Terahertz Spectral Analysis by Frequency-Selective Incoherent Detection in High-T$_c$ Josephson Junctions

DISTRIBUTION: Approved for public release, distribution unlimited
Abstract — The detector response of YBa$_2$Cu$_2$O$_x$, Josephson grain-boundary junctions to monochromatic radiation with the frequency $f$ in the range from 60 GHz to 5 THz has been studied. Odd-symmetric resonances near the voltages $V=hf/2e$ in the responses $\Delta I(V)$ of these junctions to radiation with different frequencies $f$ have been observed in a decade of spectral range for any operating temperature between 30 to 85 K. The spectral range of this selective detection has scaled with the $I_C R_n$-product of the Josephson junction, so decreasing the junction temperature from 85 to 30 K one can perform the spectral analysis in two decades.

A prototype of terahertz Hilbert-transform spectrum analyzer based on high-$T_c$ Josephson junction integrated into a Stirling cooler has been developed. A resolving power $\delta f$ of around $10^3$ has been demonstrated in the spectral analysis of output radiation from optically-pumped far-infrared CH$_3$OH laser.

I. INTRODUCTION

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 after some progress in junction fabrication, the first evaluations of high-$T_c$ Josephson junctions for this application have been carried out [6-8]. Recently, we have demonstrated a selective Josephson detection in a decade of the spectral range with the highest frequency of 3.1 THz [9].

Frequency-selective Josephson detection of electromagnetic radiation is the basic principle of Hilbert-transform spectral analysis [1]. Spectral measurements of millimeter- and submillimeter-wave radiation by Hilbert-transform technique have been carried out using both low-$T_c$ and high-$T_c$ Josephson junctions [1, 10-16]. The laboratory prototypes of Hilbert-transform spectrometers and spectral analyzers cooled by cryogenic liquids have been developed [11,13,16].

A necessity to use cryogenic liquids for cooling is considered as a main obstacle on the way of superconducting electronics into the market, and a replacement of them by cryocoolers is required [17]. Here, we report on the characteristics of a Hilbert-transform spectrum analyzer based on high-$T_c$ Josephson detector integrated into a Stirling cooler.

II. THEORY

In the simple resistively shunted junction (RSJ) model [18], the response $\Delta I = I(V) - I_d(V)$ of a Josephson junction to weak monochromatic radiation with the frequency $f$ is equal to [18]

$$\Delta I(V) = I_c^2 \left( \frac{2e}{h} \right) \left[ \frac{(f + \frac{1}{2})^2}{(f + \frac{1}{2})^2} - \left( \frac{f}{2} \right)^2 \right]$$

where $I_c$ is the critical current of the junction, $R_n$ is the normal-state resistance of the junction, $I_d$ is the amplitude of the radiation induced current, $V = h f / 2e$ is the voltage across the junction, and $f$ is the frequency of the radiation.

The response $\Delta I(V)$ (Eq. 1) is quadratic with the signal amplitude $I_c$. At low voltages $V << hf/2e$, the response $\Delta I(V)$ approaches the value

$$\Delta I_0 = \frac{I_c^2 R_n}{(2e/2)^2},$$

where $I_c = (2e/2) R_n$ 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 $f$ are close to the frequency $f$ of the incident radiation, the response $\Delta I(V)$ shows an odd-symmetric resonance. The maximum amplitude $\Delta I_{\text{max}}$ of this resonance at $V = (h f / 2e) \left( 2 \delta f / 2 \right)$ is inversely proportional to the Josephson linewidth $\delta f$:

$$\Delta I_{\text{max}} = \frac{I_c^2 R_n}{(2e/2) \left( 2 \delta f / 2 \right)^{1/2}},$$

For broadband thermal fluctuations with a noise temperature $T$ and $kT < eV$ (equilibrium case), the Josephson linewidth is equal to [18]

$$\delta f = 4 \pi (2e / h)^2 R_d / R_n + \left( I_c^2 / 2 I_c^2 + I_c^2 / 2 I_c^2 \right)^{1/2},$$

where $R_d$ is the dynamic resistance of the junction. The dynamic resistance $R_d(V) dV/dI = R_d (V^2 + I_c^2) R_d / 2$ is...
equal to the normal-state resistance $R_n$ at high voltages $V > I_c R_n$ and at small voltages $V < I_c R_n$ 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 $f > f_c$.

One can expect from Eq. 3 and Eq. 4, that the amplitude $\Delta I_{\text{max}}$ of the selective response should rise linearly with the increase of the frequency $f$ at low frequencies $f < f_c$, reach a maximum at $f = f_c$, and fall down inversely proportional to $f^2$ at high frequencies $f > f_c$. This conclusion is valid, provided the same current amplitudes $I_c$ 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 $I_c$ is difficult to fulfill experimentally.

We have solved this problem by a self-calibration procedure, where we normalize each of the measured response curves $\Delta I(V)$ to its value $\Delta I_0$ (Eq. 2) at low voltages [5]. The maximum amplitudes $\Delta I_{\text{max}}$ of 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.

The Josephson junctions which are close to those of predicted by RSJ model are good candidates for the Hilbert-transform spectral analysis [1]. Within the framework of the resistively-shunted-junction (RSJ) model, the small-signal response $\Delta I(V)$ to the radiation and perform the Hilbert transformation of normalized response function $H(V)$. Actually, the spectral resolution of HTS is determined by the linewidth of the Josephson oscillations (Eq. 4).

### III. Experiment

A laboratory prototype of spectrum analyzer based on high-$T_c$ Josephson junction has been developed. A front-end of this analyzer is shown in Fig. 1. High-quality YBa$_2$Cu$_3$O$_7$-x grain-boundary junctions fabricated on untwinned 2x14" (110) NdGaO$_3$ bicrystal substrates [19] have been used in the experiments. The widths of the junctions were in the range 1-3µm. The $I_c R_n$ products of these junctions were up to 330 µV at 78 K, and the values of resistances $R_n$ varied from 1 to 8 Ohm. A broadband YBa$_2$Cu$_3$O$_7$-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 [20]. 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 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 by a parabolic mirror through a polyethylene window in the vacuum chamber and a hyperhemispherical Si-lens on the substrate (Fig. 1).

IV. RESULTS

The response $\Delta V(V)$ of a YBa$_2$Cu$_3$O$_7$$_x$ Josephson junction to 3.1 THz radiation is shown in Fig. 2 [9]. The Josephson junction has a resistance of $R_n = 1$ Ohm and quite high $I_c R_n$ product of 1.5 mV at 34 K. The shape of the response $\Delta V(V)$ (Fig. 2a) is very close to that of the RSJ model in the voltage range from 0 to 8.5 mV. The response $\Delta V$ demonstrates a very sharp odd-symmetric resonance around the voltage near $V = hf/2e = 6.423$ mV. The width of this resonance is around 8 µV (Fig. 2b), which corresponds to the Josephson linewidth $\Delta f$ of 3.9 GHz. So, it follows from the measured response that a resolving power $f/\Delta f$ of the order of $10^3$ might be achieved with selective detection by high-$T_c$ Josephson junctions.

To obtain a normalized response $\Delta I(V)/\Delta I_0$, as it was discussed in the introduction, the current response $\Delta I(V)$ was determined by extrapolation of the low-voltage behavior of $\Delta I(V)$ to $V=0$. A set of the normalized current responses $\Delta I(V)/\Delta I_0$ of a Josephson junction with $R_n = 7$ Ohm to monochromatic signals with the frequencies from 0.404 THz up to 4.25 THz are shown in Fig. 3. 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 $2f_c$ (and the voltage is around $2f_c R_n$), reaches the maximum, and falls down with further increase of frequency. For each temperature in the range of 30 – 85 K the selective response is observed at least in one decade of frequency bandwidth [9]. The middle frequency of this bandwidth scaled with the characteristic frequency $f_c = (2e/h)I_c R_n$, so the total bandwidth of selective detection, which was covered by one Josephson junction at different temperatures, was around two decades.

The low-frequency cut-off of the appearance of the resonances in responses $\Delta I(V)/\Delta I_0$ in Fig. 3 is in accordance with the RSJ behavior. It is the result of the low-voltage increase of the linewidth of Josephson junction and a corresponding decrease of the resonance amplitude according to Eq.3. The high-frequency fall-off of the selective response was attributed to Joule heating [9] and it might be shifted to higher frequencies by increasing the junction resistance and/or further decreasing the operation temperature. As we can see from Fig.3, the increase of the resistance to 7 Ohm results in the increase of highest frequency to 4.25 THz. In the case of high-ohmic junctions the high-frequency cut-off might be also due to capacitive shunting of the junction.

V. APPLICATION

An example of application of the developed Hilbert-transform spectrum analyzer is demonstrated in Fig. 4. Radiation to the spectrometer came from a far-infrared CH$_3$OH laser, pumped by 9P36 line of CO$_2$ laser. The length of the FIR laser cavity was slightly changed from one position (a) to the other (b). In the case (a), two odd-symmetric resonances appeared at the response $\Delta I(V)$ of the spectrometer. An application of Hilbert-transformation to the normalized response $\Delta I(V)/\Delta I_0$, according to the Eq.5, gives the spectrum of incident radiation. Two lines, the main at 2.523 THz and the competing one at 1.758 THz, are clearly visible in the spectrum. The intensities of laser lines are inside the dynamic range of the spectrum analyzer and no artificial line at the difference frequency has appeared in the spectrum. Changing the length of
Acknowledgement

Support by the German BMBF (project 13N7335/8) is gratefully acknowledged.

References

18. Model SL-200, AEG INFRAROT-MODULE GmbH, D-74001 Heilbronn, Germany