High-frequency limit in the nonstationary Josephson effect

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The method of mixing two microwave signals in superconducting Nb–Nd point contacts is used to investigate the high-frequency limit in the nonstationary Josephson effect. It is found that generation up to 240 harmonics of a 70-GHz klystron signal is possible, corresponding to a frequency ~17 THz.

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One of the most important problems in the nonstationary Josephson effect is the maximum frequency up to which this effect can be used (the high-frequency (HF) limit).

So far, the maximum values of the HF limit were obtained in[1,2] by two methods. In[1] they observed steps due to the harmonics of the 70-GHz signal on the current-voltage characteristic (CVC) of superconducting point contacts. Up to 117 steps (harmonics) were obtained, corresponding to ~8.2 THz (in terms of voltage, using the known relation $f=2eV/h$, on the order of 17 mV). Since these energies correspond in Nb approximately to the end point of the phonon spectrum, it is indicated in[1] that a more consistent allowance must be made for the electron-phonon interaction when deriving the dependence of the Josephson-current amplitude on the voltage. In[2], the first step on the CVC was observed by direct application of a high-frequency signal (2.5 THz, 5.15 mV). In a recent study,[3] a beat signal was observed following irradiation of a superconducting point contact by two lasers at a frequency 31.6 THz (65 mV), but no unambiguous choice could be made between the thermal and Josephson mixing mechanisms.

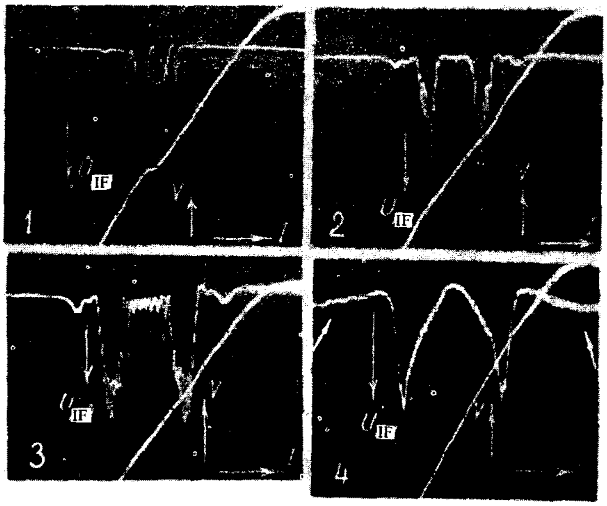
We determined the HF limit by a method based on mixing, in the superconducting point contacts, two microwave signals that are close in frequency but differ greatly in magnitude (strong heterodyne signal and weak main signal).

In this case the two signals act on the CVC like one heterodyne signal whose amplitude is modulated at the difference frequency.[4] Thus, the steps obtained on the CVC are modulated in height at the same frequency. Even if the step is very small and smeared out by the fluctuations, a difference-frequency (intermediate frequency, IF) will be observed at its location. In addition, the IF may lie in the megahertz band, for which highly sensitive receivers are available. Thus, by measuring the bias voltage at which the IF signal is observed, we can determine the maximum frequency at which the interaction of the microwave harmonic with the superconducting Josephson current is observed.

In the experiment we used Nb-Nb contacts at 4.2°K, placed in a waveguide and exposed to signals from two klystrons of frequency 70 GHz. The IF (30 MHz) was applied through a quarter-wave coaxial line and an amplifier to one of the channels of a two-beam oscilloscope. The bias voltage V was simultaneously applied from the contact to the second channel. The bias current was swept at the mains frequency 50 Hz. Thus, we observed on the oscilloscope screen the CVC of the contact (somewhat distorted at the edges), and the IF signal corresponding to each bias voltage (see the figure).

The contact resistance in the normal state was R_n ~5–40 Ω and the characteristic voltage $I_{cr}R_n$ ranged approximately from 0.5 to 2.5 mV (I_{cr} is the critical current). The use of high-resistance contacts has enabled us to confine ourselves to high microwave powers (several milliwatts) in view of the better matching at microwave frequency and to decrease the possible heating effects.[5]

The figure shows the successive variation of the CVC (lower trace) and of the IF signal with increasing heterodyne signal power P_h. The ratio P_h/P_s (where P_s is the signal power) remained fixed to maintain constant the depth of modulation of the total microwave signal. It is seen from the figure (1,2) that at low heterodyne powers one can distinguish peaks on the IF response; these peaks correspond to the steps on the CVC. A more detailed examination reveals a maximum of the IF signal, as usual, between the steps, and a drop of the signal to zero at bias voltages corresponding to the steps the IF signal in the figure (1,2,3) does not drop to zero be-



$I_{cr}=60$ μA, $R_n=23$ Ω; $P_h/P_s=10$ dB: 1) the horizontal stroke on the CVC is the critical current; the attenuation of P_h is 27.3 dB; the CVC scale is 2 mV/div; 2) P_h attenuation 18 dB; CVC scale 2 mV/div; 3) 12 dB; 5 mV/div; 4) 0 dB; 10 mV/div; the gain at the intermediate frequency is increased by 10 dB.

tween the peaks, owing to the inertia of the IF receiver at large sweeps). With increasing microwave power, the peaks merge because of the decrease of the height of the steps and the smearing of their fluctuations. In figure (4), the maximum voltage at which the IF signal is observed is on the order of 30 mV. It should be emphasized that in experiment it is possible to trace the smooth variation of the observed characteristics in the entire range of variation of the microwave power. The position of the maximum of the IF signal shifts monotonically towards larger V with increasing microwave power. This makes it possible to exclude the thermal bias mechanism.

With further increase of the heterodyne power and at large bias voltages, an IF response of different types appears (shown by the arrows in Fig. (4)). Its value was higher by several orders of magnitude and reached with increasing bias voltage a maximum at $V \sim 100$ mV. As T increased towards T_{cr}, both responses decreased in magnitude and vanished. We believe that this response is of a thermal origin, in view of the overheating of the contact at large bias voltages and microwave powers.

In addition to the indicated responses, certain contacts yielded narrow (in terms of the bias voltage) peaks in the IF signal at definite bias voltages (the bias voltages are different for different contacts; there is no such response for the contact in the figure). The cause of the appearance of these peaks is not yet clear.

It should be noted in conclusion that the maximum bias voltage at which the IF signal (of nonthermal character) is observed was ~35 mV. If the relation $f = 2\ eV/h$ applies up to such voltages, then this voltage corresponds to a frequency of approximately the 240-th harmonic of the 70-GHz signal (~17 THz). This is approximately double the maximum energy of the photons in Nb. Thus, the interaction indicated in[1] can hardly weaken significantly the amplitude of the superconducting Josephson current.

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