in [4]. Oscillogram b of Fig. 2, from which we estimated the duration of the wave front in that paper, corresponds to case (1) of the boundary condition.

CERTAIN SINGULARITIES OF ELECTROMAGNETIC RADIATION GENERATED BY A SUPERCONDUCTING TUNNEL STRUCTURE

I. M. Dmitrenko and I. K. Yanson
Physico-technical Institute of Low Temperatures, Ukrainian Academy of Sciences
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It was shown in [1,2] that the steps on the voltage-current characteristics of superconducting Sn-I-Sn tunnel structures are the consequence of excitation of resonant modes of electromagnetic waves in the tunnel structure by means of the alternating Josephson current. It is natural to expect some part of the high-frequency energy to be drawn from the tunneling region to the space outside. A study of this radiation is of great interest as a direct method of investigating the alternating Josephson current, since its frequency is uniquely connected with the quantum transitions of the electrons during tunneling, and its power indicates the degree of interaction between the current and the high-frequency field.

We have registered earlier [3] the electromagnetic radiation generated by a tunnel structure , with a frequency corresponding to the ratio of the Josephson frequencies: $\hbar\omega = 2$ eV. We present here preliminary results of an experimental investigation of the spectral composition of the Josephson high-frequency radiation. Appreciable inhomogeneities in the thickness of the dielectric of the tunnel structures investigated in [3] have resulted in a complicated picture of the steps observed there. The tunnel structure which we have investigated here had a very uniform layer of oxide between metal films, so that a clear-cut picture of the steps was observed. This apparently was the reason why the power radiated by the structures was more than 10 times the power observed in [3], reaching several times 10^{-13} W. This is several hundred times more the noise level of the receiver. The receiver bandwidth was 8 Mc.

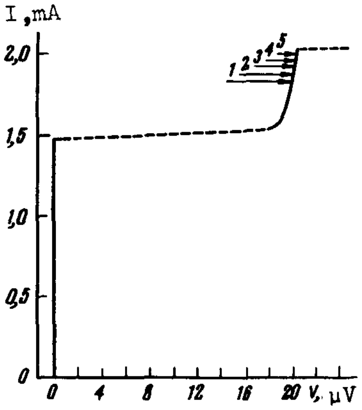

Fig. 1

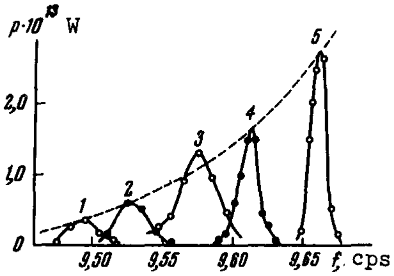

Fig. 2

No attempts were made in the investigations to match the tunnel structure to the waveguide, owing to the technical difficulty of this task. In addition, the nonresonant system used to couple the tunnel junction to the waveguide had apparently the advantage that its frequency dependence in the investigated frequency band (8900 - 9800 Mc) was very small. The measurements were made at 2.85°K, a temperature at which the first step corresponded for the given structures to the receiver frequencies. The voltage-current characteristic of the tunnel structure (Sn-I-Sn, H = 0.297 Oe, T = 2.85°K), plotted in a magnetic field corresponding to the maximum height of the first step, is shown in Fig. 1 (the numbers and the arrows designate the junction currents at which the curves of Fig. 2 were obtained). We see that at this temperature the step has a finite slope. This was very convenient, since it made it possible to regulate the frequency of the radiation within the limits of the bandwidth of the strip cavity of the structure, by varying the current through the junction and consequently the voltage across the junction. It was possible to turn the radiation on or off at will, by turning on or off the current flowing through the solenoid that produced the small constant magnetic field. The measurements could be carried out in two ways: either keep the receiver frequency constant and follow the variation of the microwave power generated by the structure (by measuring the receiver output voltage as the current is slowly increased through the junction), or else keep the current flowing through the junction constant (meaning also the voltage across the junction) and, tuning the receiver, investigate the spectral composition of the radiation. Both methods lead, in general, to the same results, but the second method is more convenient.

Figure 2 shows the frequency dependence of the radiation power, obtained by tuning the receiver at different fixed values of the junction current (meaning different values of the junction voltage, see Fig. 1). We see that the power at the maximum increases with increasing current, and the bandwidth of the radiated frequencies decreases. Within the accuracy limits of the voltage measurement (1.5 - 2%), the ratio of the Josephson frequencies is maintained during the entire time. In spite of the fact that the simple theory [2,4] predicts monochromatic radiation when V is fixed, there are apparently reasons for broadening of the radiation bandwidth. Nevertheless, the bandwidth of the radiated frequencies is much narrower than could be expected from estimates of the Q of the tunnel junction, which now assumes the role of the resonator. From the slope of the step we can obtain for the value of the Q an estimate [4] of several times ten, corresponding to a bandwidth of several hundred megacycles, whereas the observed frequency band corresponds to several times ten megacycles, reaching in some cases the bandwidth of the receiver itself (8 Mc). It is quite probable that the narrowing of the bandwidth of the radiated frequencies is connected with the specific nature of the mechanism whereby the radiation is generated.

The line shape of the Josephson radiation depends essentially on the constant magnetic field applied to the junction. Figure 3 shows the dependence of the radiation power on the frequency for a fixed junction current, and at different values of the current flowing through the solenoid (a solenoid current of 1 mA corresponds to H = 0.0625 Oe at T = 2.85° K). Near each curve is marked the corresponding solenoid current (in milliamperes). The same figure shows the power and the frequency at the radiation maximum as functions of the solenoid current. We see that the maximum interaction between the Josephson-current wave and the electro-

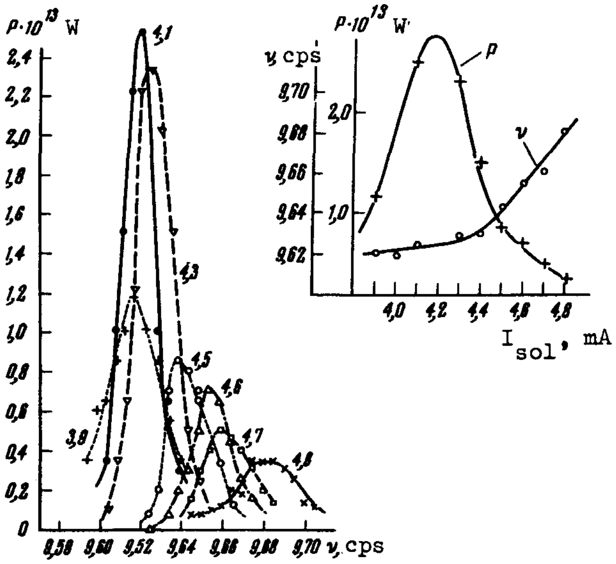

Fig. 3

magnetic wave, corresponding to maximum radiated power, occurs at H = 0.262 Oe. The frequency shift of the radiation maximum with change in the magnetic field corresponds to the frequency "pulling" in a direction such as to equate the phase velocities of the current wave and of the electromagnetic wave [1,2].

In addition, the principal radiation maxima at the frequencies indicated in Figs. 2 and 3, we observed weak secondary maxima (in individual cases - several maxima) on both sides of the central maximum. Investigations of the structure of the Josephson radiation are being continued. It is possible that this will make it possible to study the energy distribution of the "superconducting" electrons, just as a study of the ordinary tunnel effect in superconductors makes it possible to study the energy spectrum of the excitations.

Thus, on the basis of the experimental data presented above, we can draw the following conclusions:

1. The Josephson radiation, as expected, is not a noise effect, having a rather narrow spectral composition, and the bandwidth of the radiated frequencies can amount to $\lesssim 10^{-3}$ of the central frequency. The radiated frequency band is much narrower than the bandwidth of the tunnel-structure strip resonator and depends on the junction current (and thus on the potential difference across the junction) and on the constant magnetic field.

2. The dependence of the spectral composition of the radiation on the constant magnetic field confirms the mechanism proposed in [1-2] for the interaction between the tunnel-current density wave and the electromagnetic wave.

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