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Direct-current-assisted microwave quenching of YBa₂Cu₃O_{7- δ} coplanar waveguide to a highly dissipative state

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The paper reports on revealing the effect of a strong change in the microwave losses in an high-temperature superconductor (HTS)-based coplanar waveguide (CPW) at certain values of the input power P_{in} and direct current I_{dc} . CPW on the basis of 150 nm thick YBa₂Cu₃O_{7- δ} epitaxial film on a single crystal MgO substrate was studied experimentally. A sharp and reversible transition of the CPW into a strongly dissipative state at the certain values of P_{in} and I_{dc} depending on temperature were observed. Apparently, the effect can be explained by self-heating of HTS structure caused by magnetic flux flow under the joint influence of microwave field and direct current. © 2014 AIP Publishing LLC. [http://dx.doi.org/10.1063/1.4890123]

Since discovery of high-temperature superconductors (HTSs) in 1986 (Ref. 1), a lot of attention has been paid to studying nonlinear properties of HTS in microwave (MW) fields.^{2–4} Peculiarities of the MW nonlinear response of the superconductors are due to varieties of the interaction mechanisms of electromagnetic fields with these materials and are equally important for both physics and applications of HTS.

Important characteristic of a superconductor in the MW field is the surface impedance $Z_s = E_s/H_s$, where E_s and H_s are the electric and magnetic fields on the surface of the superconductor. In the case of local electrodynamics, the impedance Z_s can be expressed in terms of the complex conductivity σ as $Z_s = (i\omega\mu_0/\sigma)^{1/2} = R_s + iX_s$, where ω is the MW field angular frequency, $\mu_0 = 4\pi \times 10^{-7}$ H/m is the permeability of free space.²

Increase of the field amplitude H_{ω} (or power P_{ω}) can change the conductivity σ , which leads to a dependence of Z_s on H_{ω} . There are a number of nonlinearity mechanisms responsible for $Z_s(H_{\omega})$. However, for high-quality HTS films, which are superconductors of the second kind, the most pronounced, apparently, is the mechanism associated with the formation of vortices and flux flow.^{2–9}

In contrast to the infinite conductivity of superconductors for direct current (DC) I_{dc} smaller than the critical current I_c , MW fields produce heat in a superconductor at any value of the MW current I_{ω} . Effect of heating increases substantially when the magnetic-flux-flow resistance kicks in. These effects lead to an increase in MW loss at P_{ω} values typical for practical devices. The temperature of the superconductor can be noticeably increased as compared with a temperature provided by cryogenic system. Microwave heating may affect the whole or selected areas of the superconductor, and thus may be a global or local heating.

Soon after the discovery of high-temperature superconductivity¹ an idea of creating MW power limiter using dependence R_s (P_ω) was suggested and some of the first experiments were carried out with a planar transmission

line. 10,11 This approach was originally developed in Refs. 12 and 13. Despite that the possibility of constructing such a limiter was confirmed by Refs. 12 and 13, serious obstacles were found in the implementation of practical devices: the difficulty to control the input power handling $P_{\omega(in)}$ (Ref. 12) and the lack of stability of planar transmission line to the breakdown upon the transition to a strongly dissipative condition 13 . In Ref. 14, it was proposed to control the nonlinear impedance of a coplanar waveguide (CPW) created on the basis of HTS films by using DC bias current. This possibility, in principle, was demonstrated, however irreversible changes in the properties of HTS film in the transmission line remained an unresolved problem.

In this paper, we report on discovery of the effect of a strong and abrupt change in the microwave losses in a section of an HTS-based coplanar line at certain values of the input MW power $P_{\omega(in)} = P_{in}$ and direct current I_{dc} . Here, no irreversible changes in HTS film were observed.

For the experimental study, a CPW on the basis of 150 nm thick YBa₂Cu₃O_{7- δ} epitaxial film on a single crystal MgO substrate was fabricated by photolithography. The HTS film produced by THEVA (Germany) had the following characteristics: $T_c = 86.5 \text{ K}$, $J_c = 3.6 \times 10^6 \text{ A/cm}^2$ at T = 77 K. CPW cross-section dimensions were a = 0.186 mm, w = 0.1 mm, d = 150 nm, and h = 0.5 mm (Fig. 1(a)).

CPW is a 16.81 mm long straight section with gold-plated pads, through which the feed-in and readout of the microwave signal and, simultaneously, DC transmission from direct current source (DCS) were implemented by using the integrated planar bias tees (IPBTs). A magnetron source operated at $f=9.24\,\mathrm{GHz}$, with the output power adjustable in the range of 0–13 W. Continuous signal from the magnetron was modulated by the squarewave pulse generator with the following characteristics: pulse duration $\tau_i=5\,\mu\mathrm{s}$, the pulse repetition period $T=40\,\mu\mathrm{s}$ (repetition frequency $f_r=2.6\times10^4\,\mathrm{Hz}$). CPW was placed into a chamber filled with helium gas. The chamber was cooled by liquid nitrogen. The block diagram of the experimental setup with the DC source (DCS) is shown in Fig. 1(b).

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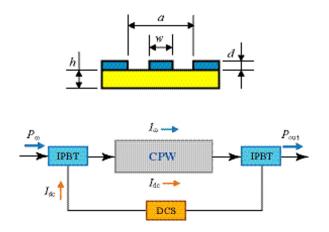


FIG. 1. (a) Cross-section of CPW. (b) Block diagram of the experimental setup: a CPW, two IPBTs, and DCS.

In the experiments, the insertion loss (IL) of CPW, $IL = 10 \lg (P_{out}/P_{in})$, was measured versus both temperature of the cooled chamber and the bias DC current I_{dc} when a fixed level of the input MW signal P_{in} was applied. Here, P_{out} is the power measured at the output of CPW.

Figure 2 shows dependence of the insertion loss IL on temperature T for several values of P_{in} . It can be seen that at a small P_{in} the function IL (T) decreases monotonically. However, with increasing P_{in} , along with a general increase in CPW losses, a peculiar feature in the form of steps appears in the dependence IL(T). The overall increase in losses is caused by an increase of the surface resistance $R_s(H_\omega)$ or $R_s(P_\omega)$ (Ref. 2) (H_ω) and P_ω are the MW magnetic field amplitude and the power in the CPW, correspondingly). The appearance of steps, possibly, is due to the formation of thermal domains 15,16 and/or the manifestation of the wave reflection from the input and output of the CPW. 13

This dependence noticeably changes when different currents I_{dc} were passed through the CPW (Fig. 3). It is seen that if the values of P_{in} and I_{dc} are fixed, there is a sharp transition of the CPW into a strongly dissipative state at a certain temperature with the jump in the losses IL of almost three orders of magnitude (in this particular case for $I_{dc} = 40 \text{ mA}$). Avalanche growth of the microwave loss IL, i.e., microwave quenching stimulated by DC, remained on the IL (P_{in}) curves

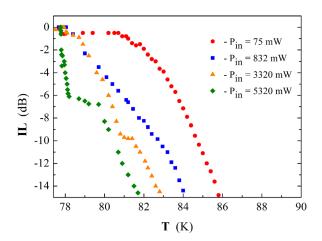


FIG. 2. The IL in CPW dependence on a temperature measured at different input powers, applied in 5 μ s microwave pulse regime.

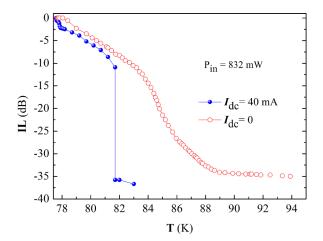


FIG. 3. The insertion loss in CPW as a function of temperature, measured in 5 μ s-long pulse regime at $P_{in} = 832$ mW with ($I_{dc} = 40$ mA) DC and without it ($I_{dc} = 0$).

at I_{dc} = const (not shown in the figure) and on the IL (I_{dc}) curves at T = const and different values of P_{in} (Fig. 4). The quenching phenomenon takes place at a specific values of $I_{dc} = I^*$. Fig. 4 shows that with increasing P_{in} , I^* values decrease. It follows that for realization of the quenching process both current components, microwave I_{co} and DC I_{dc} currents, play a role. It makes sense to find out whether the contributions of these components are additive in the observed effect of quenching.

In Ref. 17, it is shown that in YBa₂Cu₃O_{7- δ} thin film microbridge structure, similar to the HTS coplanar waveguide one studied in the present paper, a switching effect (quenching) is observed in the dissipative state when structure is exposed to millisecond-long high DC pulses. The current-voltage curves of the microbridges with widths smaller than the thermal diffusion length have been measured. It was shown that the flux-flow resistivity is independent of the microbridge width. At the same time, a strong width dependence of the quenching current density is observed. The authors of the Ref. 17 concluded that for high current densities varying in the millisecond range, the intrinsic quenching mechanism is self-heating caused by conventional flux-flow effects. However, the authors emphasized

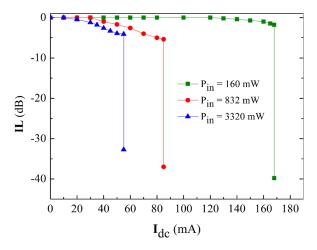


FIG. 4. The insertion loss in CPW as a function of direct current, measured at $T=77\,\mathrm{K}$ and different values of the input power P_{in} , applied in $5\,\mu\mathrm{s}$ pulse regime.

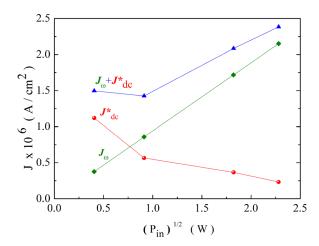


FIG. 5. Current densities $J^*_{\rm dc}$, J_{ω} , and $J^*_{\rm dc} + J_{\omega}$ as a function of the square root of the input power P_{in} applied in 5 μ s-long pulse regime.

that this conclusion does not exclude the relevance of other quenching mechanisms for another current densities and characteristic times. If we assume that the quenching mechanism in MW field remains the same, it makes sense to evaluate the ratio of DC and MW current densities, J_{dc}^* and J_{ω} , triggering the quenching effect, as a function of the input power P_{in} . Although the central conductor of CPW is not a superconducting channel where J_{dc} would be a function of the position within the cross-section of the strip, it can be assumed that in our case the J^*_{dc} varies weakly over the strip cross section S, as film is already in the resistive or preresistive state under the action of MW field alone. Therefore, $J_{dc}^* \approx I_{dc}/S$. It should be noted that at low P_{in} the characteristic value of J^*_{dc} decreases with increased P_{in} more sharply than at higher levels of P_{in} (Fig. 5). This feature might be explained by inhomogeneous distribution of the MW current in the cross-section of the CPW and the partially additive nature of $J_{d\mathrm{c}}$ and J_{ω} effects on the HTS film state. The role of J_{ω} non-uniformity in CPW, as seen in Fig. 5, decreases with increasing P_{in} . The maximum value of the sum of the current densities J_{dc} and J_{ω} always remains below the value of the passport density of the critical current $J_c = 3.6 \times 10^6 \text{ A/cm}^2$. For homogeneous MW current distribution, we might expect that the sum $J_{\rm dc}^* + J_{\omega}$ is independent of P_{in} if the nature of both $J_{\rm dc}^*$ and J_{ω} effects on the CPW transmission is the same

In summary, we have experimentally found that at certain values of the input power P_{in} in the HTS coplanar waveguide an abrupt DC-assisted microwave quenching switches the HTS film into a strongly dissipative state. We suggest that the observed effect can be explained by self-heating of HTS structure caused by magnetic flux flow under the joint influence of MW and direct currents.

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