Classical and Josephson detection of terahertz radiation using YBa$_2$Cu$_3$O$_{7-x}$ [100]-tilt bicrystal junctions

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Abstract. Detection of terahertz radiation using YBa$_2$Cu$_3$O$_{7-x}$ [100]-tilt bicrystal junctions with high $I_CR_n$ product up to 6 mV has been studied. Two types of the responses $\Delta V(V)$ have been observed. At low frequencies up to some frequency $f_l$, the responses $\Delta V(V)$ were proportional to the second derivative of the $V(I)$-curve. At high frequencies $f > f_l$, the responses $\Delta V(V)$ demonstrate odd-symmetric resonances at $V = hf/2e$. For low-resistance junctions, Josephson frequency-selective detection was found up to the frequency of 5.3 THz, which is above the frequency of the strongest optical mode ($f_0 = 4.6$ THz) in YBa$_2$Cu$_3$O$_{7-x}$. The frequency $f_l$ was found to increase with the resistance $R_n$ and the $I_CR_n$-product of the junction. For high-resistance junctions with $R_n = 23 \, \Omega$, classical detection was observed up to 0.4 THz range. The difference in detection mechanisms is attributed to a continuous type of spectra of Josephson oscillations at low voltages and to a discrete type of Josephson spectra at high voltages. Computer simulation of a Josephson detector has been carried out, considering intensive thermal fluctuations and a frequency-dependent impedance of the Josephson junction. It is shown that a classical detector, based on the [100]-tilt Josephson junctions with $R_n =100 \, \text{Ohm}$ at $T = 40 \, \text{K}$, might reach the values of noise equivalent power $\text{NEP} < 2 \cdot 10^{-14} \, \text{W/Hz}^{1/2}$ at the frequencies up to 1.8 THz.

1. Introduction

A spectral range of the ac Josephson effect in high-$T_c$ Josephson junctions and, correspondingly, a frequency-selective detection of external electromagnetic radiation by these junctions were found to scale with characteristic voltages $I_CR_n$ of the junctions [1,2]. This experimental result has been obtained for high-$T_c$ bicrystal junctions of the [001]-tilt type, which consist of two c-axis misoriented thin films and a bicrystal boundary between them as a tunnel barrier. Due to an island growth of the c-axis high-$T_c$ thin films, a real bicrystal boundary in the [001]-tilt junctions demonstrates a complicated microstructure with a faceted meandering around a substrate bicrystal boundary. This circumstance results in inhomogeneous local current distributions and low characteristic voltages $I_CR_n$ of the fabricated high-$T_c$ junctions in comparison with the values, expected from the Ambegaokar-Baratoff’s relation $I_R(0) = \pi \Delta(0)/2e$ [3], where $2\Delta(T)$ is a temperature-dependent energy gap of superconducting electrodes. Recently, the [100]-tilt high-$T_c$ Josephson bicrystal junctions with mutually tilted c-axis’s have been fabricated with an order of magnitude less meandering of the bicrystal boundary, better current homogeneity and a three-fold increase of the $I_CR_n$-values, compared with those of the
conventional [001]-tilt junctions [4,5]. It was supposed that the spectral range of the ac Josephson effect in new [100]-tilt junctions and detectors, based on them, might be extended to higher frequencies. Here, we report on detection of terahertz radiation by the [100]-tilt high-\(T_c\) bicrystal Josephson junctions.

2. Experimental details and results

2.1. Josephson detection

The details of fabrication of the [100]-tilt \(\text{YBa}_2\text{Cu}_3\text{O}_7-x\) bicrystal junctions have been reported elsewhere [5,6]. Here, we have studied the [100]-tilt \(\text{YBa}_2\text{Cu}_3\text{O}_7-x\) junctions with misorientation angles from 2x11.3\(^{\circ}\) to 2x14\(^{\circ}\). The values of normal-state resistances \(R_n\) were in the range of 1-25 \(\Omega\) and the values of the \(I_cR_n\)-products were as high as 6 mV at a temperature of 10 K. Each junction was supplied with an integrated sinuous log-periodic Ag-antenna. Solid-state multipliers, Gunn oscillators and an optically-pumped far-infrared laser were used as sources of monochromatic radiation in the frequency range 15 GHz – 6.3 THz. The voltage responses \(\Delta V(V)\) have been measured and the normalized responses \(\Delta I(V)/\Delta I_c\), containing information on the amplitude and linewidth of Josephson oscillations, have been calculated from the experimental data. The details have been published earlier [1,2,7].

Normalized experimental responses \(\Delta I(V)/\Delta I_c\) of high-resistive [100]-tilt \(\text{YBa}_2\text{Cu}_3\text{O}_7-x\) Josephson junction to electromagnetic radiation with the frequencies \(f\) in the range of 0.404 – 3.106 THz are shown in figure 1. The responses demonstrate odd-symmetric resonances with a sign reversal at the voltages \(V = hf/2e\), due to a frequency pulling of Josephson oscillations by external radiation. When the frequency \(f\) increases, the resonance amplitudes also increase and then, at terahertz frequencies, decrease. The low-frequency tendency of the experimental responses \(\Delta I(V)/\Delta I_c\) is in an agreement with theoretical responses \(\Delta I(V)/\Delta I_c\), based on the RSJ model with thermal noise [8] and showed in figure 2. But, a high-frequency falldown of the experimental \(\Delta I(V)/\Delta I_c\)-amplitudes contradicts with a behavior of calculated data (figure 2), where, due to frequency-independent amplitude of Josephson oscillations in the RSJ model, resonance amplitudes approach some saturation at high frequencies. The amplitude falldown is not a result of a broadening of the Josephson linewidth by nonequilibrium fluctuations,

\[R_n = 23 \Omega, \quad I_cR_n = 1.8 \text{ mV}, \quad T = 50 \text{ K}.\]

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because $eV < 2kT$ in this experiment and the experimental values of Josephson linewidths $\delta f$ for the curves 3,4,5 were the same within an accuracy of 5%. So, a high-frequency falldown might be ascribed to a decrease of the amplitude of Josephson oscillations. In high-resistive junctions, a weakening of the ac Josephson effect at high frequencies might be due to shunting by a junction capacitance $C$ or junction environment [7]. The values of $C \approx 4 \times 10^{-15}$ F have been estimated from the data in figure 1.

To remove the shunting effects, we tried to work with low-resistance junctions. Normalized responses $\Delta I(V)/\Delta I_c$ of low-resistance [100]-tilt $\text{YBa}_2\text{Cu}_3\text{O}_7-x$ Josephson junction are shown in figure 3. A high-frequency falldown of the resonance amplitudes is also observed, but of different nature. An exponential behavior of $(\Delta I(V)/\Delta I_c)_{\text{lin}} \propto \exp(-hf/2e)R_{n0}/(R_{n0}^2)$ with a characteristic power $P_0 = 1.4 \times 10^{-3}$ W has been found, which is due to Joule heating of the junctions. The $P_0$-values obtained for [100]-tilt $\text{YBa}_2\text{Cu}_3\text{O}_7-x$ junction were consistent with those of the [001]-tilt junctions [1,2]. For the first time, we succeeded in recording the response (curve 4) to laser radiation with the frequency of 5.2 THz, which is above the frequency of strong optical phonon in $\text{YBa}_2\text{Cu}_3\text{O}_7-x$ ($f_0 = 4.6$ THz). Using [100]-tilt junctions with optimized resistances $R_n$ and junction environment, we hope to improve further the high-frequency limit of the ac Josephson effect.

2.2. Classical detection

Low-frequency limit $f_c$ of the ac Josephson effect is reached, when separate Josephson spectral lines at $f_c = n2eV/h$ with the thermally-broadened linewidths $\delta f_c = n\pi \delta f_0$, start to overlap. We got a simple estimate of $f_c = (3\delta f_0^2/2)^{1/3}$, where $\delta f_0 = 4\pi(2e/h)kTR_n$ and $f_c = 2eI_cR_n/h$ [2]. At lower frequencies, spectrum of Josephson oscillation demonstrates a continuous form [8], so the detection process for low frequencies up to $f_c$ will not be of a frequency-selective type. We have studied this type of detection in our high-resistive [100]-tilted junctions with high $I_cR_n$ values.

The experimental results are presented in figure 4. The voltage responses $\Delta V(V)$ of the [100]-tilt junction to radiation with frequencies $f$ of 0.145 THz and 0.404 THz are practically the same and proportional to the voltage dependence of a second derivative $d^2V/dI^2$ of the $V(I)$ curve. This behavior is a feature of classical detection. Only a response to 0.762 THz follows the Josephson frequency-selective mechanism. The estimated $f_c$-value was around 0.450 THz and this value might be increased for optimized high-resistance junctions.

![Figure 3](image1.png)  
**Figure 3.** Normalized responses $\Delta I(V)/\Delta I_c$ of [100]-tilt $\text{YBa}_2\text{Cu}_3\text{O}_7-x$ Josephson junction to electromagnetic radiation with the frequencies $f$ of 2.523 THz (1), 3.106 THz (2), 4.252 THz (3), 5.237 THz (4). $R_n = 1.3$ $\Omega$, $I_cR_n = 6.0$ mV, $T = 10$ K.

![Figure 4](image2.png)  
**Figure 4.** Voltage responses $\Delta V(V)$ of [100]-tilt $\text{YBa}_2\text{Cu}_3\text{O}_7-x$ Josephson junction to electromagnetic radiation with the frequencies $f$ of 0.145 THz (1), 0.404 THz (2), 0.762 THz (3) and differential resistance $R_d(V)$. $I_cR_n = 2.8$ mV, $R_n = 23$ $\Omega$ at $T = 40$ K.
We have performed a numerical simulation of radiation detection by high-resistive Josephson junctions with high $I_R$-values, using the RSJ model. The voltage response $\Delta V$, an impedance $Z(\omega)$ and the noise voltage were calculated from the solution of Fokker-Plank equation for the Fourier-coefficients of the probability distribution of Josephson phase [8] and, after that, a responsivity $\eta$ and noise-equivalent power $\text{NEP}$ were derived. Results of computer simulation for $\text{NEP}$ of Josephson detector are shown in figure 5. The parameters of Josephson detector are close to those of our best [100]-tilt YBa$_2$Cu$_3$O$_{7-x}$ bicrystal Josephson junctions.

It follows from figure 5, that this Josephson detector, when biased at the voltage $V = 0.3$ mV, might have values of $\text{NEP}$ better than $2 \times 10^{-14}$ W/Hz$^{1/2}$ in the frequency range from 0 to 1.8 THz. The estimated value of $f_0$ is around 0.9 THz for this case, but we should remember that in our estimates we were based on the results for low-level fluctuations and applied it for the case of intensive ones. So, numerical simulations gave us more optimistic values of the spectral range of broadband detection by Josephson junctions. This classical terahertz Josephson detector requires an optimized operational temperature of 30-40 K, which can be easily realized with a cryocooler. We think that this broadband detector will find an application in terahertz imaging for medical and security screening.

3. Conclusions

The [100]-tilt YBa$_2$Cu$_3$O$_{7-x}$ bicrystal Josephson junctions are perspective for applications in terahertz Hilbert spectroscopy, where optimized low-resistance junctions with high $I_R$ might improve signal/noise ratio, and in terahertz imaging, where high-resistance junctions will significantly increase a spectral bandwidth of classical detection.

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