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Submillimeter wave signal detection by bicrystal YBCO Josephson junctions at liquid nitrogen temperatures

Yu.V. Kislinskii [a,*], K.Y. Constantinian [a], I.V. Borisenko [a], G.A. Ovsyannikov [a], P. Yagoubov [b]

[a] *Institute of Radio Engineering and Electronics, Russian Academy of Sciences, GSP-9, Mokhovaya 11-7, 101999 Moscow, Russia*
[b] *SRON, Landleven 12, 9747 AD Groningen, The Netherlands*

Abstract

The submillimeter wave signal detection has been experimentally studied for a high-T_c superconducting device, consisting of a bicrystal $YBa_2Cu_3O_x$ Josephson junction, incorporated with a log-periodic antenna. Measurements were carried out in wide range of temperatures $T = 20$–80 K. At relatively high temperatures $T > 60$ K, the thermally activated phase slippage began to predominate. At the same time, a set of clearly resolved detector response functions have been registered up to the temperatures close to the critical one. At the highest temperature $T \simeq 80$ K, where detector response has been registered, the ratio of the frequency of applied signal $f_s \simeq 500$ GHz to the critical frequency of Josephson junction f_c has been estimated as large as $f_s/f_c \simeq 40$.

Keywords: Josephson effect; High-T_c superconductor; Submillimeter waves; Detector

1. Introduction

$YBa_2Cu_3O_x$ (YBCO) thin film Josephson junctions (JJ) biased at voltages $V \approx V_j$, where self-oscillation frequency $f_J = (2e/h)V_j$ is close to the frequency f_s of external signal, exhibit well pronounced frequency selective detector response dependence $\eta(V)$ [1–4]. The temperature dependencies of $\eta(T)$ amplitudes and self-oscillation linewidths Δf recently were studied [2,3] at submm wave frequencies. Enhancing the f_s, a ratio f_s/f_c increases, where $f_c = (2e/h)I_cR_n$ is the critical frequency of JJ. That reduces the detector response η, which is proportional to $P_s(f_c/f_s)^2$ [4], where P_s is applied signal power. Low-T_c superconducting tunnel junctions at temperatures $T \ll T_c$ have $f_c \approx 3\Delta/h$ [4], defined by the energy gap Δ, but for a SIS junction with the resistive shunt, a device with non-hysteretic I–V curve has $f_c \ll 3\Delta/h$. At the same time the high-T_c superconducting (HTS) JJs demonstrate non-hysteretic I–V curve and $f_c > 1$ THz [2,3]. However, the upper frequency limit for f_J/f_c ratio where ac Josephson effect still exists in HTS JJs remains unanswered yet. Here we report on experimental study of temperature dependencies of selective detector response $\eta(V)$ functions and on data for the f_s/f_c

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[*] Corresponding author. Tel.: +7-095-2038414; fax: +7-095-2030935.

E-mail address: yulii@ns.crys.ras.ru (Yu.V. Kislinskii).

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ratio, measured in a wide temperature range up to T_c at $f_s \simeq 500$ GHz for bicrystal YBCO JJs.

2. Experimental

Experimental samples were bicrystal $d \cong 200$ nm thick and $w = 4$ μm wide YBCO thin film JJs with patterned log-periodic antenna in the electrodes, fabricated on symmetric sapphire substrates with misorientation angle 24°. The JJs demonstrated RSJ-like I–V curves with the normal state resistance $R_n = 20$–$30\ \Omega$ and a product of the $I_cR_n = 1$–2 mV at $T = 4.2$ K [2]. The I–V curves, the voltage dependencies of differential resistance $R_d(V)$ and the detector response $\eta(V)$ functions were measured. The submm wave signal source was a backward wave oscillator. Detector response functions were obtained by means of modulator–demodulator technique by help of a low-noise selective lock-in amplifier.

3. Results and discussion

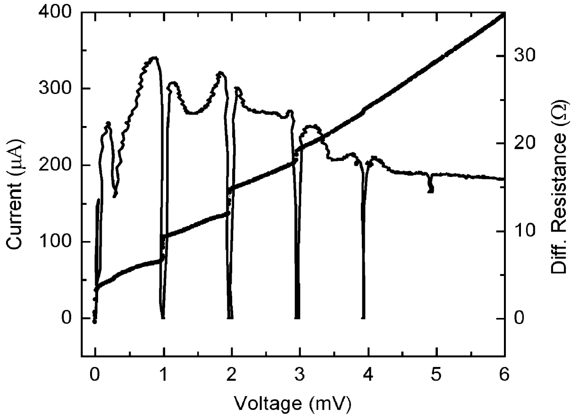

Fig. 1. The I–V curve and differential resistance $R_d(V)$ of YBCO bicrystal Josephson junction on sapphire substrate under applied signal at frequency $f_s \simeq 500$ GHz at $T = 12.5$ K.

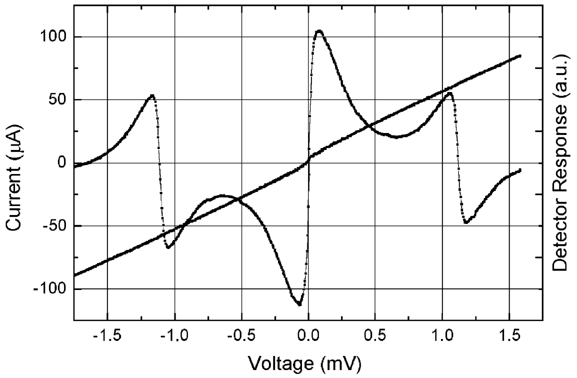

Fig. 2. The I–V curve and detector response $\eta(V)$ dependence at $f_s \simeq 500$ GHz, $T = 60.5$ K.

Fig. 1 demonstrates I–V curve and the dependence for $R_d(V)$, measured at $T = 12.5$ K under applied signal at $f_s \simeq 500$ GHz. Clearly resolved Shapiro steps are seen at the bias voltages corresponding to the voltage/frequency Josephson relation. Under a weak signal (with a microwave signal current amplitude at a junction $I_s \ll I_c$) the symmetric odd-resonant shape of selective detector response functions were registered for the both positive and negative biasing. A broadband (non-selective) detector response dependencies around the strong nonlinearity of JJ at $V \approx 0$ when $f_J \ll f_s$ were registered as well. The oscillating functions of the critical current $I_c(I_s)$ and the first Shapiro step amplitude $I_1(I_s)$ were in a good agreement to a resistively shunted junction (RSJ) model [4]. Increasing the temperature, the thermally activated phase slippage took place, washing out the curvature of I–V characteristics [5,6]. Fig. 2 demonstrates a typical I–V curve and the detector response $\eta(V)$ at $f_s \simeq 500$ GHz for relatively high temperature $T = 60.5$ K. Note, that at bias $V \gg V_J$ the exact zero output signal was registered. Fig. 3. demonstrates the temperature dependence of detector response amplitudes $\eta(T)$ for broad-band and selective detection at $f_s \simeq 500$ GHz for high temperatures. A theoretical curve for expected detector response amplitudes $\eta_t(T) \sim f_c^2(T)\alpha(T/T_c)$ is also given in the Fig. 3, it was calculated by RSJ model and corrected by a temperature dependent loss factor $\alpha(T)$ in HTS film. At high temperatures $T > 60$ K the experimental I_cR_n products depend on temperature temperature approximately as a function $(T - T_c)^2$, where $T_c \simeq 82$ K is the temperature of zero critical current of the JJ under the

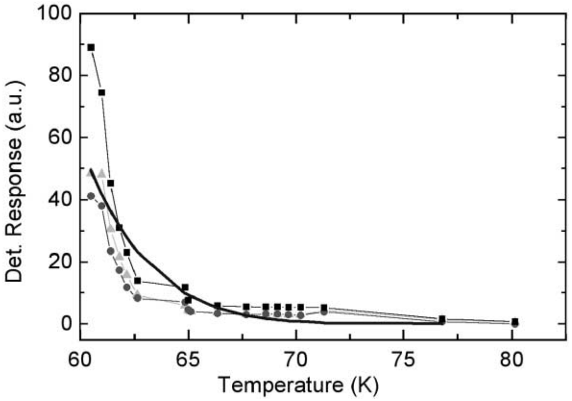

Fig. 3. The temperature dependence of detector response amplitudes for broad-band detector response (■), right-hand (▲) and left-hand (●) frequency selective responses functions at $f_s \simeq 500$ GHz. Solid line shows theoretically predicted $\eta(T)$ behavior.

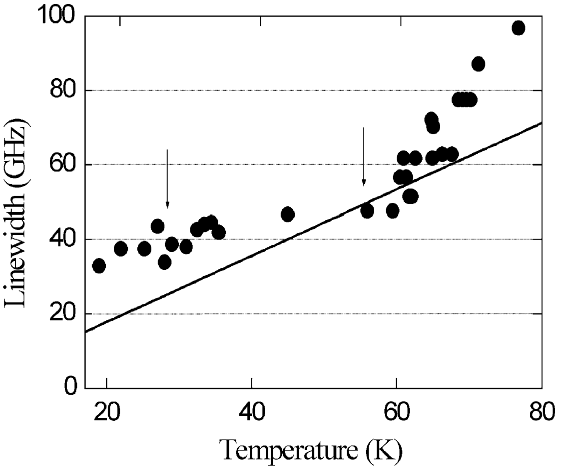

Fig. 4. The temperature dependence of Josephson oscillation linewidths Δf_J, extracted from detector response $\eta(V)$ functions, measured at $f_s \simeq 500$ GHz. The straight line is a simplified theoretical prediction for Δf, made using RSJ model. Arrows point the temperatures, where applied power was increased.

test. It gives theoretical $\eta_t(T) \sim f_c^2(T) \sim (T - T_c)^4$. A loss factor $\alpha(T/T_c) \sim (T/T_c)^4/\ (1 - (T/T_c)^4)^{1.5}$ was taken proportional to a surface resistance of a ordinary superconducting film [7]. More rapid, than the estimated, reduction of the amplitudes is seen for $T > 61$ K. Because a significant decrease in η amplitudes the applied power was increased during the measurements at temperature range $T = 27$–60 K. This results in deviations from a quadratic detection regime. In this connection only results for the temperature range of constant applied power are presented in the Fig. 3.

Temperature dependence of Josephson oscillation linewidths Δf is shown in the Fig. 4. A simplified theoretical slope for linewidths is given, using RSJ approach: $\Delta f_{\mathrm{RSJ}} = 40.5 R_n T$ (MHz). At low temperatures $T < 30$ K, where small signal amplitudes were applied, the correct values of Δf were obtained. In order to register detector response at high temperatures the applied power was increased considerably. That leads to a linewidth reduction, observed at $T > 60.5$ K, where estimated applied signal current was $I_s > I_c$ when the self-oscillation suffers synchronization under the strong external microwave force. With the further increase in temperature $T > 65$ K the losses in the antenna also increase. It reduce the I_s amplitude, the I_s/I_c ratio and terminate the synchronization process, which results in a linewidth restoration. However, in this paper we do not discuss the exact values of detector response amplitudes and Josephson oscillation linewidths, but note that the all of registered $\eta(V)$ functions at any of experimental temperature up to temperature $T \simeq 80$ K had clear symmetric odd-resonant shape, caused by Josephson effect detection. Taking estimated amplitudes for $I_c(T > 77\ \mathrm{K}) < ek_BT/\hbar$, using theoretical approach [5,6] and the measured R_n values, we have obtained the f_s/f_c, using $R_n/R_d(0)$ ratios, where $R_d(0)$ was the resistances at zero bias. Critical current I_c was calculated by $R_n/R_d = (\mathbf{I_0}(I_C/I_n))^2$ [6], where $\mathbf{I_0}$ is modified Bessel function. For $T = 77$ K an effective noise current $I_n = 4$ μA and $R_n = 25\ \Omega$, that give $R_n/R_d \cong 1.2$ and $I_c \approx 2$ μA and $f_c \approx 24$ GHz. Using $T_c \approx 82$ K for JJ (that is smaller than transition temperature of YBCO electrodes) and data for $T = 77$ K we have estimated the I_cR_n product as of 25 μV and the $f_c \approx 12$ GHz at the highest temperature, where detector response have been registered. That gave f_s/f_c ratio as large as 40 for $f_s \cong 500$ GHz at $T = 80.15$ K. This demonstrates the absence of energy gap limiting effects for YBCO JJs at least at the temperatures very close to the critical T_c.

4. Conclusion

Experimental data on frequency selective Josephson effect submm wave signal detection by HTS bicrystal junctions demonstrate existence of detector response in wide temperature range up to the critical temperature T_c. At temperatures not far from T_c, where thermal fluctuations predominate, the Josephson oscillation linewidths are about 1.5 times wider than the predicted by RSJ model. At the same time increasing the temperature, the amplitudes η of response decrease dramatically, and starting from $T/T_c > 0.75$ the power of applied signal required to be enhanced for well resolved registration of detector response. Thus, the absence of frequency limitation for HTS Josephson junctions similar to that, known for conventional superconductors with well pronounced energy gap, is a important opportunity for applications of HTS Josephson detectors. Noting, again the operating temperature of such HTS device should fulfill $T/T_c \ll 1$ in order to maintain the critical frequency f_c as large as possible, because of quadratic decrease in sensitivity with decrease of f_c/f_s ratio and noticeable loss rise in YBCO film with increase of the ambient temperature and operating frequency of submm wave range.

Acknowledgements

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