Microwave response of a $YBa_2Cu_3O_{9-x}$ superconducting ceramic

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The interaction of a $YBa_2Cu_3O_{9-x}$ ceramic with a microwave field of frequency $\omega/(2\pi) = 9.3$ GHz over a wide temperature range has been studied experimentally. The superconducting transition was inferred from a change in the microwave conductivity of the sample. As the amplitude of the alternating field was increased, the emission at the doubled frequency 2ω and that at the tripled frequency 3ω were found to intensify. The behavior of these harmonics was studied as a function of the temperature, the intensity of the wave incident on the sample, and the external magnetic field. A qualitative explanation for the experimental results is proposed.

This letter reports a study of the properties of a $YBa_2Cu_3O_{9-x}$ ceramic in a microwave field. A disk-shaped sample 4.5 mm in diameter with a resistivity of 500 $\mu\Omega$/cm was placed in a bimodal resonator which could be tuned to the frequencies ω and 2ω or to the frequencies ω and 3ω. The radiation at the fundamental frequency was guided to the input of the resonator along a waveguide with a cross-sectional area of 23×10 mm^2; the harmonics were extracted along a small waveguide with a cross-sectional area of 11×5.5 mm^2.

Figure 1 shows a representative recording of the transition of a sample to the superconducting state, as inferred from the change in the quality factor, Q, of a resonator at a frequency of 20 GHz. The amplitude of the alternating magnetic field, $H_\sim$, at the sample was 0.05 Oe when these measurements were taken.

Nonlinear-reflection experiments were carried out at large amplitudes $H_\sim$ with the help of a pulsed magnetron in pulsed operation with a pulse length of 2 μs at a repetition frequency of 50 Hz. The power coupled into the resonator at the frequency ω was varied from 10 W to 4 kW; the amplitude $H_\sim$ correspondingly varied over the range 4 Oe $< H_\sim <$ 100 Oe. The harmonic signal from the sample was directed to a superheterodyne receiver and then recorded with the help of a stroboscopic converter. We measured the pulsed power $P_{2\omega}$ or $P_{3\omega}$ of the radiated wave of frequency 2ω or 3ω. In these experiments we used a static external magnetic field $H < 300$ Oe, which could be rotated in the plane parallel to the irradiated surface of the sample.

Figure 2 shows the temperature dependence of the power $P_{3\omega}$ in the absence of a magnetic field H. The zero signal level, $P_{3\omega} = 0$, is shown. The amplitude of the alternating field in these experiments was $H = 10$ Oe. The peak near T_c, whose origin is completely understood,[1] is not found in the case of samples with a diffuse transition, and it does not depend on the static magnetic field H. The $P_{3\omega}$ signal, which is observed in the ceramic at $T \ll T_c$ and which is essentially independent of the tempera-

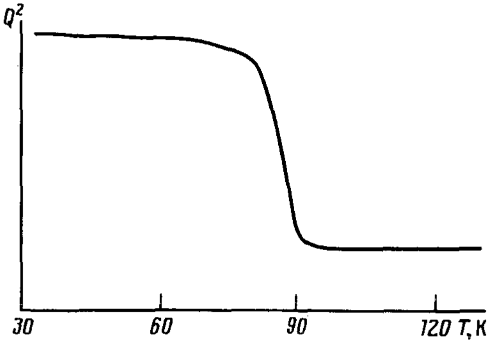

FIG. 1. Detection of the superconducting transition in the ceramic on the basis of the change in the Q of a resonator at the frequency 20 GHz.

ture, disappears in a weak field H (see the inset in Fig. 2). This signal is probably associated with generation at Josephson junctions which are situated at crystallite boundaries. If a potential difference $V = v_0 + v\cos\omega t$ is applied to a Josephson junction, the superconducting tunnel current across the junction, $I(t)$ can be described by[2]

$$I(t) = I_c \sum_{n=-\infty}^{\infty} (-1)^n J_n\left(\frac{2ev}{\hbar\omega}\right)\sin\left[\left(\frac{2ev_0}{\hbar} - \hbar\omega\right)t + \varphi_0\right], \qquad (1)$$

where I_c is the critical current of the junction, J_n is the Bessel function, and φ_0 is the jump in the phase across the weak link. It can be seen from expression (1) that even in the absence of static voltage ($v_0 = 0$ and $\varphi_0 = 0$), the current $I(t)$ would still have a component at the frequency 3ω. The behavior of a complex system of Josephson junctions in a strong rf field requires a special study, but the most general properties of a single element should persist. In particular, the application of a weak magnetic field will reduce the critical current through the junction and will tend to straighten out the I-V characteristic of the junction. The amplitude of the third harmonic should decrease, in accordance with the experimental observations.

Figure 3 shows the results of a study of the nonlinear signal $P_{2\omega}$. The labels at the

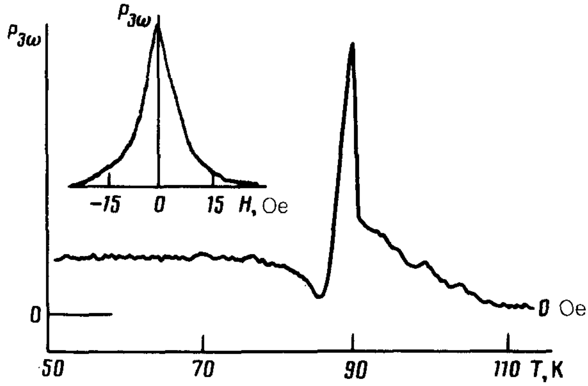

FIG. 2. Representative recording of the temperature dependence of the power of the third harmonic, $P_{3\omega}$. The inset shows $P_{3\omega}(H)$ at $T = 60$ K.

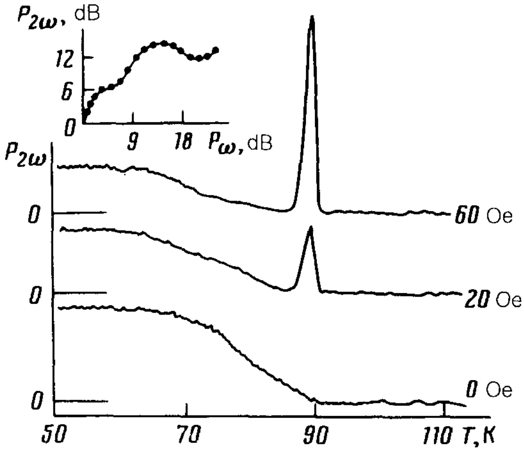

FIG. 3. The second-harmonic signal, $P_{3\omega}$, versus the temperature in various magnetic fields H (the curve labels at the right). The inset shows a curve of $P_{2\omega}(P_\omega)$ recorded at $T = 55$ K.

right of these curves are the external field H; the amplitude $H_\sim$ is 18 Oe. The mechanism for the generation near T_c is obvious, and we will not discuss it here. The signal far from T_c is suppressed by a field $H > 100$ Oe. It follows from (1) that in the case $v_0 = 0$ the current $I(t)$ has a component at the frequency 2ω if the condition $\varphi_0 \neq 0$ holds, i.e., if a supercurrent is flowing. This condition can be satisfied easily by virtue of rectification processes which occur at inhomogeneities in the sample. The nonmonotonic behavior of the power $p_{2\omega}$ as a function of the incident power is yet further evidence in favor of a Josephson generation mechanism at $T \ll T_c$.

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[2]S. Shapiro, J. Appl. Phys. **38**, 1879 (1967).

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