 kT(R_d^2/R_n)\left[1+\left(I_c^2/2I_0^2\right)\right], \quad (4)$$

where R_d is the dynamic resistance of the junction. The dynamic resistance $R_d(V)=dV/dI=R_n(V^2+I_c^2 R_n^2)^{1/2}/V$ is equal to the normal-state resistance R_n at high voltages $V>I_cR_n$, and at small voltages $V<I_cR_n$ it is inversely proportional to the voltage.

One can expect from Eq. 3 and Eq. 4, that the amplitude ΔI_{max} of the selective response should rise linearly with the increase of the frequency f at low frequencies $f<f_c$, reach a maximum at $f\sim f_c$ and fall down inversely proportional to f^2 at high frequencies $f>f_c$. This conclusion is valid, provided the same current amplitudes I_s are induced by radiation with different frequencies f. But, due to the different power level of the radiation sources and frequency-dependent coupling of radiation to the junction, the requirement of a constant I_s is difficult to fulfill experimentally.

We have solved this problem by a selfcalibration procedure, when we normalize each of the measured response curves $\Delta I(V)$ to its value ΔI_0 (Eq. 2) at low voltages [5]. The maximum amplitudes ΔI_{max} of the resonances in these normalized responses are proportional to f^3 at low frequencies $f<f_c$ and independent of the frequency at high frequencies $f > f_c$. The last circumstance just reflects the frequency-independent behavior of the amplitude of Josephson oscillations in the RSJ model. With this normalization, each set of data can be compared with the others, measured for different frequencies, and deviations from the RSJ-behavior can be easily detected.

The Josephson junctions, which are close to RSJ model, are good candidates for the Hilbert-transform spectral analysis [1]. Starting from Eq. (1) and using an additivity of the response $\Delta I(V)$ for monochromatic radiation, the small-signal response $\Delta I(V) << I_0(V)$ was generalized for radiation, inducing currents through the junction with an arbitrary spectral density $S_i^2(f)$. The calculated response $\Delta I(V)$ with the accuracy of some experimentally measured function was found to be proportional to the Hilbert transformation of the spectral density $S_i^2(f)$, so the unique deconvolution of $S_i^2(f)$ from the experimental data is possible. The exact solution of the problem was found to be [1]

$$S_{i_j}^2(f) = \left(\frac{1}{\pi}\right)\cdot \int_{-\infty}^{+\infty} \frac{H(f_j)}{(f_j - f)}\cdot df_j \quad (5)$$

where $f_j = 2eV/h$ is the voltage-controlled frequency of the Josephson oscillations, $H(V)$ is a response function

$$H(V) = (8/\pi)(h/2e)[\Delta I(V) I(V) V / I_c^2 R_n^2] \,, \quad (6)$$

consisting of the product of the response $\Delta I(V)$, the current-voltage characteristic $I(V)$ and the voltage V. The principal value of integral should be taken in Eq. 5. So, to get spectrum of radiation, one should measure the $I(V)$ - curve of Josephson junction, its response $\Delta I(V)$ to this radiation and perform the Hilbert transformation of the response function $H(V)$.

Actually, the spectral resolution of Hilbert-transform technique is equal to the Josephson linewidth δf (Eq.4) and the instrumental function of the technique is determined by spectrum of Josephson oscillations.

III. EXPERIMENT

High-quality $YBa_2Cu_3O_{7-x}$ grain-boundary junctions fabricated on untwinned 2x14° (110) $NdGaO_3$ bicrystal substrates [19] have been used in the experiments. The widths of the junctions were in the range 1-3µm. The I_cR_n-products of these junctions were up to 330 µV at 78 K, and the values of resistances R_n varied from 1 to 8 Ohm. A broadband $YBa_2Cu_3O_{7-x}$ log-periodic antenna has been integrated with each junction on the substrate.

In our previous experiments we used a liquid-helium cryostat to cool the junctions [16]. Recently, we have developed a laboratory prototype of Hilbert-transform spectrum analyzer integrated into a Stirling cooler. A photo of this analyzer and a schematic of a frontend of this analyzer are shown in Fig. 1. The substrate with the Josephson junction was mounted in a vacuum chamber on the coldfinger of a Stirling cooler [20]. Junction temperatures in the range from 30 to 90 K have been achieved in this cryogenic environment. The measurements at any of these temperatures could be carried out during several hours with a reasonable drift of 1-2 K.

Terahertz radiation was focused to the junction antenna through a polyethylene window in the vacuum chamber and hyperhemispherical Si-lens on the substrate.

An optically-pumped far-infrared laser and a backward-wave oscillator with a multiplier were used as sources of monochromatic radiation in this study. With this combination we were able to deliver radiation in the frequency range from

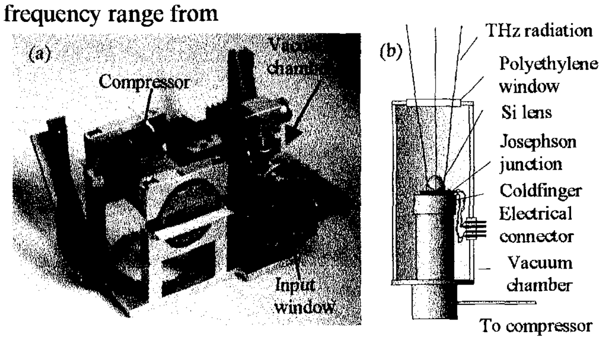

Fig. 1. Photo of a terahertz spectrum analyzer based on a high-T_c Josephson junction integrated into a Stirling cooler (a) and a schematic of the frontend of this spectrum analyzer (b).

60 GHz to 5 THz. Absorption attenuators were placed between the radiation sources and the Josephson junction to guarantee a low level of radiation for square-law detection by the Josephson junctions.

IV. RESULTS

A. Instrumental function

The *I-V* curve (a) of our typical $YBa_2Cu_3O_{7-x}$ Josephson junction at 34 K and its response $\Delta I(V)$ to 3.1 THz radiation (b) are shown in Fig. 2. The Josephson junction got a normal-state resistance of $R_n = 1.1$ Ohm and quite high I_cR_n-product of 1.5 mV at 34 K. The shapes of the *I-V* curve and $\Delta I(V)$ are very close to those of the RSJ model in the range of voltages abs(V)≤ 8.5 mV. The response ΔI demonstrates a very sharp odd-symmetric resonance around the voltages near $V = hf/2e = 6.42$ mV. This resonance in the response function $H(V) \propto \Delta I(V)*I(V)*V$ (Eq. 6) is shown in Fig. 2c.

A result of Hilbert transformation of the response function (Fig. 2c) is shown in Fig. 2d. According to the measurement procedure, the spectrum shown in Fig. 2d is an instrumental function of the spectrum analyzer and, according to the principle of analyzer operation, it is the spectrum of Josephson oscillations for the voltage $V=hf/2e$=6.423 mV. The spectrum shown in Fig.2d nicely fits to a Lorentz curve. The width of the instrumental function or Josephson linewidth δf was found to be of 4 GHz. So, it follows from the measured data that a resolving power $\delta f/f$ of the order of 10^{-3} might be achieved with the spectrum analyzer based on the selective detection by high-T_c Josephson junctions.

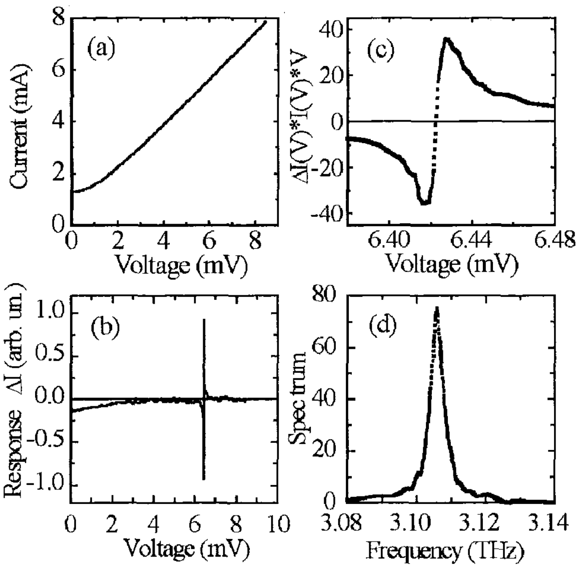

Fig. 2. (a) The I-V curve of the $YBa_2Cu_3O_{7-x}$ bicrystal Josephson junction at 34 K: (b) The response $\Delta I(V)$ of $YBa_2Cu_3O_{7-x}$ Josephson junction to laser radiation with the frequency of 3.106 THz. (c) The response function $H(V) \propto \Delta I(V)*I(V)*V$ near the resonance at the voltage V=6.423 mV. (d) Spectrum of radiation recovered by Hilbert-transformation of data on Fig. 2c.

B. Spectral range

A set of the normalized current responses $\Delta I(V)/abs(\Delta I_0)$ of the Josephson junction with $R_n = 7$ Ohm to monochromatic signals with the frequencies from 0.079 THz up to 4.25 THz are shown in Fig. 3 for two junction temperatures of 83 and 35 K. With an increase of frequency *f*, the amplitude of the odd-symmetric resonances at $V=hf/2e$ also increases, then, when the frequency is around $2f_c$ (and the voltage is around $2I_cR_n$), reaches the maximum, and falls down with further increase of frequency.

For each temperature in the range of 30 – 85 K the selective response was observed at least in one decade of frequency bandwidth. The middle frequency of this bandwidth scaled with the characteristic frequency $f_c=(2e/h)I_cR_n$, so the total bandwidth of selective detection, which was covered by one Josephson junction at different temperatures, was around two decades (Fig. 3).

The low-frequency cut-off of the appearance of the resonances in responses $\Delta I(V)/abs(\Delta I_0)$ in Fig. 3 is in accordance with the RSJ behavior. It is the result of the low-voltage increase of the linewidth of Josephson radiation and a corresponding decrease of the resonance amplitude according to Eq.3. The high-frequency fall-down of the selective response for low-ohmic junctions was attributed to Joule heating [9] and it was considered that it might be shifted to the higher frequencies by increasing the junction resistance. As we can see from Fig.3, the increase of the resistance to 7 Ohm results only in the moderate increase of highest frequency to 4.25 THz. In the case of high-ohmic junctions

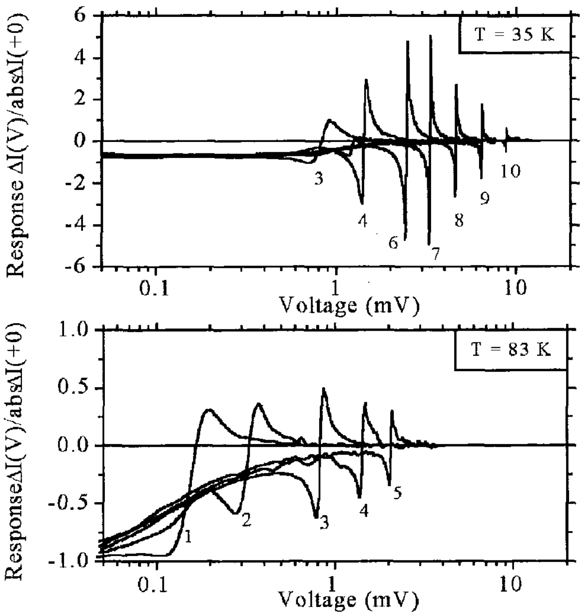

Fig. 3. Normalized detector responses $\Delta I(V)/abs\, \Delta I(+0)$ of the $YBa_2Cu_3O_{7-x}$ Josephson junction to monochromatic radiation measured at two temperatures (83 K and 35 K) and ten different frequencies: 0.079 (1), 0.158 (2), 0.404 (3) 0.693 (4), 0.992 (5), 1.194 (6), 1.611 (7), 2.252 (8), 3.106 (9) and 4.252 THz (10).

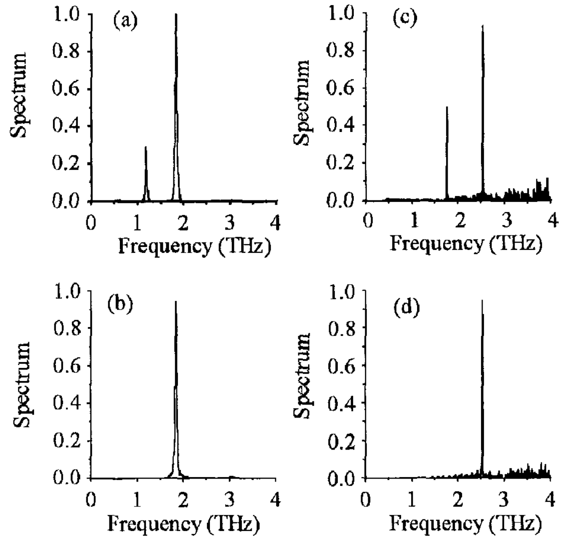

Fig. 4. Spectra of radiation from optically-pumped CH_3OH laser recovered by Hilbert-transform spectrum analyzer. The pump line of CO_2 laser was 10R38 for spectra (a), (b) and 9P36 for spectra (c), (d). Spectra have been measured for different lengths of CH_3OH laser cavity. The Josephson junctions with the normal-state resistances R_n of 7 Ohm (a),(b) and 1 Ohm (c), (d) were used in the analyzer.

the high-frequency cut-off might be also influenced by a capacitive shunting of the junction.

C. Application for optimization of FIR laser

It is known that spectrum of radiation from optically-pumped gas lasers can consists of several spectral lines even when a single pump line is used [21]. The developed Hilbert-transform spectrum analyzer has been applied for an optimization of a single-line operation of a far-infrared CH_3OH laser, pumped by CO_2 laser. The results are shown in Fig. 4 for the pump lines 10R38 (a), (b) and 9P36 (c), (d). The length of the FIR laser cavity was tuned and spectra of output radiation were measured by our spectrum analyzer.

In the case (a), two lines, the one, at 1.839 THz and the other, at 1.193 THz, are clearly visible in the spectrum. The broadening of the lines is due to a relatively large value of 7 Ohm for junction resistance R_n. After tuning the length of laser cavity and controlling the spectrum of laser radiation by our analyzer, it was possible to get a single-line operation of the optically pumped laser at f = 1.839 THz (b).

Similar optimization of single 2.522 THz-line operation of optically-pumped CH_3OH laser for 9P36 pump line is shown in Fig. 4c,d. These spectra are obtained when the Josephson junction with relatively lower resistance R_n of 1 Ohm was used and, correspondingly, a better spectral resolution has been achieved.

V. CONCLUSION

A prototype of Hilbert-transform spectrum analyzer based on high-T_c Josephson detector integrated into a Stirling cooler has been developed. The spectral range of this spectrum analyzer was shown to cover almost two decades in the subterahertz and terahertz regions. The resolving power $\delta f/f$ of the order of 10^{-3} has been achieved at terahertz frequencies. An application of this spectrum analyzer for optimization of the single-line operation of far-infrared optically-pumped CH_3OH laser has been demonstrated.

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