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Citation: [Applied Physics Letters](#) **105**, 022601 (2014); doi: 10.1063/1.4890123

View online: <http://dx.doi.org/10.1063/1.4890123>

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Direct-current-assisted microwave quenching of $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ coplanar waveguide to a highly dissipative state

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(Received 27 May 2014; accepted 2 July 2014; published online 14 July 2014)

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 $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ 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.² 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 $R_s(P_\omega)$ 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 condition¹³. 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 $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ epitaxial film on a single crystal MgO substrate was fabricated by photolithography. The HTS film produced by THEVA (Germany) had the following characteristics: $T_c = 86.5$ K, $J_c = 3.6 \times 10^6$ A/cm² 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 $f = 9.24$ GHz, with the output power adjustable in the range of 0–13 W. Continuous signal from the magnetron was modulated by the square-wave pulse generator with the following characteristics: pulse duration $\tau_i = 5$ μ s, the pulse repetition period $T = 40$ μ s (repetition frequency $f_r = 2.6 \times 10^4$ 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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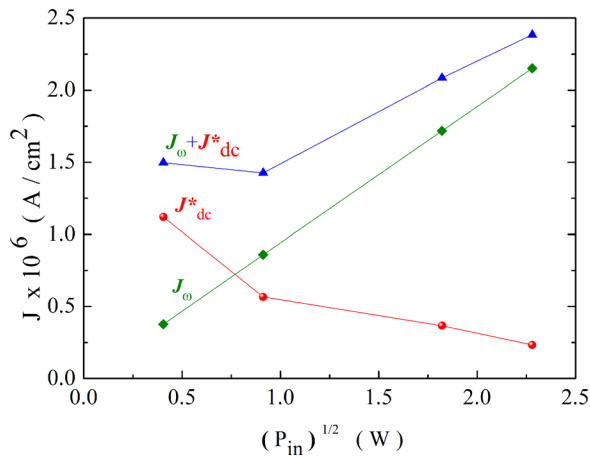


FIG. 5. Current densities J_{dc}^* , J_w , and $J_{dc}^* + J_w$ as a function of the square root of the input power P_{in} applied in 5 μ s-long pulse regime.

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_w , 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 pre-resistive 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_{dc} and J_w effects on the HTS film state. The role of J_w 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_w always remains below the value of the passport density of the critical current $J_c = 3.6 \times 10^6$ A/cm². For homogeneous MW current distribution, we might expect

that the sum $J_{dc}^* + J_w$ is independent of P_{in} if the nature of both J_{dc}^* and J_w 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.

We are grateful to Dr. A. V. Velichko from the University of Nottingham, UK for helpful discussion and useful comments.

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