Intrinsic electromagnetic radiation of high-T_c superconducting thin-film bridge structures

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(Submitted 20 September 1989)

Pis'ma Zh. Eksp. Teor. Fiz. **50**, No. 8, 355–358 (25 October 1989)

A narrow-band radiation of electromagnetic waves at a power level as high as $P = 3\times10^{-11}$ W and frequency of 21 GHz has been observed experimentally in high-T_c superconducting bridge structures. This radiation is caused by a transport-current-induced coherent motion of flux quanta (vortices) through a superconducting granular film.

In the superconducting bridge structures, when the bridge is much larger than the coherence length, the phenomena characteristic of the Josephson effect, the Shapiro jogs on the I-V characteristic, for example, which arise as a result of application of microwaves, are caused by the transport-current-induced coherent motion of quantum vortices.[1–4] Despite the fact that the dynamic processes in bridge structures have been studied extensively,[1–5] there are so far no data on direct observation of narrow-band radiation due to the coherent motion of vortices. Noiselike radiation in high-T_c superconducting films, which is associated with the motion of quantum vortices, was observed by Konopka and Lung.[6] An important feature of high-T_c superconducting granular bridge structures is the appearance of vortices with a large electromagnetic radius[7] (hypervortices) and the coherent motion of these vortices even when no electromagnetic radiation is applied.[5,8]

In the present letter we present the results of direct observation of a narrow-band self-generation which occurs in high-T_c superconducting bridge structures upon coherent motion of vortices induced by a transport current. We studied Y–Ba–Cu–O bridge structures of width (across the transport current) $w = 20$–60 μm, length $l = 40$–120 μm, and film thickness $d = 1$ μm. The critical temperature of the bridge structure is $T_{bs} = 70$–80 K and that of the edges which form the bridge structure is $T_e = 85$–90 K. The films were deposited by dc magnetron sputtering. The bridge structures were produced by photolithography methods. Sapphire substrates with bridge structures at the center were placed in the waveguide section which was fitted with a short-circuiting plunger. The sample was shielded from external electromagnetic fields by an amorphous Permalloy screen which reduced the earth's field by at least an order of magnitude. The I-V characteristics were measured at $T = 4.2$–100 K, using the standard four-point method in a current mode. The power of the rf signal generated in the bridge structure was measured simultaneously using a radiometric receiver with a fluctuation sensitivity $\Delta T = 0.1$ K. The maximum reception band was $\Delta F = 300$ MHz and the integration time constant was $\Delta t = 1$ s at one of the frequencies in the tuning range $f = 18$–22 GHz.

The shape of a single I-V characteristic, shown in Fig. 1, and the temperature

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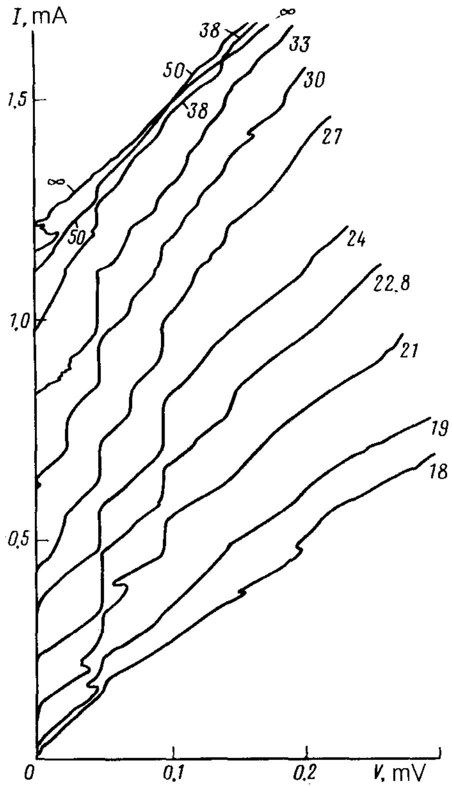

FIG. 1. The I-V characteristics of bridge structures at $T = 4.2$ K for various power levels P_e of microwaves of frequency $f_e = 23$ GHz. The labels on the curves represent the attenuation of P_e in dB.

dependence of the critical current $I_c(T)$ of a bridge structure, similar to that shown in Ref. 5, show that the nonlinearity mechanism in the test bridge structures is the appearance of vortices and their motion induced by the transport current at $I > I_c$ (Refs. 3–5). The dimensions of the bridge structure $l = 120\ \mu$m and $w = 50\ \mu$m, the grain size of the film $a = 1\ \mu$m, the London penetration depth of a given high-T_c superconductor $\Lambda_L = 150$ nm, and the superconducting current density $j_c = 2\times 10^3 A/cm^2$, which determines the Josephson penetration depth $\Lambda_j = 5\ \mu$m, show, according to Amatuni *et al.*[5] and Sonin,[7] that the bridge structures which we studied form hypervortices in which there is no order-parameter suppression region, as in Josephson vortices, and the magnetic-field penetration depth is much greater than the size of the Josephson junction formed between two grains. The constant differential resistance R_d on those parts of the I-V characteristics which correspond to the motion of a single row of vortices in a bridge structure increases with increasing direct current. The unstable sections of the I-V curve with a negative differential resistance R_d are probably a consequence of a thermally activated flux creep.[9,10] The change in the shape of the I-V characteristic of the tested high-T_c superconducting film bridge structures in a microwave field (Fig. 1) is similar in many ways to the same change in high-T_c superconducting ceramic bridge structures.[5] Specifically, the I-V characteristic is strongly asymmetric, and harmonic and subharmonic current jogs are present at

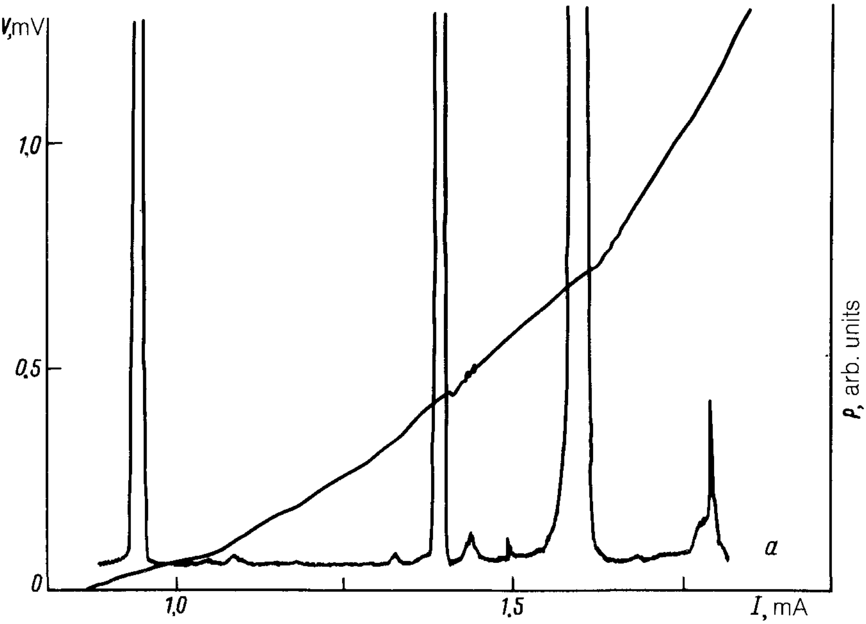

FIG. 2. The I-V characteristic of a bridge structure and a plot of $P(I)$ at a frequency of 21.15 GHz and $T = 4.2$ K, measured simultaneously.

voltages $V_{m,n}$ on the bridge structure which are related to f_e by the Josephson relation

$$V_{m,n} = (n/m)\hbar f_e/2e, \tag{1}$$

where n and m are integers.

Figure 2 shows the I-V characteristic of a bridge structure and a plot of the emission power level $P(I)$. We see that the position of the first three emission peaks (one pronounced peak and two faint peaks) is related to the emission frequency by relation (1) with $m = 1$ and $n = 1, 2, 3$. This relation and the linear segment of the I-V curve with a differential resistance $R_d = R_0 = \text{const}$ in this voltage range ($V = 40$–$120\ \mu$V) suggest that there is only one vortex row in the bridge structure. When a given current flows through a bridge structure, the motion of vortices has a periodic nature, and a passage of a single vortex changes by 2π the difference in the quantum-mechanical phases of the superconducting edges of a bridge structure. As a result, each vortex induces a variable component of the voltage with a frequency which is determined by the velocity of the vortices[11] v:

$$f = Nv/b, \tag{2}$$

where b is the length scale of the vortex structure ($b \sim w$), and N is the number of vortices in the row. The subharmonic peaks in the emission spectrum ($n = 2, 3$) occur because the relation between the current and the phase differs substantially from the sinusoidal characteristic of localized Josephson junctions.[1,2] When the voltage across

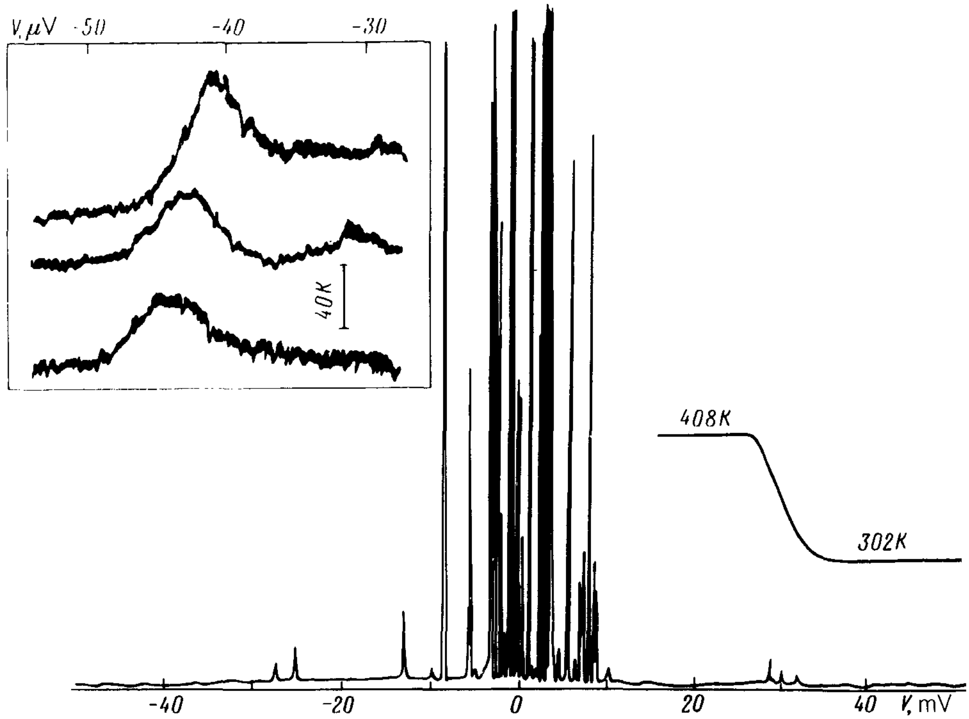

FIG. 3. Plot of $P(V)$ at $T = 4.2$ K, $f = 21.15$ GHz, $AF = 300$ MHz, and $\Delta t = 1$s. At right is the calibration plot. The labels give the temperatures of the standard, constant-temperature, matched loads. The inset shows plots of $P(V)$ of an end-type Josephson junction[13] Nb–Si–Nb at the frequencies $f = 17.9$, 19.3, and 21.8 GHz.

the bridge structure is large, the spacing of the emission spectrum $P(V)$ is nonuniform. As V is increased, the new peaks in $P(V)$ appear in the part of the I-V curve with $R_d = 3R_0$, consistent with the presence of three vortex rows in the bridge structure. Two peaks in this part of the I-V characteristic are probably caused by the change in the number of vortices in the row at $Nv = \text{const}$ [see Eq. (2)]. In the case of an even number of vortex rows ($R_d = 2pR_0$, $p = 1, 2, ...$) the emission is not detected, probably because the emission in the neighboring rows has the opposite phase. This result is also confirmed by the fact that the emission power depends only slightly on the voltage on the bridge structure, as follows from the analysis of the $P(V)$ curve on a large voltage scale, shown in Fig. 3. It can be seen from Fig. 3 that the emission occurs in the bridge structures up to the bias voltage $V = 8$ mV, consistent with the filling of the entire surface of a bridge structure with vortices.

The maximum output power level of a bridge structure, estimated with allowance for the mismatch of the impedance of the bridge structure and the microwave line and for the losses in it, is $P_m = 3 \times 10^{-11}$ W. This value is much larger than that measured experimentally in the Josephson bridge junctions[12] and larger than the value of P_m obtained by us after replacing the bridge structure with an end-type Josephson junction[13] (see the inset in Fig. 3).

We wish to thank A. F. Volkov for useful discussions and A. L. Gudkov, V. N. Laptev, and V. I. Makhov for furnishing the samples.

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Translated by S. J. Amoretty