Nonlinear behaviour of high- T_c superconducting bridges at microwaves

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Abstract. We have experimentally investigated the phenomenon of coherent hypervortices motion in high T_c superconducting Y–Ba–Cu–O thin film bridge-like structures. Narrow band internal radiation at frequency $f = 21$ GHz with intensity $P = 3 \times 10^{-11}$ W was detected. The radiation processes, occurring around the singularity of negative differential resistance at current-voltage characteristics of bridge-like structures allows one to consider their further application for sensitive microwave reception.

Keywords. Hypervortex; microwave radiation; nonlinear behaviour.

1. Introduction

High- T_c superconducting (HTCS) bridge-like structures (BS) with constriction dimensions considerably larger than coherence length exhibit phenomena inherent to Josephson effects, such as Shapiro steps, for example, due to coherent fluxon motion, forced by bias current (Amatuni *et al* 1989a, b). The essential properties of granular HTCS BS are vortice appearance with large electromagnetic interaction radiuses, called hypervortices (Sonin 1988) and their coherent motion, as well in absence of external microwave affection (Amatuni *et al* 1989a).

In this paper the experimental results of thin film BS study at microwaves are presented.

2. Experimental procedure

The samples under investigation were Y–Ba–Cu–O thin film with thickness $d = 1$ μm BS obtained by d.c. magnetron sputtering onto sapphire substrates $9 \times 1.5 \times 0.5$ mm. The films have $T_c = 85$ – 90 K, and BS have $T_c = 70$ – 80 K, critical current densities $j_c = 10^3$ A/cm². The BS constrictions were prepared by photolithography technique with following dimensions: length: $l = 40$ – 120 μm , width: $w = 20$ – 60 μm . The substrates with BS were mounted in the lowered height waveguide section provided by adjustable plunger. External magnetic field was screened by μ -metal. Current-Voltage characteristics (IVCs) were measured at $T = 4.2$ – 100 K by the usual four-probe method. The microwave power arising at BS was measured simultaneously using a tunable radiometer with sensitivity $\Delta T = 0.1$ K for bandwidth $\Delta F = 300$ MHz and integrating time $\tau = 1$ s in the frequency range $f = 18$ – 22 GHz.

3. Results and discussion

The IVCs, showed in figure 1 and the temperature dependence of critical current $I_c(T)$, analogous to results previously obtained for ceramic BS (Amatuni *et al* 1989a), indicated the fluxon nature of the nonlinearity caused by bias current influence $I > I_c$ (Gubankov *et al* 1973; Amatuni *et al* 1989a). The ratio of BS dimensions was: $w = 50 \mu\text{m}$, $l = 120 \mu\text{m}$, mean grain size $a = 1 \mu\text{m}$, London penetration depth $\lambda_L = 150 \text{ nm}$, Josephson magnetic field penetration depth $\lambda_J = 5 \mu\text{m}$, indicated the hypervortex formation in investigated BS where is absent, the area of order-parameter depression as in the case of Josephson vortices if λ_J is much longer than the dimension of Josephson junction formed by two grains. The constant values of differential resistance $R_d = R_0$ at the IVC parts, corresponding to individual vortices row motion across the bridge, are increased with bias current rise. Nonstable IVC parts with negative differential resistance R_d are caused, seemingly, by thermally activated flux creep (Dew-Hughes 1988). BS affected by microwaves exhibit IVCs behaviour very similar to HTCS ceramic BS (Amatuni *et al* 1989a) namely: considerable IVCs asymmetry, the presence of harmonic and subharmonic current steps for voltage values $V_{m,n}$ on BS, related with f_* by Josephson equation:

$$V_{m,n} = (m/n)hf_*/2e \quad (1)$$

where n, m are integers.

Figure 2 shows unperturbed IVCs of BS and internal radiation power dependence $P(I)$. One can see that the location of three first peaks (one strong and two weak ones) related to radiation frequency f by equation (1) with $m = 1, n = 1, 2, 3$. The presence of these peaks and the linearity of IVC part with $R_d = R_0 = \text{const}$ for given voltage range $V = 40\text{--}120 \mu\text{V}$ confirms the single row motion. For fixed bias current level the hypervortices motion are periodic and during a vortex passing period the quantum phase difference changes by 2π . Thus every fluxon moving induced a.c. voltage with frequency determined by vortices motion velocity v (Fiory 1971):

$$f = Nv/b, \quad (2)$$

where b is the characteristic dimension of vortex structure ($b \approx w$) and N is the number of vortices in a row.

Figure 1. IVCs of samples with $w = 50 \mu\text{m}$, $l = 120 \mu\text{m}$, $T = 4.2 \text{ K}$, $f_e = 51 \text{ GHz}$. The figures indicate the attenuation levels in dB.

Figure 2. IVC and radiating power dependence $P(I)$ in arbitrary units. The heads of the largest peaks are cut out.

The subharmonic peaks ($n = 2, 3$) could be explained by significant divergence from sine-type current-phase relationship of BS. At larger values of voltages on BS the radiation peaks $P(V)$ are located not equidistantly along the V axis. The second group of peaks appear at IVC part with $R_d = 3R_0$, which correspond to three rows of motion across the bridge. Two peaks at this part of IVC appears, probably due to variance of N number in a row, whereas $Nv = \text{const}$ (see equation (2)). Note that radiation was observed at BS up to $V = 8$ mV, the case corresponding to complete occupation by vortices in the BS area (Amatuni *et al* 1989b). The estimation of maximal power intensity, taking into account the impedance difference of BS and the waveguide section, becomes $P_{\text{max}} = 3 \times 10^{-11}$ W. This is considerably larger than the values obtained for classic Josephson junction (Gubankov *et al* 1975), and also larger than the power measured in our set-up changing the BS sample by edge-type Josephson junction (Gudkov *et al* 1985).

From figure 3 it is seen that contrary to the unperturbed case (see figure 2) the peak at $P(I)$ dependence, corresponds to $V = 43 \mu\text{V}$ ($m = n = 1$) divided into two peaks, located symmetrical to the centre of the first Shapiro step. Thus, the BS behaviour with nonlinearity nature explained in terms of coherent vortices motion, being affected by microwaves, is analogous to the Josephson junction (Likharev 1979).

For practical application of such BS as nonlinear element, one must take into account the flux creep mentioned earlier, which guides to undesirable nonstability at IVC (Amatuni *et al* 1989a, b).

Figure 4 shows characteristic dependences $P(V)$ for two directions of bias current and the IVCs belong to the sample with distinct singularities caused by flux creep. It is seen that the IVC part with negative differential resistance leads to a considerably large instability of internal radiation if the former coincided with voltage value corresponding to radiation frequency f .

Probably, this nonlinearity of negative differential resistance at the IVC of BS can be exploited for amplification or generation of microwaves, but this is a separate subject for study.

Figure 3. IVCs and $P(I)$ BS in the presence of microwave affection at $f_e = f_{LO} = 21$ GHz.

Figure 4. Part of IVC with negative R_d and corresponding $P(V)$ dependence. The dashed curve is obtained at reverse current flow.

4. Conclusion

The present investigation enables us to conclude that HTCS BS exhibit strong nonlinearity at microwaves, caused by vortice motion. The results obtained show that HTCS BS could be used for generators, mixers, videodetectors and other devices of high sensitive microwave receivers.

References

- Amatuni L E *et al* 1989a *Pis'ma v ZhETF* **49** 559 (in Russian)
Amatuni L E *et al* 1989b *Pis'ma v ZhETF* **50** 335 (in Russian)
Dew-Hughes D 1988 *Cryogenics* **28** 674
Fiory A T 1971 *Phys. Rev. Lett.* **27** 501
Gubankov V N *et al* 1973 *Pis'ma v ZhETF* **18** 292 (in Russian)
Gubankov V N *et al* 1975 *Pis'ma v ZhETF* **21** 489 (in Russian)
Gudkov A L *et al* 1985 *Pis'ma v ZETF* **11** 1423 (in Russian)
Likharev K K 1979 *UFN* **127** 185 (in Russian)
Sonin E B 1988 *Pis'ma v ZhETF* **47** 415 (in Russian)