Microwave response of a YBa$_2$Cu$_3$O$_{9-x}$ superconducting ceramic

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The interaction of a YBa$_2$Cu$_3$O$_{9-x}$ 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 $2\omega$ and that at the tripled frequency $3\omega$ 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$_2$Cu$_3$O$_{9-x}$ ceramic in a microwave field. A disk-shaped sample 4.5 mm in diameter with a resistivity of 500 $\mu$Ohm/cm was placed in a bimodal resonator which could be tuned to the frequencies $\omega$ and $2\omega$ or to the frequencies $\omega$ and $3\omega$. The radiation at the fundamental frequency was guided to the input of the resonator along a waveguide with a cross-sectional area of $23 \times 10$ mm$^2$; the harmonics were extracted along a small waveguide with a cross-sectional area of $11 \times 5.5$ 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, $H_-$, at the sample was 0.05 Oe when these measurements were taken.

Nonlinear-reflection experiments were carried out at large amplitudes $H_-$ with the help of a pulsed magnetron in pulsed operation with a pulse length of 2 $\mu$s at a repetition frequency of 50 Hz. The power coupled into the resonator at the frequency $\omega$ was varied from 10 W to 4 kW; the amplitude $H_-$ correspondingly varied over the range 4 Oe < $H_- < 100$ 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 $2\omega$ or $3\omega$. 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, 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-
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

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

where $I_c$ is the critical current of the junction, $J_n$ is the Bessel function, and $\varphi_0$ 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 $3\omega$. 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 $P_{3\omega}$. The labels at the
right of these curves are the external field $H$; the amplitude $H_-$ 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 $2\omega$ 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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