Frequency-selective incoherent detection of terahertz radiation by high-T_c Josephson junctions

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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 4 THz has been studied. Frequency-selective odd-symmetric resonances in the responses $\Delta I(V)$ of these junctions to radiation with different frequencies f have been observed near the voltages $V=hf/2e$ in almost a decade of spectral range for any operating temperature in the range from 30 to 85 K. The spectral range of the selective detection has scaled with the I_cR_n product of the Josephson junction, reaching the range of 0.16–3.1 THz for a I_cR_n product of 1.5 mV. A resolving power $\delta f/f$ of around 10^{-3} has been demonstrated in the selective detection by Josephson junctions. The high-frequency falldown of the amplitude of the selective response has been found to be proportional to $\exp[-P/P_0]$, where $P=(hf/2e)^2/R_n$ is the power dissipated in the junction at the resonance and P_0 is a characteristic power level. The values of P_0 for our junctions were around 20 μW at 34 K and 2 μW at 78 K. © *2000 American Institute of Physics.* [S0003-6951(00)03720-7]

One of the promising applications of superconducting junctions is the detection of electromagnetic radiation. Among them, the detectors using the ac Josephson effect can give an information on the spectrum of incident radiation.[1] 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,[2–5] and only recently, after some progress in junction fabrication, the first evaluations of high-T_c Josephson junctions for this application have been carried out.[6–9] One of the main unanswered questions in this field is the spectral range where the frequency-selective Josephson detection can take place. Here, we report on the results of our study of this problem.

In the simple resistively shunted junction (RSJ) model,[10] the response $\Delta I=I(V)-I_0(V)$ of a Josephson junction to weak monochromatic radiation with the frequency f is equal to[10]

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

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 ($I_s \ll I_c$), I_0 is the direct current flowing through the junction, $V=R_n(I_0^2-I_c^2)^{1/2}$ is the voltage across the junction, $f_j=2eV/h$ is the voltage-controlled frequency of internal Josephson oscillations, and δf is the Josephson oscillations linewidth.

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

$$\Delta I_0=-(I_s^2R_n/2)(2e/h)(f_c/2f^2), \tag{2}$$

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 $\Delta I_{\max}$ of this resonance at $V=(h/2e)\times[f+(\delta f/2)]$ is inversely proportional to the Josephson linewidth δf

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

For broadband thermal fluctuations with a noise temperature T and $kT<eV$ (equilibrium case), the Josephson linewidth is equal to[10]

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

where R_d is the dynamic resistance of the junction. The dynamic resistance $R_d(V)=dV/dI=R_n(V^2+I_c^2R_n^2)^{1/2}/V$ 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. So, the linewidth and the width of the odd-symmetric resonance in the response $\Delta I(V)$ [Eq. (1)] will decrease with the increase of the frequency f at low frequencies $f<f_c$ and will be frequency independent at high frequencies $f>f_c$.

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One can expect from Eqs. (3) and (4), that the amplitude $\Delta I_{\max}$ 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 falldown 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 $\Delta I_{\max}$ 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.

High-quality $YBa_2Cu_3O_{7-x}$ grain-boundary junctions fabricated on untwinned $2\times14°(110)$ $NdGaO_3$ bicrystal substrates[11] have been used in the experiments. The widths of the junctions were in the range 1–3 μm. 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 0.5 to 16 Ω. A broadband $YBa_2Cu_3O_{7-x}$ log-periodic antenna has been integrated with each junction on the substrate.

The substrate with the Josephson junction was mounted in a vacuum chamber on the coldfinger of a Stirling cooler.[12] 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. The compressor of the Stirling cooler and the vacuum chamber were magnetically shielded by several layers of mu-metal foil.

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 60 GHz to 4.25 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. Radiation was focused to the junction antenna by a parabolic mirror through a polyethylene window in the vacuum chamber and a hyperhemispherical Si-lens on the substrate.

The response $\Delta V(V)$ of a typical $YBa_2Cu_3O_{7-x}$ Josephson junction to 3.1 THz radiation is shown in Fig. 1. The Josephson junction has a resistance of $R_n = 1.1\,\Omega$ and quite high I_cR_n product of 1.5 mV at 34 K. The shape of the response $\Delta V(V)$ [Fig. 1(a)] is very close to that of the RSJ model in the voltage range from 0 to 8.5 mV. The response ΔV demonstrates a very sharp odd-symmetric resonance around the voltages near $V = hf/2e = 6.423$ mV. The width of this resonance is around 8μV [Fig. 1(b)], which corresponds to the Josephson linewidth δf of 3.9 GHz. So, it follows from the measured response that a resolving power $\delta f/f$ of the order of 10^{-3} might be achieved with selective detection by high- T_c Josephson junctions.

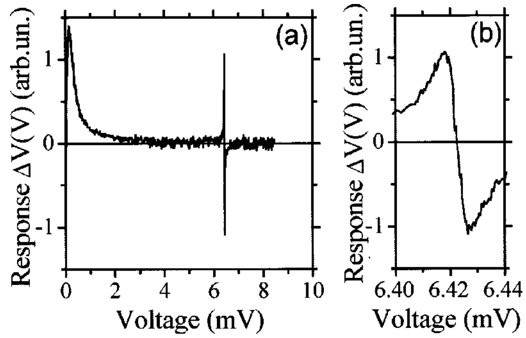

FIG. 1. (a) The response $\Delta V(V)$ of a $YBa_2Cu_3O_{7-x}$ bicrystal Josephson junction to far-infrared laser radiation with the frequency of 3.106 THz. (b) The same response near the resonance at the voltage $V = 6.423$ mV. The junction temperature was kept at 34 K.

To obtain a normalized response $\Delta I(V)/abs(\Delta I_0)$, as it was discussed in the introduction, the current response $\Delta I(V) = -\Delta V(V)/R_d(V)$ was calculated and the value of ΔI_0 was determined by extrapolation of the low-voltage behavior of $\Delta I(V)$ to $V=0$. Four sets of the normalized current responses $\Delta I(V)/abs(\Delta I_0)$ of a Josephson junction with $R_n = 1.1\,\Omega$ to monochromatic signals with the frequencies from 0.079 up to 3.1 THz are shown in Fig. 2. Starting from

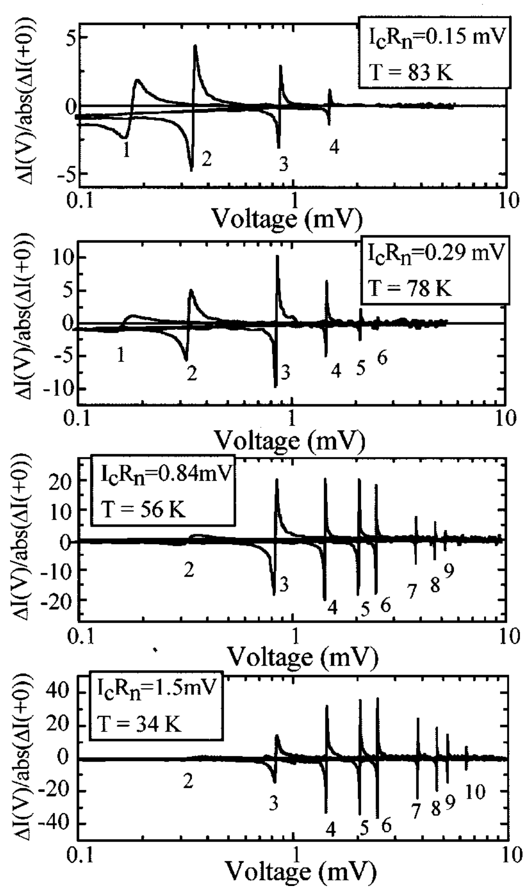

FIG. 2. Normalized response $\Delta I(V)/abs(\Delta I_0)$ of a $YBa_2Cu_3O_{7-x}$ bicrystal Josephson junction to far-infrared laser radiation measured at four different temperatures (83, 78, 56, and 34 K, from earlier to later) and ten different frequencies. The radiation frequencies were 0.079 (1), 0.158 (2), 0.404 (3), 0.693 (4), 0.992 (5), 1.194 (6), 1.758 (7), 2.252 (8), 2.523 (9), and 3.106 THz (10).

before, each set has been measured at junction temperatures T of 83, 78, 56, and 34 K, correspondingly.

As it follows from Fig. 2, each set of response curves shows the same behavior. 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 $2 f_c$ (and the voltage is around $2I_cR_n$), reaches the maximum, and falls down with further increase of frequency. For each temperature the selective response is 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.

The low-frequency cutoff of the appearance of the resonances in responses $\Delta I(V)/abs(\Delta I_0)$ in Fig. 2 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 falldown of the resonance response might also be related with the increase of Josephson linewidth due to, for example, nonequilibrium fluctuations at $eV/kT > 1$.[11] But, this mechanism might give only a slow reduction of the response amplitudes for the lowest temperature of 34 K and for the detected frequencies from 1.5 to 3.1 THz, where eV/kT is ranging from 1 to 2. For all other responses measured at higher temperatures, the ratio of eV/kT is less than one, the widths of the responses in the range of the falldown are practically the same, but the high-frequency gradual decrease is still observed (see data at 56, 78, and 83 K).

This high-frequency falldown of the resonances in the response of the Josephson junction to monochromatic radiation might be explained by a decrease of the amplitude of Josephson oscillations due to Joule heating of the junction. According to Tinkham *et al.*,[13] heating effects in a Josephson junction can result in an exponential decrease of the amplitude of Josephson oscillations, namely

$$I_c(P) = I_c(0)\exp(-P/P_0), \tag{5}$$

where P is the power dissipated in the junction, $P_0 = [1 - (T/T_c)^2]^{1/2} T_c K(T_c) \xi_0 \Omega$ is a characteristic power level, which is proportional to the critical temperature T_c. $K(T_c)$ denotes the heat conductivity of the superconductor at T_c, ξ_0 is the coherence length and Ω is a solid angle for cooling of the junction.

If we put for the dissipated power its value at the voltage of the resonance in the response $\Delta I(V)$, we should expect a falldown of the resonance response as $\exp[-(hf/2e)^2/R_nP_0]$. To check this idea, we have plotted the maximum amplitudes of the resonances in logarithmic scale vs. the dissipated power $(hf/2e)^2/R_n$ at the resonance. The results are presented in Fig. 3 for one junction with $R_n = 1.1\ \Omega$ at three temperatures. The dashed lines are the linear fit for each set of data and represent actually Eq. (5) with different P_0 values for different temperatures. The correspondence of the data and the dependence according to Eq. (5) is clearly seen from Fig. 3.

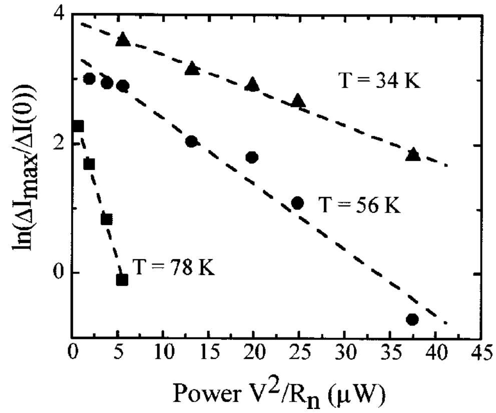

FIG. 3. The maximum amplitudes $\Delta I_{max}/abs(\Delta I_0)$ of the normalized response $\Delta I(V)/abs(\Delta I_0)$ at the resonance vs dissipated power P at the voltage $V = hf/2e$ of the resonance. The dashed lines are the fitting functions $\sim\exp(-P/P_0)$. The values of P_0 were equal to 18.5 μW at $T = 34$ K, 9.9 μW at $T = 56$ K, and 2.1 μW at $T = 78$ K.

In summary, in the terahertz frequency range we have demonstrated almost a decade bandwidth of the selective detection by $YBa_2Cu_3O_{7-x}$ Josephson junctions for any temperature in the range of 30–85 K. The bandwidth scaled with the I_cR_n product of the junction, and using one junction at different temperatures one can cover up to almost two decades with a selective detection. Broadband operation of Hilbert-transform spectroscopy[1] in the terahertz range with a resolving power of around 10^{-3} might be achieved according to these experiments. The high-frequency falldown of the selective response is attributed to Joule heating and it might be shifted to higher frequencies by increasing the junction resistance and/or further decreasing the operation temperature.

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[1] Y. Y. Divin, O. Y. Polyanski, and A. Y. Shul'man, Sov. Tech. Phys. Lett. **6**, 454 (1980).
[2] H. Kanter and F. L. Vernon, J. Appl. Phys. **43**, 3174 (1972).
[3] Y. Y. Divin and F. Y. Nad', Sov. Tech. Phys. Lett. **4**, 316 (1978).
[4] D. A. Weitz, W. J. Skocpol, and M. Tinkham, Phys. Rev. B **18**, 3282 (1978).
[5] Y. Y. Divin and N. A. Mordovets, Sov. Tech. Phys. Lett. **9**, 108 (1983).
[6] Y. Y. Divin, J. Mygind, N. F. Pedersen, and P. Chaudhari, Appl. Phys. Lett. **61**, 3053 (1992).
[7] P. A. Rosenthal and E. N. Grossman, IEEE Trans. Microwave Theory Tech. **42**, 707 (1994).
[8] Y. Y. Divin, H. Schulz, U. Poppe, N. Klein, K. Urban, and V. V. Pavlovskii, Appl. Phys. Lett. **68**, 1561 (1996).
[9] K. Nakajima, J. Chen, H. Myoren, T. Yamashita, and P. Wu, IEEE Trans. Appl. Supercond. **7**, 2607 (1997).
[10] K. K. Likharev, *Dynamics of Josephson Junctions and Circuits* (Gordon and Breach, New York, 1986).
[11] Y. Y. Divin, I. M. Kotelyanskii, P. M. Shadrin, O. Y. Volkov, V. V. Shirotov, V. N. Gubankov, H. Schulz, and U. Poppe, in *Proceedings of EUCAS 97*, edited by H. Rogalla and D. H. A. Blank (IOP Publishing Ltd., Bristol, 1997), pp. 467–470.
[12] Model SL-200, AEG INFRAROT-MODULE GmbH, D-74001 Heilbronn, Germany.
[13] M. Tinkham, M. Octavio, and W. J. Skocpol, J. Appl. Phys. **48**, 1311 (1977).