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Observation of a voltage-tunable sub-mm wave response from a YBCO Josephson device, operating in self-pumping mode

Karen Y Constantinian[1], Gennady A Ovsyannikov[1], Igor V Borisenko[1] and Pavel Yagoubov[2]

[1] Institute of Radio Engineering and Electronics RAS, 101999, GSP-9, Mokhovaya, 11-7, Moscow, Russia
[2] Space Research Organisation of the Netherlands, Landleven 12, 9747 AD Groningen, The Netherlands

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Abstract
The first experimental data are presented on the observation of a response of a noise signal applied to a tunable-by-voltage high-T_C Josephson mixer operating in a self-pumping mode within the frequency band of $f =$ 750–970 GHz at ambient temperature $T = 12.5$ K. The mixer device was a thin-film YBaCuO bicrystal Josephson junction coupled with the electrodes patterned in log-periodic antenna. Experimental junctions exhibit RSJ-like I–V characteristics with a product of $I_C R_N \approx 2$ mV (I_C is the critical current and R_N is the normal state resistance). Down-converted signal response was examined at an intermediate frequency band within 1–2 GHz by means of the Fourier transform spectroscopy technique. Evaluated from Fourier transform spectrograms clear double-side band mixer response functions were registered at any of the fixed bias voltages in the range of $V = 1.65$–2.1 mV.

1. Introdction

Fixing the bias voltage V at a Josephson junction, the oscillation power at frequency $f_J = (2e/h)V$ may serve as a pumping source for signal frequency f_s mixing, and an output signal at intermediate frequency (IF) $F = \mp f_S \pm f_J$ should be registered. Josephson-effect self-pumped mixer [1], built on high-T_C superconducting (HTS) bicrystal Josephson junctions (JJ) may reach a low enough noise temperature, defined in a simplified approach as $T_M \approx 10\alpha_{IN}\alpha_{OUT}T(f_S/f_C)^2$, where α_{IN} and α_{OUT} are impedance mismatch factors for input and output mixer ports, T is the ambient temperature, $f_C = (2e/h)I_C R_N$ is the critical frequency, I_C is the critical current and R_N is the normal state resistance of JJ while e and h are the fundamental constants. Starting from experimentally obtained values of the product $I_C R_N \approx 1.6$–2.2 mV, $R_N \approx 15$–40 Ω at $T = 4.2$ K for YBCO JJ on sapphire substrates [2] an estimation for $f_S \approx 1$ THz gives $f_S/f_C \approx 1$ and taking realistic $\alpha_{IN}\alpha_{OUT} =$ 2 dB gives optimistic $T_M \approx 100$ K. Noting that for a properly operating mixer, the linewidth of the pumping source (local oscillator in the case of heterodyne mixer) must be $\Delta f_{LO} << f_{IF}$. However, the HTS JJs exhibit linewidths Δf_J of Josephson self-oscillations greater than a few Gigahertz [3, 4] and usually $\Delta f_J > F$. That may result in crucial rise of T_M. From this point of view heterodyne mixers seem preferable, but require long-term stable operating heterodyne oscillators which is a problem that remains unsolved for THz frequencies. At the same time (contrary to a nonlinear resistive mixer) the Josephson-effect heterodyne mixer has an additional signal—the Josephson self oscillation at f_J —which, as the signals at frequencies f_S and f_{LO}, is also involved in the mixing process. This leads to a problem (known since long) of output stray response, resulting in a nonlinear relationship between input signal power P and output power at IF. Moreover, as a local oscillator the power of Josephson intrinsic oscillations at f_J could be much stronger than the external weak signal. In this connection, an experimental study of HTS self-pumped mixer, being the two-frequency device (f_S and f_J) operating at THz frequencies, becomes a subject of high interest.

2. Experimental details

Experimental JJs coupled with the log-periodic antenna were fabricated by YBCO thin-film deposition by dc sputtering at

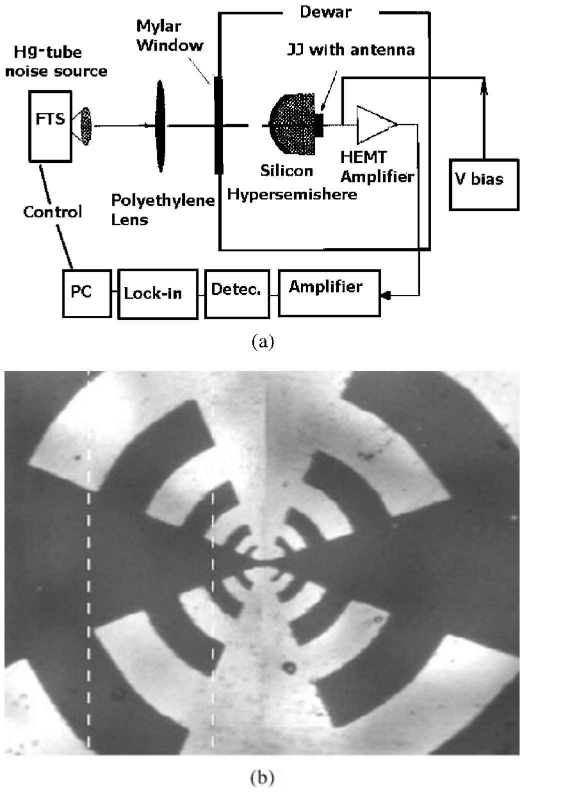

Figure 1. (a) A sketch of sub-mm wave experimental set-up. Operating temperature $T = 12.5$ K, JJ— bicrystal YBCO Josephson junction, FTS—Fourier transform spectrometer, Lock-in—low noise selective lock-in amplifier, Detec—detector, V bias—unit for biasing and measurements of IVC and dI/dV functions. Signal modulator, temperature control units and reference channel are not shown. (b) Bicrystal YBCO Josephson junction with antenna on sapphire substrate. Shining is adjusted to demonstrate a vertical bicrystal line. Dashes show scale of 100 μm.

high oxygen pressure using bicrystal sapphire substrates with symmetric misorientation angle of 12°. The rf magnetron sputtering of an epitaxial CeO_2 buffer layer was used before the deposition of the YBCO film [2]. The YBCO thin-film bridges 5 μm wide and 10 μm long, crossing the bicrystal boundary and electrodes with antenna, designed for frequency band $f = 100$–1500 GHz, were patterned by rf plasma and Br_2-ethanol etching. Choosing samples with large enough values of $R_N = 15$–40 Ω for the required impedance matching at both the input and output frequencies, the critical frequency f_C was kept not less than 1 THz. However, a mismatch took place as the impedance of the antenna was roughly estimated at 80 Ω with the input impedance at 50 Ω for the IF preamplifier with standard coaxial input termination, connected to the JJ electrodes by bounded low-inductive gold wires. Measurements were carried out in optic cryostat with Mylar window at $T = 12.5$ in conditions when the sample was attached by its bottom side to a silicon hyperhemispherical lens. Sub-mm wave measurements were carried out by applying to JJ either a monochromatic signal which was available from a set of backward wave oscillators (BWO) or a noise source, using the Hg-tube of the Michelson Fourier transform spectrometer (FTS). A sketch of the sub-mm wave experimental set-up and a photo of the experimental sample are given in figures 1(a) and (b).

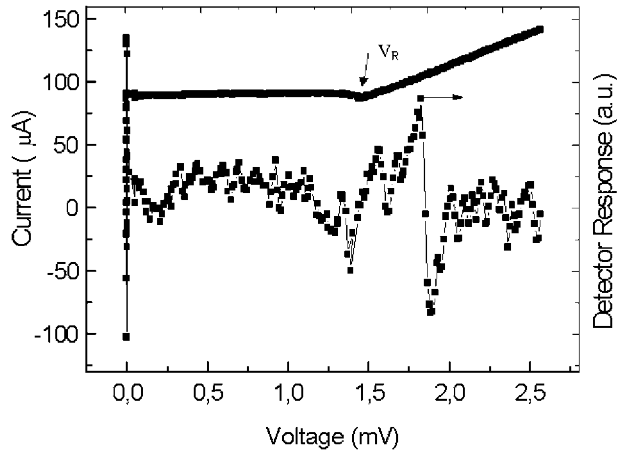

Figure 2. IVC of YBCO Josephson junction and detector response on weak monochromatic signal at frequency $f = 900$ GHz, $T = 12.5$ K, V_R points at the 'return' voltage of hysteretic part of IVC.

The power of the noise signal from FTS modulated by amplitude was focused to the JJ via antenna and after the signal processing (as shown in the figure) was synchronously demodulated by the lock-in amplifier. The automatic resonator positioning of FTS and the data registration was made in PC-control regime. The biasing voltage at JJ was maintained with high accuracy for the whole period of run, e.g. for integration time $\tau = 9$ s (the most usual case was $\tau = 3$ s) a plotting period was extended up to 2–3 h. A cooled balanced HEMT IF preamplifier with noise temperature $T_N \cong 8$ K and gain of 18 dB (measured at $T = 4.2$ K) was connected to a JJ via a coplanar mounting. The noise power from Hg-tube in units of noise temperature was of the order 2700–3000 K. It should be noted that due to the high Q-factor of Michelson resonator, the noise signal applied to the device was no longer white noise. Down-converted signal frequency from the output of the second IF amplifier was detected in quadratic regime and measured by the lock-in amplifier. FTS detector response functions were measured using the current channel of the 'V bias' and Lock-in units.

3. Results and discussion

A typical IVC of a YBCO JJ plotted in voltage biasing mode is shown in the figure 2. Voltage V_R separates the region on IVC of a large differential resistance and a region of almost linear part of IVC. A detector response function measured at $f = 900$ GHz is also presented in the same figure. It is seen that detector response is observed at the voltages of large nonlinearity of IVC: around $V = 0$ and $V = V_R$ and also at a linear part of IVC $V > V_R$ when a selective response around $V = V_J$ takes place due to phase-sensitive interaction of applied monochromatic signal from BWO and self-Josephson oscillation. It demonstrates that the Josephson effect exists also at the linear part of IVC. Figure 3 demonstrates the detector response obtained from measurements at FTS. Bias voltage was fixed at $V = 1.15$ mV corresponding to the frequency of Josephson oscillation at $f_J \approx 500$ GHz. In general, when applying a noise signal (white noise) to the Josephson junction, no selective detector response should be registered [1] because no phase-locking takes place. In the case discussed, a relatively

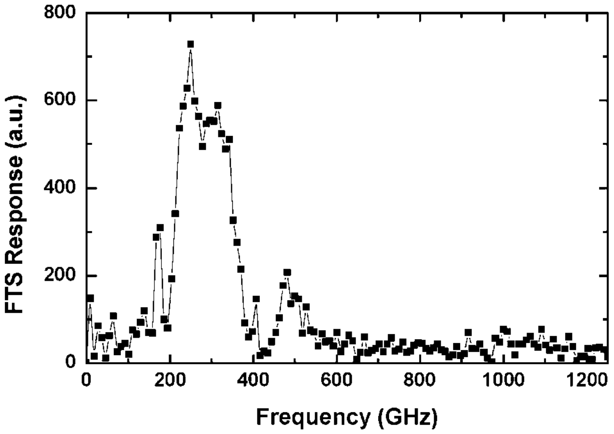

Figure 3. Fourier transform spectrogram, obtained from detector response from JJ at $T = 12.5$ K for fixed bias $V = 1.15$ mV.

large Josephson linewidth, $\Delta f_J > \Delta f_S$, of Hg-tube noise, filtered by a Michelson resonator, resulted in both: an intensive broad-band detection at $f = 200$–400 GHz and a moderate detector peak at $f = 400$–600 GHz, also demonstrating the Josephson selective detection process. The large FTS response signal characterizes the frequency range of antenna coupling to JJ and losses [5]. Coupling α_{IN} of JJ with the antenna is changed at $V = V_R$ because of the change in differential resistance. However, in the discussed case the frequency range of FTS response lies below $V_R > V = 1.15$ mV and the main contribution to the FTS response comes from losses in YBCO film for frequencies $f > 300$ GHz.

Due to the specific nonlinearity of complex impedance of the Josepson junction [1], effective frequency multiplication and mixing are also expected for HTS JJs. At the same time, as mentioned above, the Josephson-effect mixer is a much more complicated device than a nonlinear resistive diode. Figure 4(a) shows the case when a strong signal at $f = 500$ GHz was applied to the HTS JJ. The power P was of an order that should be used for pumping in heterodyne Josephson mixing. The IF response at $F = 1$–2 GHz was measured in modulator–demodulator regime at $T = 12.5$ K. That also has an effect on IVC. The first, second and third Shapiro steps are seen on IVC, and fourth and very weak fifth on IF response function. The modulated pumping effect is seen from widths of modulating intervals on IVC. The wider the dark (modulated) interval, the stronger the pumping was. As expected for Josephson mixers, better pumping takes place in between $V = 0$ and the first Shapiro step. At the same time, the IF response in figure 4(a) demonstrates that the stray output signal is too strong. In a properly operating mixer no phase-sensitive IF signal should be registered. Suppressing the power of an applied signal and enhancing the operating temperature up to $T = 20.5$ K for eliminating hysteresis on IVC, the IF response was measured once again. Figure 4(b) demonstrates the IVC and the IF response for the case of a weak signal. A radical change in the response function is seen. There are three response peaks around $V = 1$ mV (corresponding to a frequency $f_J = 500$ GHz) at both the positive and negative bias-sides of IVC. At the same time a wrong signal also exists at the voltages $V < 1$ mV.

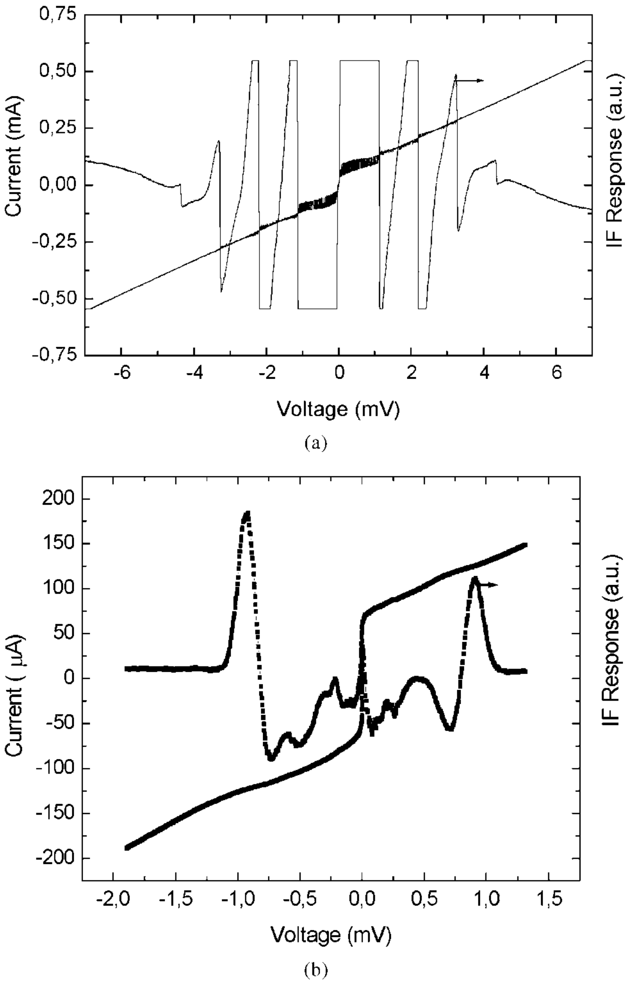

Figure 4. IVC and response at intermediate frequency $F = 1$–2 GHz, measured in modulator–demodulator regime for applied monochromatic signal at $f = 500$ GHz. (a) Strong applied power $P \approx 10$ nW, $T = 12.5$ K, (b) weak power $P < 0.1$ pW, $T = 20.5$ K.

Josephson self-oscillation at frequency F = 1–2 GHz of HEMT amplifier was also registered. It should be noted that in the case when a monochromatic narrow band signal is applied to the Josephson junction, the output self-pumped mixer product at IF should be much smaller than that in the case of mixing of a broadband (noise) input signal [1]. In the case shown in the figure 4(b) the linewidth of a signal from BWO is much smaller than the IF frequency band. Thus, for mixing a weak noise signal it is expected that one may obtain a significantly larger IF response and a higher difference between true mixing and a wrong signal. This issue was verified by a study of IF response with the help of FTS technique. Starting with measurements from $V = V_R$, we have registered the self-pumping response at any of the biasing voltages in the range $V = 1.65$–2.1 mV. Figure 5 demonstrates FTS down-converted IF response frequency for three fixed voltage biasing V, corresponding to self-pump frequency at 750, 845 and 970 GHz. The plot in figure 5(a) corresponding to bias $V \cong V_R$ demonstrates a wrong (non frequency selective) response with decreasing frequency, showing the loss rise in YBCO antenna. At $V > V_R$ no wrong response peaks were observed. To our knowledge it is the first observation of the tunable-by-voltage self-pumped mixing of external noise

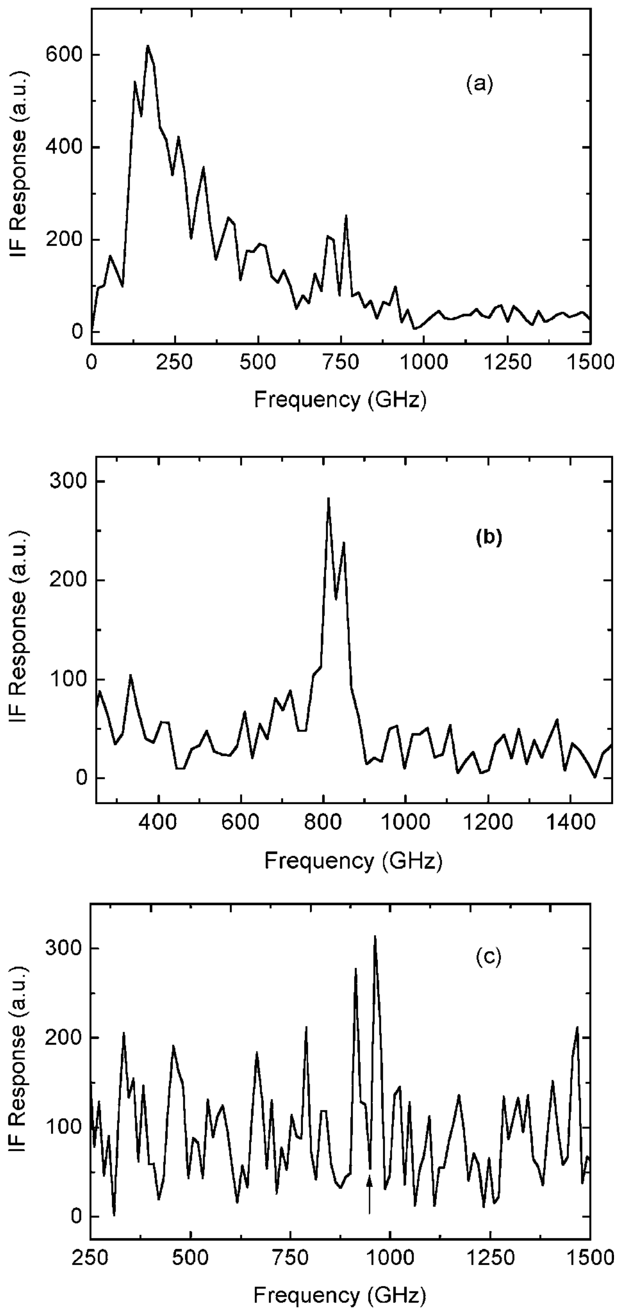

Figure 5. FTS response at intermediate frequency $F = 1$–2 GHz in down-conversion double-side band mixing in self-pumping mode for JJ with $R_N = 23\ \Omega$, $I_C = 90\ \mu$A and $V_R = 1.65$ mV at $T = 12.5$ K. Bias voltages correspond to pump frequency: (a) 750 GHz, (b) 845 GHz and (c) 970 GHz, the arrow indicates the frequency of intrinsic Josephson self-oscillation pumping.

signal for HTS Josephson junction, operating at temperature $T = 12.5$ K. The splitting of the response peak is caused by a double-side band frequency mixing regime. The non-sensitive 'dark' IF interval was about 2 GHz wide, this allows us to define the frequency of the input signal of a THz range with an accuracy of 1 GHz. The arrow in figure 5(c) indicates the central point of the 'dark' part when $f_S = f_J$.

4. Conclusion

It was shown experimentally that in order to realize a properly operating heterodyne mixer at sub-mm waves, built on a Josephson junction, particularly on HTS JJ, the problem of filtering the wrong signal response should be solved. At the same time, already achieved large values of $I_C R_N \approx 2$ mV and $R_N \approx 20$–$40\ \Omega$ of the RSJ-type JJs on sapphire substrates at $T = 12$ K are high enough for practical applications. For these samples we have demonstrated that YBCO JJ can operate as a tunable-by-voltage frequency selective device of THz range with frequency resolution of order of 1 GHz. Down-conversion frequency in the self-pumping mode was observed by FTS technique, demonstrating for the first time a clear double-side band response to a noise signal at any frequency in the band of $f = 750$–970 GHz by tuning the bias voltage of YBCO bicrystal JJ. Noting that for these frequencies the ratio $f_S/f_C \approx 1$ did not vary much by change in frequency $f_J \cong f_S$ (by changing the bias V_J), also the impedance of JJ at $V > V_R$ was near to R_N and antenna design covered a large frequency range at least up to 1.5 THz, the decrease in sensitivity at $f >$ 1 THz is likely due to frequency-dependent loss rise in YBCO film. For practical applications of self-pumped HTS mixers at THz frequencies the relatively large self-oscillation linewidths of JJ should be reduced.

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