Terahertz Josephson Detectors and Hilbert Spectroscopy

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Abstract

Frequency-selective high-T_c Josephson detectors have been fabricated and characterized. A spectral range from 15 GHz to 4.3 THz has been demonstrated for these detectors. A power dynamic range of 50 dB and a noise equivalent power of 10^{-14} W/Hz$^{1/2}$ have been realized. A spectral resolution $\delta f/f$ of 10^{-3} has been achieved in the terahertz range. As an alternative to Fourier-transform spectroscopy, fast Hilbert-transform spectroscopy, based on these detectors, have been applied for various cw and pulsed terahertz sources.

Introduction

Due to the larger values of the energy gaps (2Δ = 20-60 meV) in high-temperature superconductors, it has been expected that the spectral range of high-T_c Josephson detectors might be extended to much higher frequencies than for low-T_c Josephson junctions. But, quite a small improvement of the spectral range has been observed in the first experiments, performed at liquid-helium temperatures [1], [2]. Other detector characteristics, like power dynamic range and NEP, have not been studied. Here, we present the results of fabrication and characterization of the Josephson detectors based on $YBa_2Cu_3O_{7-x}$ bicrystal junctions, and also their application in Hilbert-transform spectroscopy [3] for fast spectral analysis of terahertz sources.

$YBa_2Cu_3O_{7-x}$ bicrystal junctions

Grain-boundary Josephson junctions were produced by high-oxygen-pressure dc sputtering of $YBa_2Cu_3O_{7-x}$ on $NdGaO_3$ bicrystal substrates. The [001]-tilt junctions were deposited on (110) bicrystal substrates and the [100]-tilt junctions were deposited on the bicrystal substrates, where the [110]-axis of each part of the bicrystal was tilted in the direction perpendicular to the bicrystal boundary. In both cases the misorientation angles 2α were in the range 2x10.5° - 2x14°.

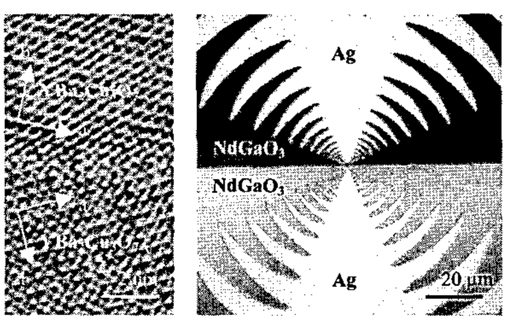

Fig. 1: HREM image of a [001]-tilt $YBa_2Cu_3O_{7-x}$ grain-boundary Josephson junction (left) and micrograph of Josephson detector with the $YBa_2Cu_3O_{7-x}$ junction with an integrated broadband Ag antenna on a bicrystal $NdGaO_3$ substrate (right).

High quality of $YBa_2Cu_3O_{7-x}$ epitaxial growth on the 2x14° (110) $NdGaO_3$ bicrystal substrate is shown on HREM image in Fig.1 (left). An optical micrograph of one of the fabricated junctions is shown in Fig. 1 (right) in reflected polarized light. In the middle of the image, a narrow 2µm-wide $YBa_2Cu_3O_{7-x}$ thin film bridge crosses the $NdGaO_3$ bicrystal boundary, revealed by polarization contrast. A double Ag/ $YBa_2Cu_3O_{7-x}$ thin-film layer is patterned in the form of log-periodic antenna, connected to the $YBa_2Cu_3O_{7-x}$ bridge.

Spectral range of Josephson detectors

The spectral range of Josephson detectors was studied in the frequency range from 5 GHz to 4.3 THz, where the monochromatic sources were available. A set of the normalized current responses of one of our [001]-tilt junction to monochromatic radiation with different frequencies is shown in Fig. 2. The odd-symmetric resonances in the curves $\Delta I(V)/\Delta I_c$ at $V=hf/2e$ correspond to the interaction of the Josephson oscillations with external monochromatic radiation. This behavior is the basis of frequency-selective detection and Hilbert spectroscopy with Josephson junctions. The width of the resonance response for radiation with 3.106 THz corresponds to the Josephson linewidth δf of 4 GHz.
As it is shown in Fig. 2, the spectral range is around one decade for this junction at temperature of 35 K. The middle frequency of the spectral range was found to scale with the characteristic frequency $f_c=(2e/h)I_cR_n$, where I_c is a temperature-dependent critical current and R_n is a resistance of the junction. So, it was possible to cover the range from some GHz to several THz, using one junction at two temperatures.

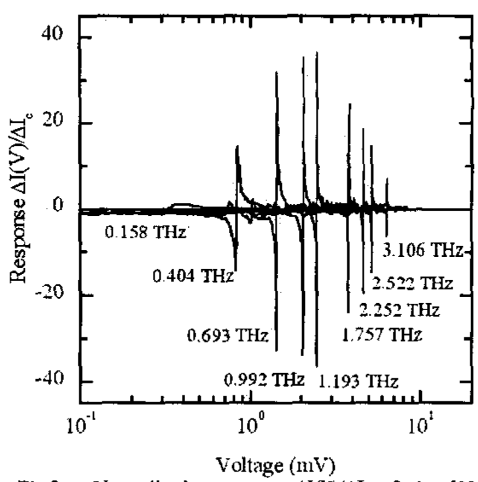

Fig.2: Normalized responses $\Delta I(V)/\Delta I_c$ of the [001]-tilt $YBa_2Cu_3O_{7-x}$ Josephson junctions to monochromatic radiation with the frequencies from 0.158 THz to 3.106 THz. The Josephson detector is in a Stirling cooler at T = 35 K. R_n =1.1 Ω and I_cR_n = 1.5 mV.

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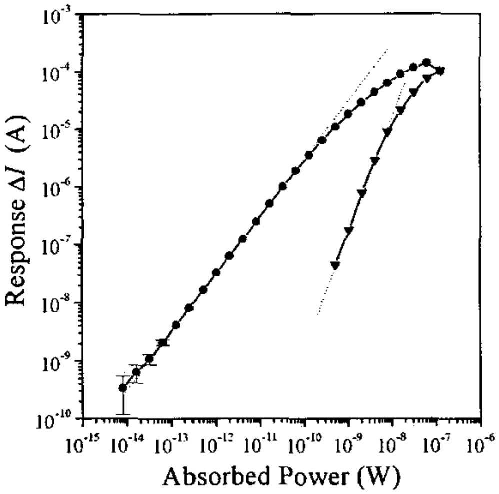

Fig. 3: The amplitudes of frequency-selective responses ΔI of Josephson detector at the voltage $V = hf/2e$ (•) and at the voltage $V = 2(hf/2e)$ (▼) vs. absorbed 86GHz power. R_n = 1,2 Ω and I_cR_n = 0.22 mV at T = 80 K.

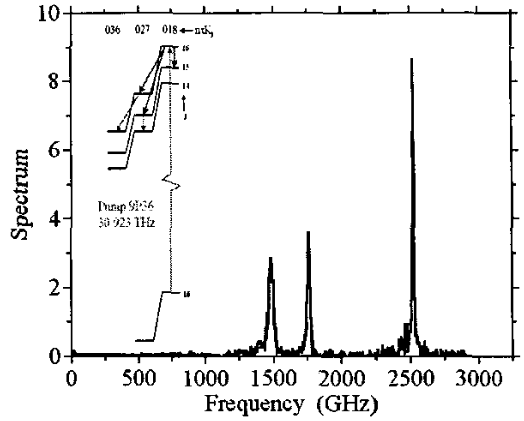

Fig. 4: Emission spectra of optically-pumped CH_3OH laser measured by Hilbert spectroscopy. Energy level diagram of optically-pumped CH_3OH [6] is shown in the inset. The Josephson detector is in a LN optical dewar at T = 55 K. The [100]-tilt $YBa_2Cu_3O_{7-x}$ junction is used with R_n =2.9 Ω and I_cR_n = 2.5 mV.

Power dynamic range

The experimental study of the power dynamic range of frequency-selective Josephson detectors was performed at the frequencies around 100 GHz, where stable sources, precise power meters and calibrated attenuators are available. So, the [001]-tilt junctions at liquid-nitrogen temperatures were used because their characteristic frequency $f_c=(2e/h)I_cR_n$ are better fit to this frequency range. The typical dependences of the amplitudes of the resonance responses on the power absorbed by the junction are presented in Fig. 3. The absolute calibration of the power scale has been reached using a theoretical value of radiation amplitude for the first maximum of the first Shapiro step at $V = hf/2e$ [4]. As follows from Fig. 3, the amplitudes of resonance response at the voltage $V_1= hf/2e$ are linearly dependent on the absorbed power in the power range of around five orders. The amplitudes of the second resonance response at $V_2= 2(hf/2e)$ are proportional to the square-law power dependence.

The value of noise equivalent power NEP = $(8\pm5)\cdot10^{-15}$ W/Hz$^{1/2}$, determined from these measurements, was close to the theoretical level of NEP for thermal fluctuations in the Josephson junction. The responsivity inside the dynamic range was equal to $(3\pm1)\cdot10^4$ A/W.

The dynamic range of 10^5 is sufficient for fast measurements with the Josephson detectors and pulsed radiation sources with repetition rates in MHz range. The first such experiments are reported in [5], where subterahertz spectra have been measured for 7 ms using [001]-tilt $YBa_2Cu_3O_{7-x}$ junctions at liquid-nitrogen temperatures.

Application of Josephson detector for spectral analysis of terahertz laser

The applicability of [100]-tilt $YBa_2Cu_3O_{7-x}$ junction for spectral analysis of terahertz radiation was studied by us at liquid-nitrogen temperatures. The I_cR_n –values was high enough for terahertz operation at the temperatures 50-60 K for this type of junctions and these temperatures could be reached by pumping liquid nitrogen.

Emission spectra of optically-pumped CH_3OH laser at various laser cavity lengths and pump frequencies have been analysed by Hilbert spectroscopy [3] using the [100]-tilt $YBa_2Cu_3O_{7-x}$ junctions. Laser radiation was modulated by a mechanical chopper with the frequency of 6 kHz. The scan time of the voltage from 0 to 7 mV was equal to 2 seconds. It was possible to observe the spectral content on the oscilloscope screen when making adjustment of the cavity length of the CH_3OH laser and that of for CO_2-pump laser. It was often possible to get large total output power with the mixed content of different lines.

One of these spectra is shown in Fig. 4. Spectrum contains three lines at 2.52 THz, 1.76 THz and 1.48 THz. The frequencies of the lines are in agreement with the assignment of the CH_3OH laser lines, pumped by 9P36 pump line of the CO_2 laser [6]. This experiment shows applicability of high-Tc Josephson junctions for spectral analysis of terahertz sources.

Conclusion

Using the ac Josephson effect in the $YBa_2Cu_3O_{7-x}$ bicrystal junctions, sensitive detectors and fast spectrum analysers can be realized in the terahertz range.

Due to the large I_cR_n-values, the [100]-tilt $YBa_2Cu_3O_{7-x}$ junctions might have an advantage in terahertz applications.

References

[1] P. A. Rosenthal, E. N. Grossman, IEEE Trans. Microwave Theory Tech., vol. 42, 1994, 707-714.

[2] K. Nakajima, J. Chen, H. Myoren, T. Yamashita, P. Wu, IEEE Trans. Appl. Supercond., vol. 7, 1997, 2607-2610.

[3] Y.Y.Divin et al.,"Terahertz Hilbert Spectroscopy by High-T_c Josephson Junctions", in Advances in Solid State Physics, vol. 41, Ed.: B.Kramer, Springer, Berlin, 2001, 301- 313.

[4] K. K. Likharev, "Dynamics of Josephson Junctions and Circuits", Gordon and Breach, New York, 1986.

[5] V. Shirotov et al., IEEE Trans. Appl. Supercond., vol. 13, 2003, 172-175.

[6] J. O. Henningsen. IEEE J. Quant. Electr., vol. QE-13 1977, 435-441