Low-field microwave absorption in single-crystal superconducting $YBa_2Cu_3O_{7-\delta}$

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The low-field microwave absorption line spectrum of a single crystal of superconducting $YBa_2Cu_3O_{7-\delta}$ has been studied as a function of the external magnetic field. The threshold microwave power necessary to nucleate fluxons is found to vary with field in such a way that only about one thousandth of the junction length is active in interacting with the microwaves to create fluxons.

Introduction

Since the discovery of the high-T_c cuprate superconductors, there have been many reports [1–13] of their microwave absorption in very low magnetic fields. The experiments are usually performed in a conventional ESR spectrometer, where the absorption is detected by a derivative technique involving the application of a small modulation field. The broad absorption found in ceramic samples has been attributed to damped fluxon motion driven by the microwave field [14]. In these granular materials a superconducting critical state is formed at very low applied fields, and the effect of an even smaller modulation field is to cause some of the fluxons which are kept nearly depinned by the critical currents to become less mobile. The resulting modulated signals change sign upon field reversal for small modulations, leading to a hysteresis [15] that is very similar to the hysteresis of the magnetization. As the modulation field is increased, the effect of the lower mobility is reduced and the hysteresis becomes less apparent [15].

Experiment and discussion

An apparently different, more intense, line absorption has been found in single crystals of $YBa_2Cu_3O_{7-\delta}$ [16] and small particles of $PbMo_6S_8$ and Nb [17]. The regular series of which **Figure 1** represents just a small part is attributed to fluxon nucleation and annihilation within a single low-fluxon-viscosity Josephson junction [18] at one of the numerous domain boundaries. Additional fluxons are created by the microwave-induced currents where the energies of neighboring fluxon states cross as a function of the applied field, H [17]. The junction critical current is also smaller at these values of the field. Experimentally the absorption peaks are found to be anisotropic and vary with field according to the simple relation [16]

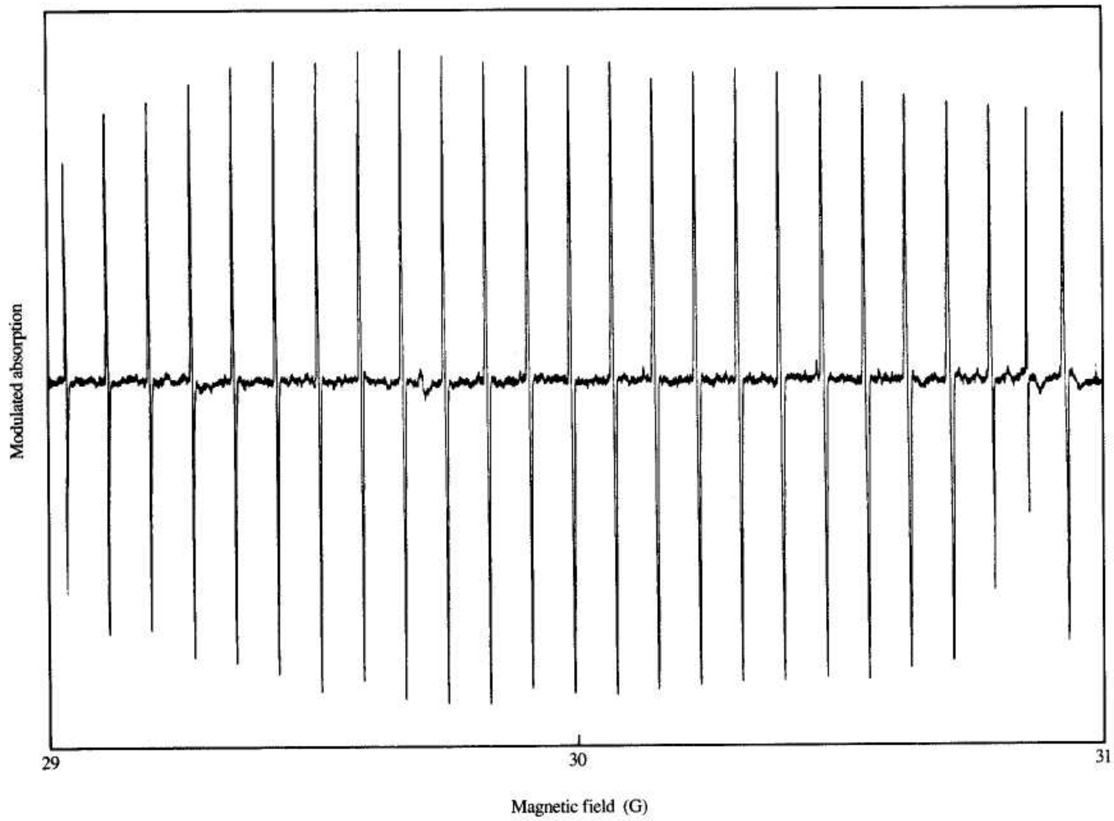

Figure 1

A segment of the 9.44 GHz microwave absorption line spectrum of a $YBa_2Cu_3O_{7-\delta}$ single crystal between 29 and 31 gauss at 4.3 K. The applied magnetic field is $\perp \langle c \rangle$ and $\parallel \langle 110 \rangle$, and the microwave field $\parallel \langle c \rangle$.

$$H \cos \phi = \left(p + \frac{1}{2}\right)\Delta H,$$

where ϕ is the angle between the applied field and a $\langle 110 \rangle$ direction and ΔH the period of the spectrum which is 80 mG in Figure 1. Although the line spectrum of Figure 1 is from the same crystal as that used in [16], it was produced by another junction than that studied there. In all cases the observed sequence is more regular than the characteristic Fraunhofer interference pattern for the critical current of a point-like Josephson junction, where the minima near $H = 0$ have twice the separation of all other minima [19]. In fact, the spectrum is more reminiscent of the behavior of a double-junction quantum interferometer with all lines equally spaced. A single long junction in a microwave field which penetrates and creates fluxons only over a strictly limited distance at each end of the junction is expected to behave similarly to a quantum interferometer. Moreover, the surfaces of $YBa_2Cu_3O_{7-\delta}$ single crystals are known to be of poorer quality than the interior. This may further contribute to an effective nonuniform critical current profile [19] at the edges of the active Josephson junction causing the periodic spectrum.

The line series of Figure 1 appears above a certain threshold microwave power beyond which each line broadens linearly with the square root of the microwave power. New series are induced in other junctions at successively increasing thresholds of microwave power and also with increasing temperature, which effectively lowers the required thresholds. An example of the microwave power broadening of the line spectrum is shown in **Figure 2**. This line broadening is proportional to the microwave magnetic field and is described [17] by

$$\frac{\delta H}{\Delta H} = \left(\frac{P}{P_0}\right)^{1/2} - \left(\frac{P_c}{P_0}\right)^{1/2}$$

where δH is the linewidth, ΔH the field interval of the

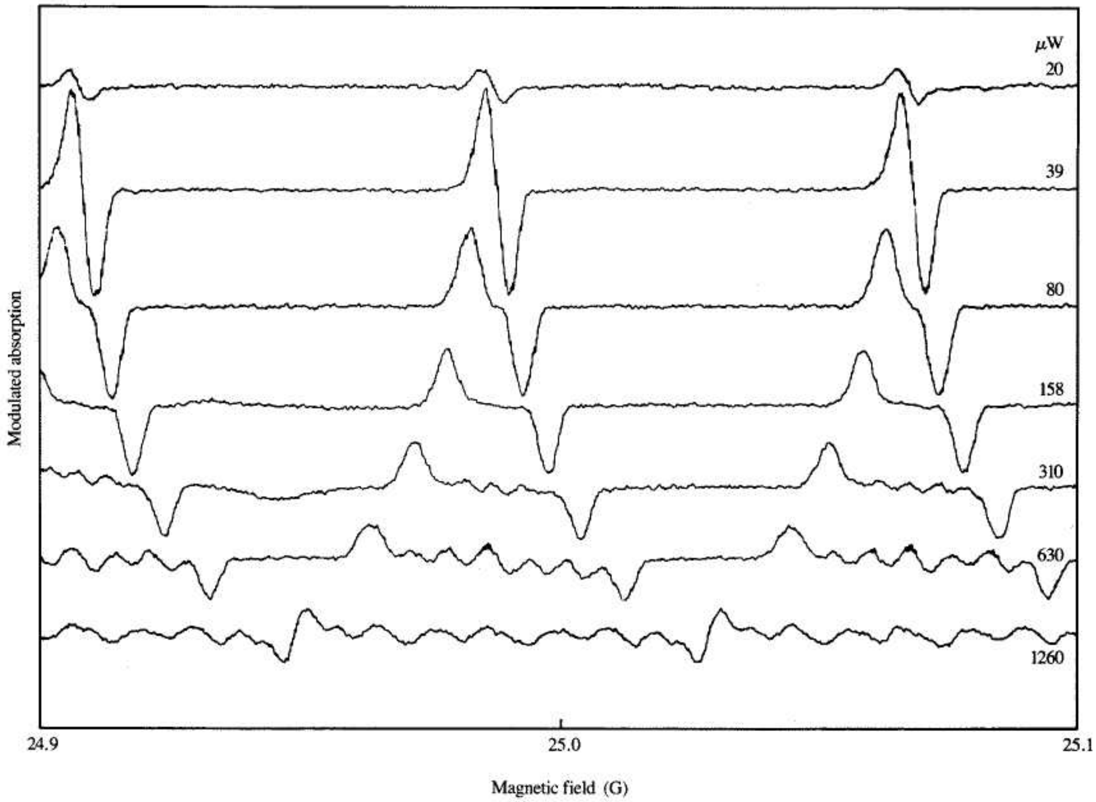

Figure 2

Microwave power broadening of the line spectrum of Figure 1 around 25 G. The incident microwave power is indicated for each spectrum.

spectrum, $P_c(T)$ the threshold power, and P_0 the temperature-independent rate at which $\delta H/\Delta H$ increases above threshold. The threshold microwave power $P_c(T)$ necessary for fluxon nucleation may be obtained by plotting the variation of linewidth of a particular line in Figure 2 against the square root of the incident microwave power and extrapolating to zero linewidth. Of particular interest in Figure 2 is the appearance of additional structure throughout the bands in the higher-power absorption spectrum. This secondary fluxon excitation bandwidth extrapolates back to the same threshold as the primary absorption process, but the rate of power broadening differs markedly. Whereas all the strong bands of the primary process broaden at approximately the same rate, ~2.6 $\mathrm{mG}/\mu\mathrm{W}^{1/2}$, with increasing microwave power the secondary bands widen at about 0.6 $\mathrm{mG}/\mu\mathrm{W}^{1/2}$ in a 5-G field, decreasing to about 0.25 $\mathrm{mG}/\mu\mathrm{W}^{1/2}$ in fields greater than 50 G. This secondary fluxon excitation was not observed in Josephson junctions in irregular Nb particles [17].

The variation with magnetic field of the threshold microwave power for primary fluxon nucleation is shown for successive lines of the single crystal of $YBa_2Cu_3O_{7-\delta}$ in **Figure 3**. This apparent oscillatory field dependence is another consequence of the limited spatial penetration of the microwaves in the junction. The active depth of the junction may be shown to be given [17] by

$$\delta = L\,\frac{\Delta H}{H_a},$$

where H_a is the field interval between minima in the microwave threshold power as a function of the applied field in Figure 3 and L the total length of the junction, assumed uniform. From Figures 1 and 3 $\Delta H = 0.08$ G and $H_a \sim 80$ G, which gives an active length of about one thousandth of the total length of the junction. The latter quantity is difficult to estimate, because the crystal contains many domain boundaries and there is no way of knowing which of them causes the spectrum of Figure 1.

The majority of the theory of Josephson junctions has been concerned with the $I-V$ characteristics with and without an applied magnetic field. The effect of a microwave field on $I-V$ characteristics has also been investigated [20], but very little has been done on the microwave response itself. In this respect, it is hoped that the experiments reported here may stimulate additional rigorous theoretical work.

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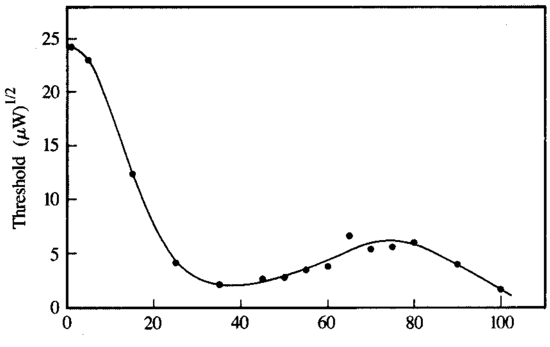

Figure 3

Variation of the square root of the threshold power with magnetic field along the line spectrum of Figure 1.

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