Certain properties of superconducting junctions in a CO_2-laser radiation field

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(Submitted 11 October 1984)
Zh. Eksp. Teor. Fiz. **88**, 1395–1401 (April 1985)

The effect of radiation from a CO_2 laser ($\nu \approx 3 \cdot 10^{13}$ Hz) on the characteristics of superconducting niobium junctions is investigated. At low laser-radiation intensities the junctions still exhibit Josephson properties even though the lasing frequency exceeds by 40 times the frequency corresponding to the niobium superconducting energy gap. A characteristic radiation intensity exists above which the thermal effects predominate over the Josephson effects. It is shown that by application of a supplementary microwave field it is possible to increase substantially the sensitivity of superconducting IR detectors.

INTRODUCTION

Adoption of a unified standard for frequency, length, and time was made feasible in the last decade by the development of highly stabilized optical-band lasers.[1] The existing elements for the synthesis of the optical-band frequency, which are essential if the latter are to be related to the radio band, are complicated and unwieldy. One possible way of simplifying them is to use superconducting frequency multipliers.[2] Direct experiments[3,4] have shown that superconducting nonlinear elements can be effectively used up to $4 \cdot 10^{12}$ Hz. It is of interest to extend the range of their use into the infrared.

An attempt at mixing the radiation of two CO_2 lasers in a superconducting Nb–Nb Josephson junction and separating the resonance frequency was reported in Ref. 5. Since the CO_2 laser frequency is 40–45 times higher than the frequency corresponding to the niobium energy gap $\Delta_{\rm Nb}$, the laser can heat substantially the central part of the Josephson junctions. It was therefore stated in Ref. 6 that the laser-frequency mixing of Ref. 5 was "bolometric" rather than due to the Josephson effect. The use of Josephson multipliers at such high frequencies is thus still a moot question.

We report here some results of an experimental investigation of the properties of superconducting niobium junctions in a CO_2-radiation field.

Unequivocal proof that the junction possesses Josephson properties at the laser frequency ω_L would be the observation, on the current-voltage characteristic (IVC) of the junction, of a first step at a voltage satisfying the condition $2eV = \hbar\omega_L$ (e is the electron charge). In the case of a CO_2 laser the current step should occur close to 60 mV and when the junction is biased to operate in this IVC region its temperature can reach 70 K (Ref. 6). This is apparently what prevented us from observing on the IVC of the superconducting junctions the current step induced by the CO_2 laser radiation ($\nu \approx 3 \cdot 10^{13}$ Hz), although in Ref. 4 we have observed relatively easily a current step at the frequency of a D_2O laser ($3.6 \cdot 10^{12}$ Hz).

A manifestation of Josephson properties of the junction at high frequencies can also be a dependence of the critical Josephson current J_c on the external-radiation power P. A simple theoretical model[7] yields

$$I_c(P) \approx I_c(0) J_0^2(ev_{ac}/\hbar\omega_L) I_p(\omega_L), \tag{1}$$

where J_0 is a Bessel function of zero order, v_{ac} is the alternating voltage, of frequency ω_L, induced in the junction by the laser radiation, and $I_p(\omega_L)$ is a factor that takes into account the frequency dependence of the superconducting Josephson current. Since the factor $I_p(\omega_L) \propto \omega_L^{-1}$ at $\omega_L \gg \Delta_{\rm Nb}/\hbar$ (Ref. 7), the critical current of the junction should oscillate as the radiated laser power increases.

Finally, the preservation of superconductivity in an IR-irradiated junction is attested by the dependence of the response $V_{\rm dc}$ of the junction to the action of this radiation on the bias voltage V. The response $V_{\rm dc}$ of the junction can be calculated in the following manner.[8] According to the resistive model of a Josephson point junction, we have

$$I_c(P) = I_c(0)\,|J_0(2ev_{ac}/\hbar\omega_L)| \approx I_c(0)\,[1-(ev_{ac}/\hbar\omega_L)^2]. \tag{2}$$

Application of external radiation changes the critical current $I_c(P)$ by an amount ΔI and causes the dc junction voltage to change by $\Delta V = R_d I$ (R_d is the differential resistance of the junction at the operating point of the IVC). As a result, since $\Delta I = I_c(0) - I_c(P)$, we find that the response of the junction is

$$V_{dc} = \Delta V = I_c(0)\,(ev_{ac}/\hbar\omega_L)^2 R_d. \tag{3}$$

It can be seen that in the case of Josephson detection the response of the junction to an external electromagnetic field is proportional to the differential resistance, and not to the IVC curvature (dR_d/dI) as for a classical radiation detector. A rigorous theory[9] that takes the frequency dependence of the Josephson current into account yields at $\omega_L \gg 2eV/\hbar$ an expression close to (3).

At the same time, we know that heating the junction by laser radiation should decrease the critical current $I_c(0)$, therefore the response of the junction to heating will also be proportional to the differential resistance R_d. We shall return to this question in the discussion of the results.

EXPERIMENT

We used controllable single-crystal niobium junctions with resistances 0.1–20 Ω.[10] To improve the matching of the junction to the radiation the diameters of their points were 0.1–0.3 mm.

The experimental setup consisted of a helium cryostat, apparatus to plot the IVC and the dependence of dV/dI on V, microwave apparatus, a CO_2 laser with a frequency-stabilization block, an optical system to guide the radiation to the junction, and standard radiometry apparatus to record the response V_{dc}.

The cryostat, the apparatus to record the IVC, and the microwave apparatus are described in Ref. 4. The CO_2-laser radiation entered the cryostat through a BaF_2 window, an NaCl window in the nitrogen screen, and an internal Ge window.

The 10-watt single-frequency single-mode CO_2 laser ($\lambda = 9$–$11\ \mu$m) was a revamped LG-25 laser.[11] To operate the laser in a single-frequency regime and to lower the power-pulsation level, the output mirror was mounted on a piezoconverter, and an additional RC filter was included in the power supply. The laser frequency was stabilized at the center of the gain line of the chosen junction by automatic frequency control, using an optogalvanic signal.[12] The laser radiation was focused on the superconducting junction by a BaF_2 lens. The radiation power was regulated by a calibrated metal-grid attenuator (attenuation factor $K = 0.7$) and by CaF_2 and BaF_2 plates ($K = 0.5$ and 0.95, respectively). The power was monitored with a photoreceiver.

The response of the junction to the laser radiation was recorded by lock-in detection with the radiation modulated with a chopper (at 740 Hz). Owing to the appreciable absorption of the laser radiation by the cryostat windows, the liquid helium near the inner window boiled and the laser beam was scattered by the gas bubbles. The measurements were therefore performed under conditions when the helium level was lower than the superconducting junction. The bulky adjustment device was then immersed in the liquid helium, and the time to heat the junction from 4.2 to 10 K was several hours. A germanium thermometer was located in the adjusting device near one of the junction electrodes. Its readings and the temperature values determined from the superconducting energy gap of the niobium and from the transition of the contact to the normal state agreed within the accuracy limits of our experiment.

MEASUREMENT RESULTS

1. Since the experiments called for knowledge of the point-junction temperature, we selected for the investigations junctions whose IVC showed clearly the gap singularity and the subharmonic structure. After tuning, the junction was exposed to CO_2-laser radiation of varying power and its IVC characteristics were recorded. Figure 1 shows the initial sections of these characteristics. The curves are numbered in increasing order of the laser power, except for curve 14 which, just as curve 1, corresponds to zero radiation power, but was recorded after plotting curves 1–13. The fact that $I_c(0)$ is the same on curves 1 and 14 is evidence of the stability of the junction characteristics. It can be seen that, just as in the case of low frequencies $\omega_L < \Delta_{Nb}/\hbar$, the critical current of the junction decreases with increasing radiation power, but starting with a certain value of the laser power, at still relatively large values of I_c, the junction is heated by the radiation and its IVC becomes unstable.

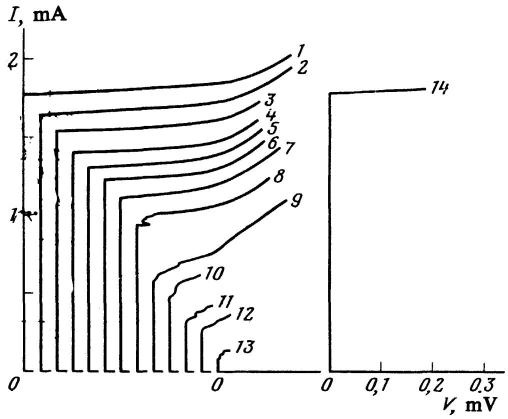

FIG. 1. Initial sections of the IVC of a superconducting Nb–Nb junction at various laser-radiation power levels. The curves are numbered in increasing order of radiation power. Curves 1 and 14 correspond to zero radiation power, but the latter was recorded after plotting curves 1–13 ($T = 4.5$ K).

To estimate the temperature T of the "near-contact" regions in the electrodes, the niobium superconducting gap Δ_{Nb} was first determined from the measured IVC at various laser powers. The known $\Delta_{Nb}(T)$ dependences was then used to determine the temperature of the near-contact region and the corresponding laser power. The results have shown that at low external-radiation powers the junction temperature T is close to linear in the laser power P. At powers $(P/P_0)^{1/2} > 0.5$ (P_0 is the maximum laser power) this dependence deviates noticeably from linearity and becomes nearly exponential at powers corresponding to the transition of the near-contact sections of the electrodes to the normal state. Since the critical junction current is linear in the temperature at temperatures close to T_c,[13] and begins to decrease exponentially with P at higher powers,[6] it can be assumed that our experimental results for $T(P)$ agree with the data of Ref. 6, which were obtained with weak and strong heating of a Josephson point junction as models. It must be recognized, however, that at large P, when the temperature of the near-contact regions is close to T_c, the temperature of the central part of the junction may exceed T_c substantially,[6] and the entire system is in a nonequilibrium state. The procedure of determining the junction temperature from the energy gap may not be valid in this case. The experimental data can therefore be regarded as reliable only at low laser powers $(P/P_0)^{1/2} \lesssim 0.5$, when the maximum temperature rise of the near-contact regions (at a distance from the junction center equal to the coherence length) does not exceed 1–2 K.

To separate the thermal contribution from the dependence of the critical current I_c of the junction on the laser-radiation power we investigated the current $I_c(0)$ at zero laser power as a function of temperature in the range 2.6–9.3

K. Combining this temperature dependence of $I_c(0)$ and the data for $T(P)$ we obtained a curve that describes the junction critical-current decrease due to heating of the near-contact regions by the absorbed radiation. The dots and the dashed line of Fig. 2 show alongside this (solid) curve the measured values of the critical current of four junctions at different laser powers. These data show that low-power $[(P/P_0)^{1/2} \lesssim 0.5]$ laser radiation causes the critical junction current to decrease more rapidly than by heating alone. At powers $(P/P_0)^{1/2} \gtrsim 0.5$ the thermal effects predominate (inset of Fig. 2). At the same radiation powers, the IVC of the junctions turn out to be unstable.

There are thus grounds for assuming that at low CO_2-laser powers experiments reveal, besides thermal effects, a decrease of the junction critical current, due to Josephson interaction of the superconducting current with the external radiation. A confirmation of this assumption would be an experimental $I_c(P)$ plot that agrees with Eq. (1). Experiments have shown, however, that the laser heating of the junctions causes the critical current to become zero before the Bessel function J_0 in (1) reaches its first zero.

To get around this difficulty and verify that the Josephson current interacts with the CO_2 laser radiation, we studied the dependence of the amplitude of microwave-induced current steps on the junction IVC on the laser-radiation power. It is known (see, e.g., Ref. 14) that when two microwave signals of frequency ω_1 and ω_2 act on a Josephson junction these signals become mixed in the junction and alternating currents are produced at the frequencies $n\omega_1 + m\omega_2 + \omega_J$ (n and m are integers and ω_J is the Josephson frequency corresponding to the bias voltage). If the power of one radiation, say with frequency ω_1, is constant while that of the one of frequency ω_2 varies, the amplitudes of the alternating currents at the intermediate frequencies will oscillate like the Bessel functions of the appropriate order, causing oscillations of the main IVC current steps corresponding to the expression $2eV = n\hbar\omega_1$.

In the experiments the junction was irradiated with microwaves of constant power such that several induced current steps were observed on the IVC. With the microwave power unchanged, the junction was irradiated by the laser and the dependences of the sizes of these current steps on the laser power were measured. The amplitudes I_n of the microwave-induced current steps on the IVC of niobium junctions agree well with the known expression

$$I_n = I_c(0) J_n(2ev_{ac}^k/\hbar\omega_k) \tag{a}$$

(the index k labels the microwave voltage and frequency). If no Josephson mixing of the two radiations takes place in the junction, and the decrease of I_c with increasing laser power is due only to heating of the junction, the amplitudes of the current steps induced by the microwave field should decrease with I_c. The points in Fig. 3 show the normalized values of these current steps (with numbers $n = 1, 2, 3$, and 4) at various values of the relative laser power for one of the superconducting junctions. The dashed curves show the absolute values of the Bessel functions of the respective order. It can be seen that the current-step amplitude oscillates against the background of its general decrease due to the junction heating.

Oscillations of the current steps were observed in the experiment only at lower laser powers $(P/P_0)^{1/2} < 0.5$, when the maximum temperature rise of the contact regions did not exceed 1 K. Under these conditions, changes of the junction resistance and the ensuing changes of induced microwave voltage have low probability. It remains therefore to assume that at low laser powers, when the thermal effects are insignificant, the superconducting junctions preserve their Josephson properties.

2. We measured also the response V_{dc} of the superconducting junctions to CO_2 laser irradiation. Figure 4 shows the IVC of a superconducting junction (1) together with the dependences of the differential resistance (2) and of the response (3) on the bias voltage. Curve 2 was recorded at zero laser power. The data indicate that the response of the junction to the CO_2-laser radiation is proportional to the differential resistance of the junction, as follows indeed from Eq. (3).

To plot the response, which did not exceed several μV,

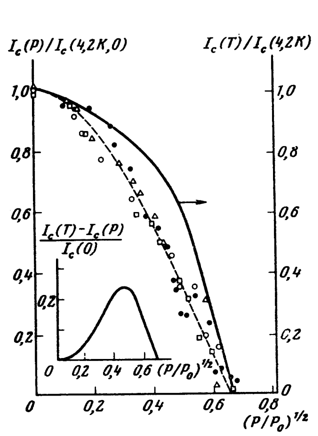

FIG. 2. Decrease of critical current of four junctions with increasing laser power (points and dashed line). The solid curve shows the junction critical-current change due to heating by the absorbed radiation. The inset shows the difference of the two curves.

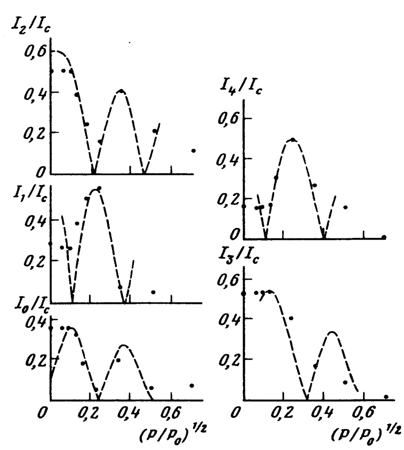

FIG. 3. Current steps, normalized to $I_c(0)$ ($n = 0, 1, 2, 3, 4$), produced on the junction IVC by microwave radiation (70 GHz) of constant power, vs the CO_2 laser radiation power. The dashed curves show the moduli of the Bessel functions of the corresponding order ($T = 4.5$ K).

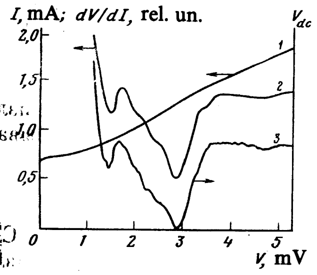

FIG. 4. IVC of superconducting junction (1) together with the dependences of the differential resistance (2) and of the response (3) of the junction on the bias voltage ($T = 4.5$ K).

the junctions were irradiated with very low laser power. The ensuing decrease of the junction critical current was less than 1%, and the junctions themselves were hardly heated. This confirms the data obtained for the junction response to laser radiation in the initial range of bias voltages. A subharmonic structure was distinctly resolved on the V_{dc} curves (and could be seen also on the plots of dV/dI vs V) and made it possible to determine uniquely the junction temperature. [See also the positions, on the V axis, of the gap singularity and of the first gap subharmonic $2\Delta_{Nb}/2$ on curves 2 and 3 of Fig. 4.]

Since the response of the superconducting junction to the radiation is proportional to R_d, it is desirable that the junctions for use as IR sensors have IVC with large differential-resistance sections. The value of R_d, however, is limited by the optimal values of the junction resistance in the normal state and of the critical current.[8] At the same time, the sensitivity of any junction to external radiation can be increased by applying an extraneous microwave field. In this case, when the junction is biased to an IVC region between current steps such that R_d can become very large, the sensitivity of the junction is increased. This is confirmed by the data of Fig. 5, which shows a junction IVC without irradiation (1), irradiated by a microwave field (2), and by a microwave field together with a laser (3); it shows also the response of the junction to laser radiation (4, 5). (The response between the first steps was not recorded in view of the large values of R_d.) Curve 5 was obtained at a lower laser power than curve 4, and reveals an additional structure that corresponds to the fine structure of R_d. The initial section of curve 5 reveals also classical detection ($V_{dc} \propto dR_d/dI$) due to the curvature of the IVC.

The measurements of the response of the niobium junctions to laser radiation demonstrated the possibility of gaining information on the size of the energy gap of the superconductor and on the structure of the IVC of Josephson junctions by an optical method. In addition, these data attest also to the feasibility of using superconducting junctions and controllable IR-band detectors.

In sum, it can apparently be deduced that superconducting Nb–Nb junctions exhibit Josephson properties even at a frequency $3 \cdot 10^{13}$ Hz. Just as in earlier study,[15] where the junctions were irradiated at frequencies $2.5 \cdot 10^{11} - 2.5 \cdot 10^{12}$ Hz, there exists a certain characteristic radiation power above which the thermal effects predominate over the Josephson effects. In our experiments with a CO_2 laser the junctions ceased to exhibit Josephson properties after the critical current was decreased by approximately 40%. It should be noted in this connection that in Ref. 5, where radiation from two lasers was mixed, the power was too high, as demonstrated by the almost complete suppression of the junction critical current. In all probability, therefore, no Josephson mixing was observed in Ref. 5.

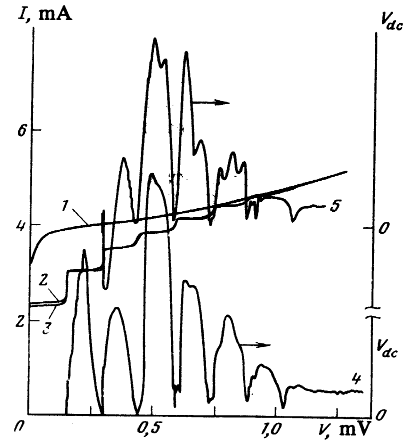

FIG. 5. IVC of non-irradiated junction (1) and of a junction irradiated by a microwave field (2) and by a combined microwave and laser field (3). Response of the junction to laser radiation (4, 5). Curve 5 was obtained at a lower laser power than curve 4 ($T = 5$ K).

[1]New Measurement of the Frequency of an He–Ne Laser. Bulletin G-5, Government Standard. Joint Commission for Standard Time Service. Principal Metrological Center of the State Time and Frequency Service [in Russian], Vol. 3, No. 5 (1981).
[2]N. G. Basov, É. M. Belenov, S. I. Vedeneev, *et al.*, Usp. Fiz. Nauk **128**, 721 (1979) [Sov. Phys. Usp. **22**, 662 (1979)].
[3]T. G. Blaney, N. R. Cross, D. J. E. Knight, *et al.*, J. Phys. **D13**, 1365 (1980).
[4]N. G. Basov, E. M. Belenov, S. I. Vedeneev, *et al.*, Kvant. Elektron. (Moscow) **10**, 574 (1983) [Sov. J. Quant. Electron. **13**, 339 (1983)].
[5]D. G. McDonald, F. R. Petersen, J. D. Cupp, *et al.*, Appl. Phys. Lett. **24**, 335 (1974).
[6]M. Tinkham, M. Octavio, and W. J. Skocpol, J. Appl. Phys. **48**, 1311 (1977).
[7]C. A. Hamilton, Phys. Rev. **B5**, 912 (1972).
[8]A. Barone and J. Paterno, The Josephson Effect, Physics and Applications [Russ. transl.]. Mir, 1984.
[9]H. Kanter and F. L. Vernon, J. Appl. Phys. **43**, 3174 (1972).
[10]S. I. Vedeneev, E. M. Golyamina, and V. A. Stepanov, Fiz. Tverd. Tela (Leningrad) **26**, 313 (1984) [Sov. Phys. Solid State **26**, 187 (1984)].
[11]O. K. Il'ina, G. A. Machulka, and L. A. Perova, Kvant. Elektronika (Moscow) **6**, 78 (1971) [Sov. J. Quant. Electron. **9**, 43 (1971)].
[12]A. L. S. Smith and S. Moffatt, Opt. Commun. **30**, 213 (1979).
[13]I. O. Kulik and A. N. Omel'yanchuk, Pis'ma Zh. Eksp. Teor. Fiz. **21**, 216 (1975) [JETP Lett. **21**, 96 (1975)].
[14]L. Solymar, Superconductive Tunneling and Applications, Chapman and Hall, London, 1972.
[15]D. A. Weitz, W. J. Skocpol, and M. Tinkham, Phys. Rev. **B18**, 3282 (1978).

Translated by J. G. Adashko