Spectral Range of the ac Josephson Effect in [001]-tilt $YBa_2Cu_3O_{7-x}$ Bicrystal Junctions

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***Abstract*—We have studied the ac Josephson effect in $YBa_2Cu_3O_{7-x}$ bicrystal junction by monitoring the voltage dependence of the dc current response $\Delta I(V)$ induced by low-power monochromatic radiation with the frequencies f_i. The intensity of odd-symmetric resonances in the function $\Delta I(V)$ near the voltages $V_i = hf_i/2e$ is proportional to the amplitude of Josephson oscillations at the frequency f_i. The resonance intensities have been mapped as a function of the Josephson frequency f_i in the range from 5 GHz to 5 THz, the junction resistance R_n in the range from 0.4 to 80 Ohm and junction characteristic voltages I_cR_n in the range from 5 μV to 1.8 mV. The central frequency of the range was scaled with the I_cR_n-product of the junction and it could be shifted from GHz-range to the THz-range by a temperature decrease. The spectral range was limited by an enhanced noise broadening of the Josephson linewidth at low frequencies and by increased dc Joule heating at high frequencies.**

***Index Terms*—Detectors, high-temperature superconductors, Josephson effect, spectral analysis.**

I. Introduction

AMONG the various aspects of physics of high-T_c superconducting junctions, the spectral range of the ac Josephson effect has not received enough attention. But, this feature is of importance both from fundamental and practical points of view. An operation of RSFQ logic, Hilbert spectroscopy, submillimeter-wave detectors and mixers might be improved by a better understanding of the frequency limits of the ac Josephson effect.

Practically all previous studies of the spectral range of the ac Josephson effect have been made by monitoring the amplitudes of constant-voltage steps, induced on the I-V curve at the voltages $V_n = nhf/2e (n = 1, 2, 3 \ldots)$ by intensive monochromatic radiation with the frequency f[1]–[3]. But, due to a specific dynamic nonlinearity in the Josephson effect, the observation of the n-step does not mean that there are Josephson oscillations at the frequency $f_j = nf$ in the junction (see [4], Problem 11.2). Only measurements of the amplitudes of the first step at various frequencies f can give the information about the spectral range of Josephson oscillations. Using this approach both at high [2] and low [5] intensities of far-infrared radiation, the high-frequency fall-down of Josephson oscillations in low-T_c Nb point contacts has been observed above the gap frequency $f = 2\Delta/h$.

Due to the larger values of the energy gaps ($2\Delta = 20-60$ meV) in high-temperature superconductors, it has been expected that the spectral range of high-T_c Josephson detectors and mixers might be extended to much higher frequencies. But, quite a small improvement of the spectral range has been observed in the first experiments [3], [6]. Even the recent result, where the ac Josephson effect have been demonstrated in a decade spectral range with the highest frequency of 4.2 THz [7], is far from the expectations.

Here, we report on the dependences of the spectral range of the ac Josephson effect in the high-T_c bicrystal junctions on the junction parameters.

II. Theory

In the simple resistively shunted junction (RSJ) model [4] with thermal fluctuations, the response $\Delta I = I(V) - I_o(V)$ of a Josephson junction to weak monochromatic radiation with the frequency f is equal to [4]

$$\Delta I(V) = I_s^2 \left(\frac{2e}{h}\right) \frac{I_c^2 R_n^2}{8 I_0 V} \times \left[\frac{(f_j + f)}{(f_j + f)^2 + \left(\frac{\delta f}{2}\right)^2} + \frac{(f_j - f)}{(f_j - f)^2 + \left(\frac{\delta f}{2}\right)^2}\right], \quad (1)$$

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 current induced in the junction by radiation ($I_s \ll I_c$), 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 Josephson oscillations and δf is the linewidth of Josephson oscillations. For broadband thermal fluctuations with a noise temperature T and $kT > eV$, the Josephson linewidth is equal to [4]

$$\delta f = \delta f_0 \left(\frac{R_d^2}{R_n^2}\right) \left[1 + \left(\frac{I_c^2}{2I_0^2}\right)\right] = \delta f_0 \left(1 + \frac{3f_c^2}{2f_j^2}\right), \quad (2)$$

where $\delta f_0 = 4\pi(2e/h)^2 kTR_n$ is the Josephson linewidth at the junction voltages $V \gg I_cR_n$, $R_d(V) = dV/dI =$

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$R_n(V^2 + I_c^2 R_n^2)^{1/2}/V$ is the dynamic resistance of the junction, $f_c = (2e/h)I_c R_n$ is a characteristic frequency of the Josephson junction.

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

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

One could study the spectral range by measuring the $\Delta I_{\max}$ as a function of f, if it were not for requirement to keep the current amplitudes I_s constant during the measurements.

To solve this problem, a selfcalibration procedure has been suggested [5], where the $\Delta I_{\max}$ is normalized to the suppression of the critical current $\Delta I_c = -(I_s^2 R_n/2)(2e/h)(f_c/2f^2)$ by the same radiation, and the result is

$$\frac{\Delta I_{\max}}{\Delta I_c} = \frac{f f_c}{2}(f_c^2 + f^2)^{1/2} \delta f. \quad (4)$$

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 first circumstance is the result of a low-voltage decrease of the amplitude of the first harmonic of Josephson oscillations due to an increase of the linewidth of Josephson radiation and a redistribution of the amplitudes of the Josephson harmonics. The last circumstance just reflects the frequency-independent behavior of the amplitudes 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 frequency-independent behavior of the amplitudes of Josephson oscillations can be easily detected.

III. Experiment

High-quality [001]-tilt $YBa_2Cu_3O_{7-x}$ grain-boundary junctions have been fabricated on untwined 2 × 14° (110) $NdGaO_3$ bicrystal substrates [8]. The thickness of the $YBa_2Cu_3O_{7-x}$ junctions was varied in the range of 50 –500 nm. The widths of the junctions were in the range 1-3 μm, which are close to a correlation length of the inhomogeneous current distribution in our junctions [8], [9]. This choice of the widths allows us to maximize the yield of RSJ-like junctions. Even with these precautions, the RSJ-like nonhysteretic I-V curves for the junctions with the resistances R_n in the range 0.4 –80 Ohm have been observed only at the temperatures above 30 K.

At the temperature of 35 K, the $I_c R_n$-products of the RSJ-like junctions decreased from the 1.8 mV to around 0.5 mV with an increase of the resistances R_n from 0.45 to 80 Ohm. A broadband double-layered Ag/$YBa_2Cu_3O_{7-x}$ log-periodic planar antenna has been integrated with each junction on the substrate. The Josephson junctions were mounted on the cold finger of a Stirling cooler or a LN optical dewar.

An optically pumped far-infrared laser, a backward-wave oscillators and solid-state oscillators were used as sources of monochromatic radiation in this study. With this combination we were able to deliver radiation in the frequency range from 5 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. Radiation was focused to the junction antenna through a polyethylene window in the vacuum chamber and hyper hemispherical Si-lens on the substrate.

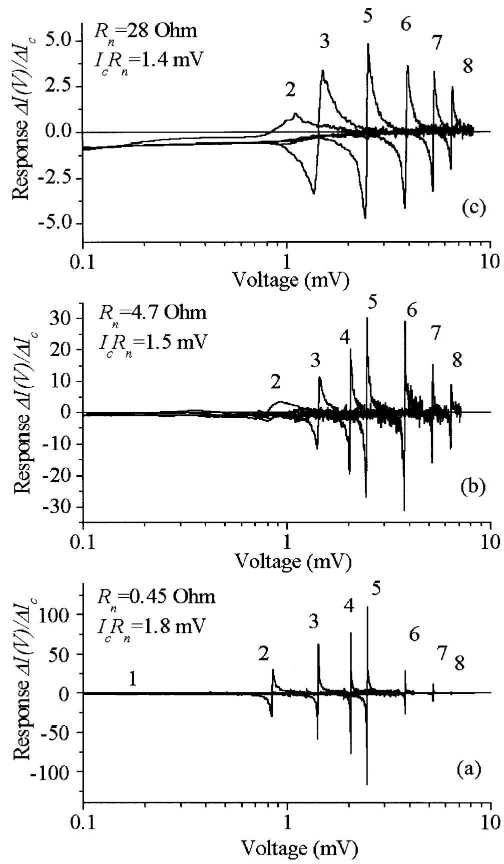

Fig. 1. Three combined sets of normalized responses $\Delta I(V)/\Delta I_c$ of the $YBa_2Cu_3O_{7-x}$ Josephson junctions with the resistances R_n : 0.45 Ohm (a), 4.7 Ohm (b), 28 Ohm (c). The frequencies of the external radiation f are equal to 79 GHz (1), 404 GHz (2), 693 GHz (3), 992 GHz (4), 1194 GHz (5), 1757 GHz (6), 2523 GHz (7), 3106 (8). The junction temperatures are around 37 K.

IV. Results

A. Responses

Three sets of the normalized current responses $\Delta I(V)/\Delta I_c$ of the Josephson junctions with $R_n = 0.45$ Ohm, 4.7 Ohm and 28 Ohm to monochromatic signals with the frequencies from 79 GHz up to 3.1 THz are shown in Fig. 1. The junction temperatures were in the range of (37 ± 3) K and the $I_c R_n$-products of these three junctions are practically the same.

With an increase of frequency f, the amplitudes of the odd-symmetric resonances at $V = hf/2e$ first increase, then reach the maximum, and fall-down with further increase of frequency. The last circumstance means that the strength of Josephson oscillations in these junctions decreases in terahertz range.

The maximum response for each junction at 1.19 THz goes down from the value of 120 (a) to around 4 (b) with the increase of the junction resistances from 0.45 to 28 Ohm, mainly

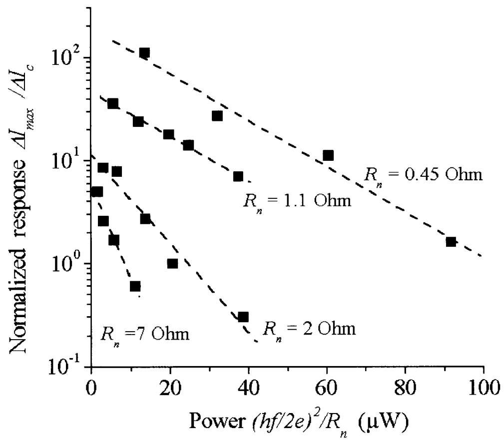

Fig. 2. The maximum amplitudes $\Delta I_{\max}/\Delta I_c$ of the normalized responses at the resonance vs. dissipated power P at the voltage $V = hf/2e$ of the resonance for the junctions with the resistances $R_n = 0.45$; 1.1; 2.0: and 7.0 Ohm. The dashed lines are fitting functions $\sim \exp(-P/P_0)$. $T = 35$ K.

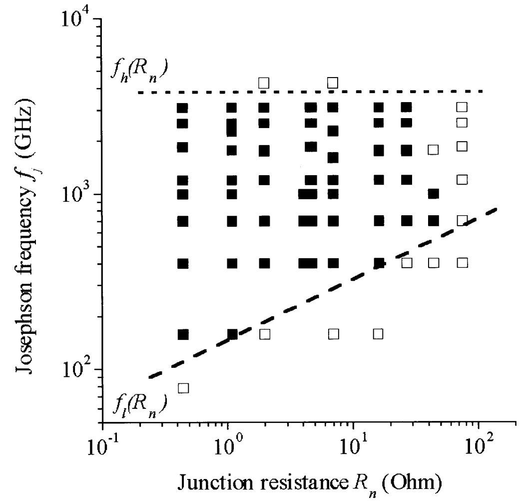

Fig. 3. The mapping of the maximum normalized responses $\Delta I_{\max}/\Delta I_c$ of [001]-tilt $YBa_2Cu_3O_{7-x}$ grain-boundary junctions to monochromatic radiation in the frequency-resistance plane. The solid squares – the responses $\Delta I_{\max}/\Delta I_c > 1$, the open squares – the responses $\Delta I_{\max}/\Delta I_c \leq 1$. $T = (37 \pm 3)$ K.

reflecting the increase of the Josephson linewidth according to (2) and (4), and corresponding decrease of the amplitude of Josephson oscillations. The low-voltage behavior of the resonances in each set of the responses $\Delta I(V)/\Delta I_c$ in Fig. 1 is in accordance with RSJ-like behavior of the amplitude of Josephson oscillations and increased linewidth of Josephson oscillations.

B. High-Frequency Fall-Down

The high-frequency fall down of the selective responses in Fig. 1 is not followed by an increase of the Josephson linewidth, e.g., due to nonequilibrium fluctuations at the voltages $V > 2kT/e$. This contribution to the noise was found negligible for the data presented in Fig. 1.

As we can see from Fig. 1, an increase of the resistance from 0.45 Ohm to 28 Ohm results in slower fall-down of the amplitudes of the responses at higher frequencies. We may expect the mechanism of weakening the strength of the ac Josephson effect might be resistance-dependent. This possibility to explain high-frequency fall-down might be related with Joule heating of the junctions. According to Tinkham *et al.* [10], heating can result in an exponential decrease of the amplitude of Josephson oscillations with the power P dissipated in the junction:

$$I_c(P) = I_c(0)\exp\left(\frac{-P}{P_0}\right), \quad (5)$$

where $P_0 = (1/\sqrt{2})[1-(T/T_c)^2]^{1/2}K(T_c)T_c\xi(0)\Omega$ is a characteristic power level, which is proportional to the critical temperature T_c of the superconducting material of the junction, $K(T_c)$ is the heat conductivity at T_c, $\xi(0)$ is the correlation length and Ω is the solid angle for cooling of the junction.

The maximum normalized response should follow the same exponential behavior, as in (5), at high voltages. In Fig. 2 we have plotted the maximal amplitudes of the resonances in logarithmic scale vs. dissipated power at the resonance for Josephson junctions with different resistances at $T = 35$ K. The dash lines are the exponential fits ((5)) with different values of characteristic power P_0. The values of P_0 were equal to 18 μW for junctions with $R_n = 0.45$ and 1.1 Ohm, 10 μW for the junction with $R_n = 2.0$ Ohm and 5 μW for 7 Ohm junction. With further increase of the resistance to 76 Ohm, the P_0-values have gradually decreased to 0.5 μW.

C. Mapping

The resonance amplitudes of the normalized response $\Delta I(V)/\Delta I_c$ at voltages $V = hf/2e$ is a result of the interaction of the external signal with a frequency f with a first harmonic of the Josephson oscillation with a frequency $f_j = 2eV/h$. Mapping the intensities of resonance amplitudes $\Delta I_{\max}/\Delta I_c$ as a function of the frequency f and junction parameters should give us the information on the spectral range of the ac Josephson effect. As a criterion for the existence of the ac Josephson effect in studied junctions, we have chosen $\Delta I_{\max}/\Delta I_c > 1$.

The results of the mapping of the strength of the ac Josephson effect in the [001]-tilt $YBa_2Cu_3O_{7-x}$ bicrystal junctions are shown in Figs. 3 and 4. In Fig. 3, where the mapping is presented for the frequency-resistance plane, the low-frequency limit $f_l(R_n)$ of the spectral range goes proportional to $R_n^{1/3}$ (dashed line), which is in accordance with the estimate of $f_l = (3\delta f_0 f_c^2)^{1/3}$ from (4).

The high-frequency limit $f_h(R_n)$ does not practically depend on the normal-state resistance (dotted line). The last observation is in accordance with a decrease of the P_0-values of the junctions with an increase of the resistance R_n from 1 to 80 Ohm, so that the product of P_0R_n is about 20-40 mV^2. This allow us to suspect that in addition to dc Joule heating, there is a suppression of the ac Josephson effect by some frequency-selective mechanism. It might be an interaction of the ac Josephson oscillations with the strongest optical phonon mode in $YBa_2Cu_3O_{7-x}$ electrodes at 4.6 THz [11].

The mapping of the ac Josephson effect in the frequency-I_cR_n plane has been done for the Josephson junctions

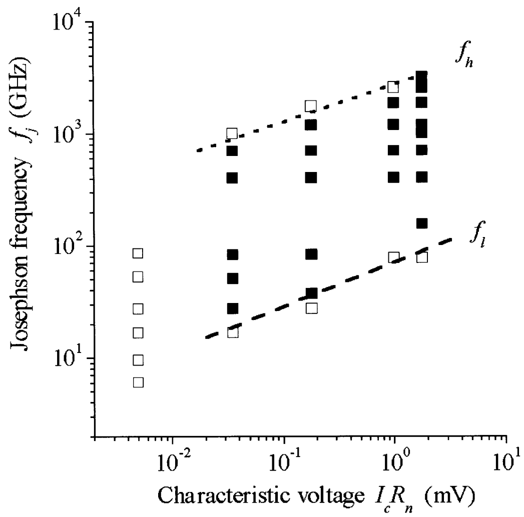

Fig. 4. The mapping of the maximum normalized responses $\Delta I_{\max}/\Delta I_c$ of [001]-tilt $YBa_2Cu_3O_{7-x}$ grain-boundary junctions to monochromatic radiation in the frequency-I_cR_n plane. The solid squares – the responses $\Delta I_{\max}/\Delta I_c > 1$, the open squares – the responses $\Delta I_{\max}/\Delta I_c \leq 1$. $R_n = 0.45$ Ohm.

with $R_n = 0.45$ Ohm at the temperatures from 88 K to 35 K. The I_cR_n-product of the junction has increased from 5 μV to 1.8 mV and the spectral range of the Josephson effect has shifted from microwave range to terahertz range (Fig. 4). The maximum ratio f_h/f_l for these spectral ranges was around 30.

We may expect that a tendency to scale the spectral range with an increase of the I_cR_n-product may proceed further. It would be of interest to study high-frequency limit of the ac Josephson effect in the [001]-tilt $YBa_2Cu_3O_{7-x}$.bicrystal junctions, where the I_cR_n-product of 8 mV has been recently demonstrated [12] and the Josephson frequencies will be close to the frequencies of the optical phonons in $YBa_2Cu_3O_{7-x}$.

V. Conclusions

The ac Josephson effect in [001]-tilt $YBa_2Cu_3O_{7-x}$ bicryctal junctions can be observed in the spectral range between one and two frequency orders in the subterahertz and terahertz range. The high-frequency limit of the Josephson effect is determined by dc Joule heating and, tentatively, by interaction of Josephson oscillations with the optical phonons in $YBa_2Cu_3O_{7-x}$.

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