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Josephson spectroscopy at submillimetre waves

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Abstract. An HTS Josephson spectrometer has been designed, fabricated and experimentally studied. The spectrometer circuit consists of a YBCO bicrystal Josephson junction integrated with a double-slot or log-periodic antenna, connected in parallel with a gold low-inductance shunt. The selective detector response and RF response at intermediate frequency $f_{IF} = 1.4$ GHz were measured in the signal frequency range $f_s = 400$–1250 GHz and the linewidth of Josephson oscillations (LJO) was determined by using three different methods. (1) The Hilbert spectroscopy approach was used in the processing of the selective detector response. (2) In case of $f_{IF} <$ LJO the detector and RF responses have similar shapes, allowing the spectrum and LJO to be extracted from the RF response and even processing by modified Hilbert spectroscopy. (3) The RF response at $f_{IF} >$ LJO corresponds to the frequency down-conversion in a self-pumped Josephson mixer mode. For the processing of the RF response in the high f_{IF} limit we suggest a novel method that allows extraction of the signal spectrum by means of simple operations: shifting, summing and subtracting. The advantage of the RF response method is in its simplicity and higher sensitivity that allows it to be proposed for spectroscopy applications.

1. Introduction

The millimetre and submillimetre wave spectrometers based on HTS Josephson junctions can operate in the attractive temperature range 4–77 K. Compared with Schottky mixers the Josephson spectrometers (JSs) can have a 2–3 times lower noise temperature. Until now JSs have been based on the processing of the detector response by the Hilbert transform method. Another possible method to obtain the spectrum is to use the processing of the RF signal measured in self-pumped Josephson mixer (SPJM) mode.

In a mixer with self-pumping the input signal at the frequency f_s is mixed with the internal Josephson oscillations (JOs). If the input signal is monochromatic, then the linewidth of the output signal at f_{IF} is the same as linewidth of JOs (LJO) and this gives natural estimation for the frequency resolution of such a spectrometer. The losses can be low and resolution high if we reduce the LJO by applying a low-inductance resistive shunt. The minimum value of the double-side-band (DSB) noise temperature in a Josephson mixer (JM) with self-pumping (see [1, 2]) equals the physical temperature T for $f < 0.2f_c$ and increases as $8(f/f_c)^2$ with frequency increase above f_c. A low-inductance resistive shunt improves the noise temperature of the mixer with an external local oscillator (LO) and the noise temperature of the self-pumped mixer; it also improves resolution of Hilbert spectrometer [3].

2. Experimental setup

The integrated receiving structure consists of a YBaCuO Josephson junction formed on a bicrystal MgO or sapphire substrate and Au complementary log-periodic or double-slot antenna (see figure 1). The misorientation angle in the bicrystals was 24°. The YBaCuO film, 80–100 nm thick, was deposited by laser ablation. The 2 μm wide junction has a normal-state resistance of 10 Ω and a critical current of 300 μA, measured at 4.2 K. The remarkable features of the I–V curves are low excess current, a clear Fraunhofer pattern in the I_c dependence on magnetic field and correct oscillations of the critical current and Shapiro steps with applied LO power. For the low-inductive shunting of Josephson junctions we use hybrid resistive shunts made by bonding a loop of Au wire 30 μm thick and 5 mm in diameter or an integrated thin-film loop deposited on the substrate together with the contact pads. The shunting resistive loop about 5 mm in diameter brings the resistance below 0.1 Ω at 4.2 K and a relatively low inductance that does not shunt sufficiently the output signal at an intermediate frequency (IF) of 1.4 GHz.

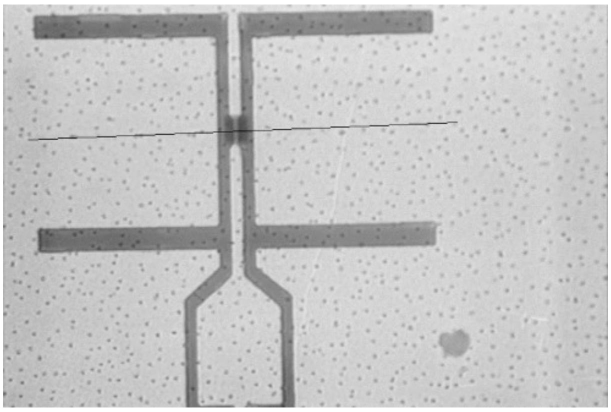

Figure 1. The layout of integrated structure with a bicrystal Josephson junction and a double-slot antenna. The horizontal line in the centre indicates the bicrystal grain boundary. A resistive low-inductive shunt made of Au wire 0.03 mm thick is bonded to the contact pads outside the view.

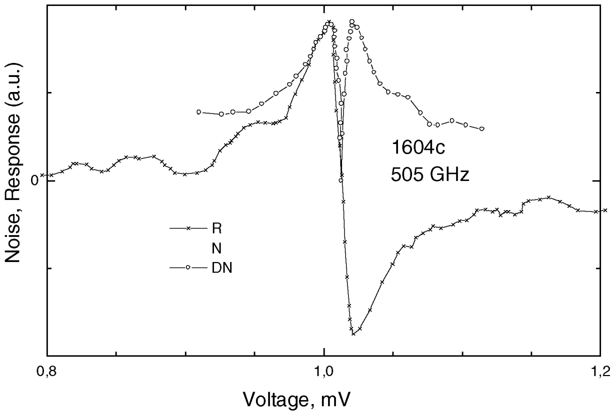

Figure 2. Selective detector response R and noise DN, the latter after the deduction of autonomous noise and extraction of the square root.

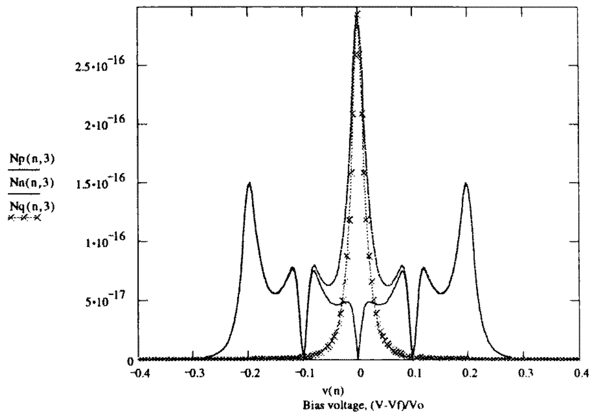

Figure 3. Recovered spectrum $N_q = N_p(v) - |N_n(v)|$ (crosses), sum $N_p = N_e(v + v_{if}) + N_e(v - v_{if})$ (full curve) and difference $N_n = N_e(v + v_{if}) - N_e(v - v_{if})$ (broken curve) of output signal shifted dependences $N_e(v + v_{if})$ and $N_e(v - v_{if})$.

The substrate with integrated receiver structure is attached to the MgO extended hyperhemisphere lens and placed in an LHe cryostat with an optical window. Backward wave oscillators (BWOs) in the frequency ranges 350–650 GHz and 880–1250 GHz are used as signal and LO sources for mixer measurements and receiving structure microwave evaluation. At lower frequencies down to 60 GHz we use also Gunn and IMPATT diode oscillators. A broadband signal from a black-body absorber is combined with the LO signal by using a simple polyethylene beam splitter. For filtering off infrared signal contributions we use black polyethylene and Fluorogold cold filters. The IF signal from the junction is connected to a matching circuit and amplified by a cold 4.2 K amplifier with a cold circulator at the input.

3. Experimental results

We have measured the selective detector response and IF noise under low BWO power at frequencies up to 1250 GHz. Measurements of the IF noise and the selective detector response can be used for evaluation of the Josephson radiation linewidth. Maxima measured by means of both methods can coincide (see figure 2) when the linewidth of Josephson oscillations exceeds the IF. The calculation of the spectrum from the detector response of the Josephson junction is known as Hilbert spectroscopy [3]. We propose to estimate the Josephson linewidth from the IF dependence, which allows us to simplify the measurement technique and improve sensitivity and frequency resolution. At 500 GHz and 77 K the linewidth is 17 GHz in an unshunted junction and 6 GHz in a junction shunted by a 0.1 Ω resistance. The configuration of the measurement setup in this case is the same as for the JM with self-pumping. The linewidth at 4.2 K and 1000 GHz is 34 GHz for a 20 Ω junction, 28 GHz for a 4 Ω junction and 4.5 GHz for a 0.7 Ω shunted junction. These values are about 6–8 times over the simple estimations according to the resistively shunted junction (RSJ) model with Johnson noise as the main source of fluctuations $\Delta f\,(\mathrm{MHz}) = 40(R_d^2/R_n)T$, with T in kelvins, from [1, 2] and can be explained by excess noise mechanisms [4, 5].

4. Response processing for spectrum recovery

In the case of narrow Josephson oscillation linewidth the IF maximum corresponds to the $v_{sig} - v_{if}$ and $v_{sig} + v_{if}$ bias voltages, which allows us to simplify the data processing. Here $v_{sig} = f_{sig}\Phi_0$ and $v_{if} = f_{if}\Phi_0$. We suggest the following procedure for extracting the spectrum of incident radiation. First we subtract the IF noise without a signal $N_a(v)$ from the IF output under signal irradiation $N_s(v)$, giving $N_e(v) = N_s(v) - N_a(v)$. Then we shift this dependence in bias voltage by $+v_{if}$ and by $-v_{if}$. These two shifted curves are used to deduce the sum $N_p(v) = N_e(v+v_{if})+N_e(v-v_{if})$ and difference $N_n(v) = N_e(v+v_{if}) - N_e(v - v_{if})$ dependences (see figure 3). The two last give the required incident spectrum $N_q(v) = N_p(v) - |N_n(v)|$. An example of such a calculation is presented in figure 3 for a model theoretical curve and in figure 4 for a practical measured curve.

5. Discussion

The noise voltage maximum in detector response measurements coincides with the voltage position of the dynamic resistance R_d maximum. The position of the latter can be

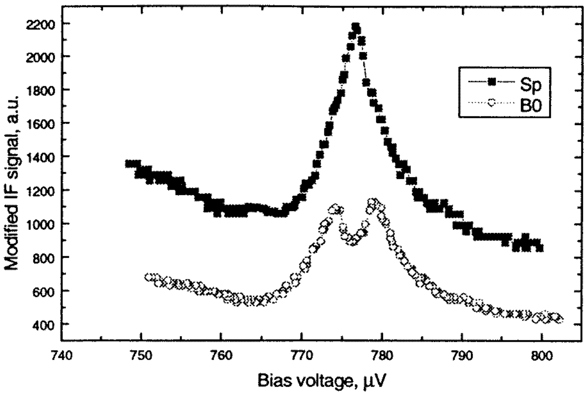

Figure 4. Experimental IF output signal (circles) and extracted spectrum (squares).

deduced from the analytic expression for the I–V curve near a Shapiro step in the presence of Johnson noise of a normal resistance R_0. The step smearing is characterized by the dimensionless parameter

$$\gamma = 2ekT/\hbar I_{st} \tag{1}$$

where I_{st} is a step half-width in the absence of noise. Exact analytic calculations according to [1] are rather complicated, but for a practical estimation simplified relations can be deduced:

$$\Delta V \cong 1.92 R_0 (2ekT I_{st}/\hbar)^{1/2} \qquad \text{for } \gamma \leqslant 1 \tag{2a}$$

$$\Delta V \cong 4\sqrt{3}kT R_0/\hbar \qquad \text{for } \gamma \geqslant 1 \tag{2b}$$

$$\Delta V = 2 f_{if} h/2e \qquad \text{for } I_{st} \cong 0. \tag{2c}$$

One can see that, when the linewidth of Josephson oscillations exceeds f_{IF}, the maxima for detector response and RF response coincide. For the opposite case the detector response maxima remain at R_d maxima positions, and the RF response voltage position is locked to the sidelobes of the self-pumped mixer, i.e. $f_J \pm f_{if}$. The sensitivity of these methods in a first iteration depends on the amplifier sensitivity. For low-frequency noise it is $1/f$ limited and for estimations we can take the low-frequency amplifier voltage sensitivity to be about $V_n = 5$ nV Hz$^{-1/2}$. For RF response measurements the cold IF amplifier noise temperature can be below 10 K. Taking into account the conversion gain for the self-pumped mixer that can be of the order of 10 dB, measured input noise temperature of about 1000 K and volt per watt detector sensitivity up to $\eta = 10^6$ V W^{-1} one can estimate the spectrometer sensitivity as follows:

$$S_{det} = V_n/\eta = 5 \times 10^{-9}/10^6 = 5 \times 10^{-15} \text{ W Hz}^{-1/2}$$

$$S_{spm} = kT_n = 1.4 \times 10^{-23} \times 1000 = 1.4 \times 10^{-20} \text{ W Hz}^{-1/2}.$$

The frequency resolution of both methods equals the Josephson oscillation linewidth, which can be greatly improved by means of low-inductance shunting. Such shunting does not affect significantly the sensitivity of the RF response but reduces proportionally the detector sensitivity, which means that for high-resolution low-noise spectroscopy the RF method is preferable. Another advantage of the RF method is that spectral resolution does not depend on the step size and it can have a much wider dynamic range.

6. Conclusion

We have fabricated a HTS Josephson spectrometer and tested it in mm and sub-mm wave ranges. In the low-frequency or detector response processing we have utilized the Hilbert transform method. The measurement of the RF response is equivalent to the self-pumped mixer mode. For the extraction of the spectrum from the RF response a novel method of Josephson spectroscopy by processing the IF noise dependence has been suggested. This method allows us to simplify the measurement technique, to improve greatly the sensitivity and dynamic range and to increase the spectral resolution by low-inductance shunting without reduction of sensitivity.

Acknowledgments

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