Microwave interaction in granulated superconductor YBaCuO

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We investigate the interaction of two centimeter-band microwaves produced by radiation incident on the surface of a ceramic sample. The main nonlinearity mechanism in this interaction is of the Josephson type. The experimental results are evaluated in the context of a model of long Josephson junctions. In a strong constant magnetic field the wave interaction is due to pinning of a soliton lattice.

INTRODUCTION

The microwave response of HTSC has a clearly pronounced nonlinear character. This is manifest in the dependence of the surface resistance on the wave amplitude, the subject of many recent investigations of both films[1,2] and ceramic specimens.[3–5]

We have used the more convenient, in our opinion, two-frequency method of investigating the nonlinear response of a superconductor when one wave (weak) directed to the sample is a probing one, and study the impedance at the frequency of this wave. The amplitude of the second wave responsible for the change of the impedance can be varied in a wide range. We use the model of long independent Josephson junctions to describe the interaction of two waves in a HTSC in the presence and absence of a constant magnetic field.

EXPERIMENT AND RESULTS

A YBaCuO disk 18 mm in diameter and 2 mm thick was placed on the bottom of a cylindrical cavity tuned simultaneously to two frequencies, $\omega_1/2\pi = 9.4$ GHz and $\omega/2\pi = 18$ GHz. At the lower of the frequencies the power was modulated by rectangular pulses and could vary in a wide range. The irradiation at the high frequency ω was continuous. The experimental setup is shown in Fig. 1. The setup could record changes of the real or imaginary part of the surface impedance of the sample. It was possible to vary in the experiment and record with required accuracy the temperature and the external field; the pump power (of the strong wave of frequency ω_1) was adjusted by an electrically driven attenuator and measured with a thermistor bridge. The voltage on diodes *7* and *8* was determined by the interference of the waves reflected from the cavity and from the piston, with amplitudes $\Gamma E_{\rm inc}$ and $E_{\rm ref}$, respectively:

$$U = f(|\Gamma E_{\rm inc} + E_{\rm ref}|).$$

The coefficient Γ of reflection from the cavity takes here near the resonant frequency the form:[6]

$$\Gamma = \Gamma' + i\Gamma'' = \frac{Q_e^{-1} - Q_0^{-1} - i\Delta\omega/\omega_0}{Q_e^{-1} + Q_0^{-1} + i\Delta\omega/\omega_0}, \tag{1}$$

where Q_e and Q_0 are the external and intrinsic Q of the cavity, ω_0 is the cavity frequency, and $\Delta\omega = \omega - \omega_0$ is the deviation from resonance. Choosing a reference-signal amplitude such that $E_{\rm ref} \gg \Gamma E_{\rm inc}$ we get

$$U \sim \Gamma' E_{\rm inc} E_{\rm ref} \cos\varphi + \Gamma'' E_{\rm inc} E_{\rm ref} \sin\varphi, \tag{2}$$

where φ is the phase difference between the wave incident on the cavity and the reference wave. Using switch *6* to set a phase shift $\varphi = 0$ or $\varphi = \pi/2$, we can measure the real part Γ' or the imaginary part Γ'' of the reflection coefficient.

Generator pulse *1* changed the reflection at the frequency ω and the oscilloscope screen displayed a corresponding pulse duplicating exactly the form of the initial pulse, at least at pulse durations $\tau_u < 10$ μs. At resonance the reflection coefficient is real and the expression for Γ' takes the simpler form

$$\Gamma' = \frac{q_e^2 - q_0^2}{(q_e + q_0)^2}. \tag{3}$$

Here $q_e \equiv Q_e^{-1}$ and $q_0 \equiv Q_0^{-1}$ are the energy losses inside the cavity and in the coupling elements. The internal losses are determined by dissipation in the walls and in the specimen.

$$q_0 = q_{\rm wall} + q_{\rm sp} = q_{\rm wall} + \beta R_s. \tag{4}$$

Here R_s is the surface resistance of the specimen is a geometric factor that takes into account the structure of the mode and the shape of the specimen. This very same factor determines the frequency shift, in view of the finite imaginary part X_s of the surface impedance:[7]

$$\omega_0 = \omega_{\rm ideal} + (\beta/2)\omega_{\rm ideal} X_s. \tag{5}$$

If the phase is chosen equal to zero, the signal on diode *7* is proportional to ΔR_s in the time of the pulse ΔU of generator *1*:

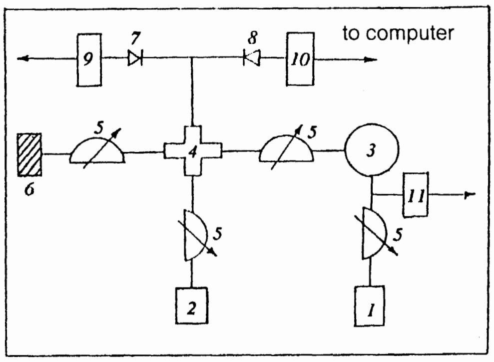

FIG. 1. Block diagram of setup for the observation of microwave interaction. *1*—Oscillator of frequency $\omega_1/2\pi = 9.4$ GHz, *2*—oscillator of frequency $\omega/2\pi = 18.4$ GHz, *3*—cavity with sample, *4*—dual waveguide bridge, *5*—attenuator with electric drive, *6*—movable piston, *7,8*—microwave diodes, *9*—stroboscopic integrator, *10*—dc voltmeter, *11*—microwave power meter.

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$$\Delta U \sim \Delta\Gamma' \sim \Delta R_s. \tag{6}$$

The circuit of the diode *8* does not respond to short pulsed signals, but records slow changes ΔR_s due to change of the temperature or of the external magnetic field. The presence of two coupling irises in the cavity made it possible to change it at high frequencies for transmission, a fact used to estimate the ratio $\Delta R_s/R_s$.

The experimental results are shown in Figs. 2–5.

DISCUSSION

The sensitivity of HTSC ceramic samples to both constant and microwave magnetic fields is due to the presence of a large number of weak Josephson couplings between the superconducting granules. Microwave investigations make it possible to estimate the parameters of these couplings. Many studies have been made of the influence of a constant magnetic field H_0 on the surface impedance $Z(H_0,\omega)$ of ceramic HTSC samples (see, e.g., Ref. 8). The method used in the present study makes it possible to investigate the suppression of Josephson couplings by microwave fields for different dc fields. Thus, the interaction of a Josephson medium with microwave fields is characterized by two physical parameters, the impedance $Z(H_0,\omega)$ at the test frequency ω and its change $\Delta Z(H_0,H_1,\omega,\omega_1)$ by application of an additional microwave field H_1 at a frequency ω_1. We shall discuss mainly the real part of the impedance, i.e., the surface resistance $R_s(H_0,\omega)$ and its change $\Delta R_s(H_0,H_1,\omega,\omega_1)$. The field dependences of these quantities are characterized by the following distinguishing features:

1. At $H_1 = 0$ the surface resistance $R_s(H_0,\omega)$ saturates in sufficiently strong constant magnetic fields $H_0 \gg H_{0\,\mathrm{sat}} \approx 30$ Oe (Fig. 2a).

2. For each value of H_0 the surface resistance is increased by additional pumping at a frequency ω_1 (Fig. 2b). The change $\Delta R_s(H_0,H_1)$ of the surface resistance also saturates at large pump amplitudes $H_1 \gg H_{1\,\mathrm{sat}}$ (Fig. 3). The maximum increase of the surface resistance $\Delta R_{s\,\max} \times (H_0) = \Delta R_s(H_0, H_1 \gg H_{1\,\mathrm{sat}})$ decreases with increase of H_0 and reaches a plateau at $H_0 \gg H_{0\,\mathrm{sat}}$. The foregoing peculiarities are illustrated in Fig. 6.

3. A weak microwave field influences the surface resistance much more strongly than a constant field of the same strength. At low power levels the difference can exceed an order of magnitude. This circumstance is noted also in Refs. 1–3.

It is natural to attribute the saturation of ΔR_s at large values of H_1 to complete disruption of the Josephson couplings within the skin depth. The penetration of the test field over the contacts into the interior of the sample is limited only by dissipation. The presence of a finite change $\Delta R(H_0)$ induced in the surface resistance by the pump at $H_0 > H_{0\,\mathrm{sat}}$ shows that in such fields the Josephson junction still influences the penetration of the test field into the sample.

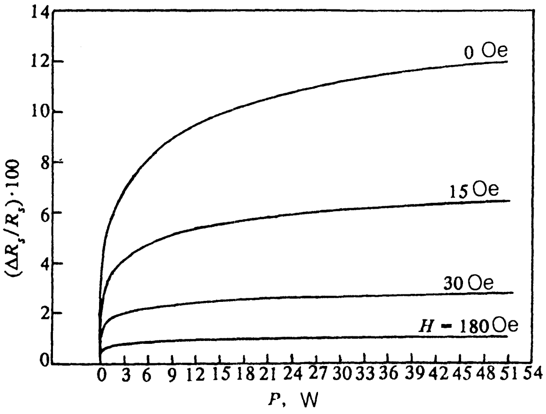

FIG. 3. Dependence of relative change $\Delta R_s/R_s$ of surface resistance at 18.4 GHz on the pump power at 9.4 GHz at different values of the dc magnetic field. [Under the conditions of our experiment we had on the sample surface $H_\sim \sim \alpha P^{1/2}$, where $H_\sim$ is the microwave amplitude and P the microwave power (watts), and $\alpha \sim 1.2$ (Oe/W)$^{1/2}$].

THEORETICAL MODEL

The physical properties of granulated superconductors depend substantially on the relation between the granule size and the Josephson depth δ_J. The latter can be estimated by using the characteristic value of the field that changes substantially the sample impedance, $H_0 \approx 10$–30 Oe,

$$\delta_J = \Phi_0/(\pi^2 H_0 \lambda). \tag{7}$$

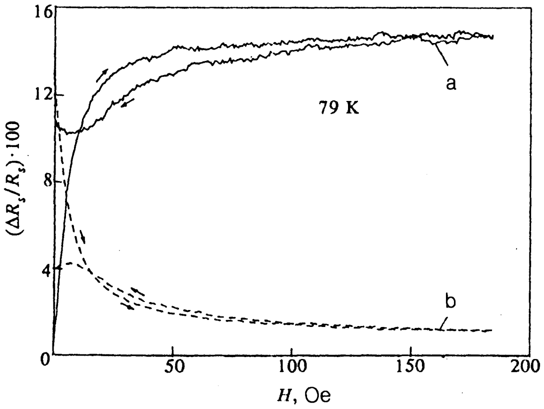

FIG. 2. a) Relative change $\Delta R_s/R_s$ of surface resistance at 18.4 GHz as a function of the dc magnetic field (without pump); b—relative change of surface resistance under the action of a wave with amplitude 7.5 Oe and frequency 9.4 GHz as a function of the dc magnetic field.

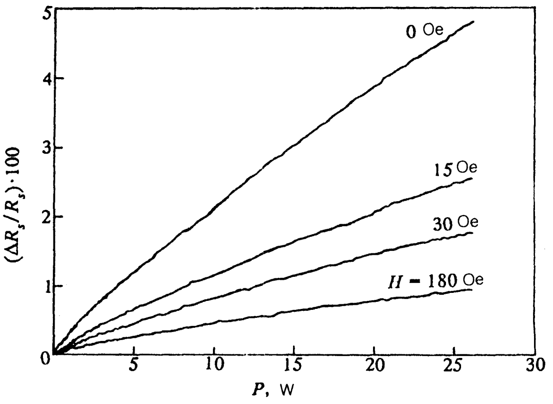

FIG. 4. The same as Fig. 2b, but the pump amplitude is 0.15 Oe.

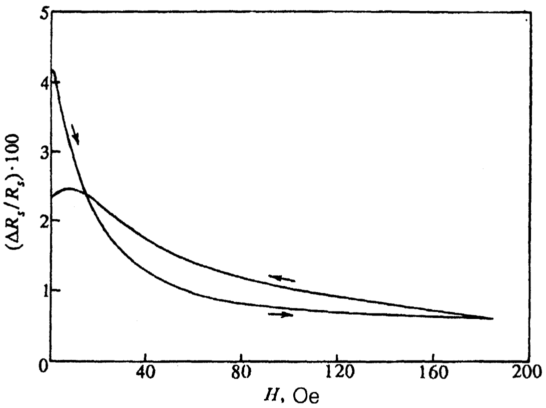

FIG. 5. Change $\Delta R_s/R_s$ of surface resistance at the trial frequency at low pump power levels for different values of the dc magnetic field.

Here λ is the London penetration depth and Φ_0 is the flux quantum. For YBaCuO at 77 K $\lambda \approx 2.2\cdot 10^{-5}$ cm. An estimate yields $\delta_J \approx 1$ μm. Since a typical granule size is $L \approx 10$ μm, a limit $\delta_J < L$ is realized for the samples employed. In this limit, the physical properties of the system are adequately described by a simple model of non-interacting long Josephson junctions.[9,10] This means that the response of the superconductor to an alternating field consists of independent responses of the junctions, and the surface resistance can be represented as

$$R_s = n_J \langle R_J \rangle, \tag{8}$$

where n_J is the total length of the junctions per unit area, $\langle R_J \rangle$ is the average surface resistance of an individual junction. The problem thus reduces to a determination of the surface resistance of a junction as a function of its parameters, and to averaging over the parameters.

The response of a junction to an alternating field is described by the sine-Gordon equation

$$\omega_0^{-2}\frac{d^2\theta}{dt^2} + \tau\frac{d\theta}{dt} - \delta_J^2\left(\frac{d^2\theta}{dx^2} + \frac{d^2\theta}{dz^2}\right) + (1 + g(\mathbf{r}))\sin\theta = 0 \tag{9}$$

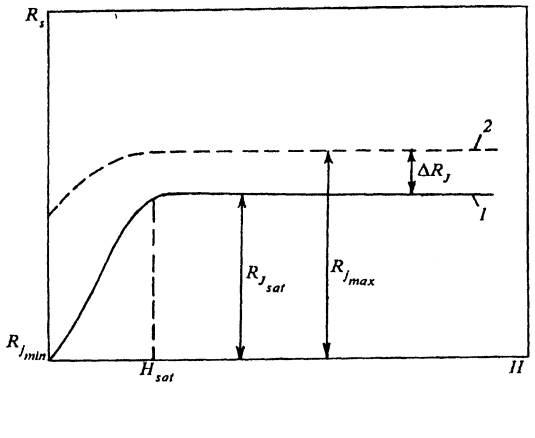

FIG. 6. Schematic dependence of the surface resistance on the dc magnetic field without (curve 1) and with microwave (curve 2).

with the boundary condition on the surface

$$-\delta_J \frac{d\theta}{dx}\bigg|_{x=0} = \frac{4}{\pi H_J}(H_0 + \tilde{H}\cos\omega t + H_1\cos\omega_1 t). \tag{10}$$

Here $\omega_0 = [(2\pi c/\Phi_0)(j_J/C)]^{1/2}$ is the plasma frequency, $\tau = \Phi_0/(2\pi C j_J R)$ is a dissipative parameter, C and R are the capacitance and quasifrequency per unit area, j_J is the Josephson current density, and $H_J = \Phi_0/(\pi^2\delta_J\lambda)$ the critical field of the junction. The random function $g(\mathbf{r})$ describes the structural inhomogeneities in the Junction. It is further assumed that

$$\langle g(\mathbf{r})g(\mathbf{r}')\rangle = \gamma\delta(\mathbf{r} - \mathbf{r}'). \tag{11}$$

The structural inhomogeneities lead to pinning of the soliton lattice produced when the constant field breaks into the junction. The critical current at which the lattice breaks away from the pinning centers does not depend on the field in fields $H \gg H_J$ and is estimated at[11]

$$j_c \approx j_J\gamma/\delta_J^2. \tag{12}$$

We use for estimates the parameter values $j_J \sim 10^4$ A/cm^2,[1)] $H_J \sim 10$ Oe, $\omega_0 \sim 10^{13}$ s^{-1}, $j_c/j_J \sim 10^{-3}$, $\tau \sim 10^{-13}$ s. Since the test field $\tilde{H}$ is assumed weak, it is convenient to express the phase in the form

$$\theta(\mathbf{r},t) = \theta_0(\mathbf{r},t) + \theta(\mathbf{r},t). \tag{13}$$

The surface resistance of the junction is determined by the value of the alternating component of the phase $\tilde{\theta}(\mathbf{r},t) = \theta(\mathbf{r})\exp(i\omega t)$ on the boundary $x = 0$:

$$R_J = \mathrm{Re}\left(\frac{2i\omega\Phi_0}{c^2}\frac{\tilde{\theta}(0)}{\tilde{H}}\right). \tag{14}$$

The minimum impedance for typical transitions ($\omega \ll \omega_0$, $1/\tau$) is realized at $H_0 = H_1 = 0$

$$R_{J\,min} = \frac{4\Phi_0\omega^2\tau}{\pi H_J c^2}. \tag{15}$$

A strong high-frequency field destroys the Josephson junction completely. This is equivalent to a possibility of neglecting the term proportional to $\sin\theta$ in the left-hand side of Eq. (9). The impedance of the junction reaches then a maximum value

$$R_{J\,max} = \frac{4\sqrt{2}\,\Phi_0\omega_0}{\pi H_J c^2}\left\{\frac{1 + (1 + (\omega_0^2\tau/\omega)^2)^{1/2}}{1 + (\omega^2\tau/\omega)^2}\right\}^{1/2}. \tag{16}$$

The nature of the high-frequency response in the presence of weak additional pumping depends substantially on the ratio of the external field H_0 to the Josephson field H_J. In weak fields $H_0 < H_J$ the alternating field penetrates into the junction to a distance on the order of the Josephson depth. The surface resistance increases then by a value on the order of $(H_0/H_J)^2 R_{J\,\min}$ compared with the value $R_{J\,\min}$ in a zero magnetic field. A soliton lattice is produced in the junction in fields $H_0 > H_J$, facilitating greatly the penetration of the alternating field into the sample and increasing the dissipation. In this limit, the field penetration into the junction is limited by pinning of the soliton lattice. This means that in the region $H_0 > H_J$ the response is determined by structural inhomogeneities in the junction. It is convenient to define the disorder intensity by the value of the critical current j_c.[11] The presence of a finite current value j_c denotes that the dc field does not destroy the Josephson coupling completely. This is the cause of the nonlinear signal in strong fields $H_0 \gg H_J$. Let us estimate the surface resistance in this field region. In the soliton-lattice state the phase distribution in the junction can be written in the form

$$\theta(\mathrm{r}, t) = \theta_0(x + U_p(\mathrm{r}) + U(\mathrm{r}, t)), \tag{17}$$

where the function $\theta_0(x)$ describes the phase distribution in an ideal junction, $U_p(\mathrm{r})$ and $U(\mathrm{r},t)$ are the displacements of the soliton lattice as a result of inhomogeneities and variable fields, respectively. The displacement $U(\mathrm{r},t)$ satisfies the equation

$$\rho U'' + \eta U' = C_{11}\frac{d^2U}{dx^2} - f_p \sin 2\pi \frac{U}{a} + \frac{H(t)\Phi_0}{4\pi\delta_J a}\exp\left(-\frac{x}{\delta_J}\right), \tag{18}$$

where ρ and η are the mass and viscosity of the soliton lattice per unit area, a is a soliton-lattice parameter, C_{11} is the flexural modulus, and f_p is the pinning force.

At $x = 0$ the connection between the surface resistance and the lattice displacement $U(0)$ is

$$R_J = \mathrm{Re}\left(\frac{2i\omega\Phi_0}{c^2}\frac{4H_0}{\pi H_J \delta_J}\frac{U(0)}{\tilde{H}}\right). \tag{19}$$

Substituting in (19) the solution of Eq. (18) in an approximation linear in U we arrive at the estimate

$$R_J = R_{Jsat} \approx \frac{4\sqrt{2}\omega\Phi_0}{\pi c^2 H_J} \frac{[-j_c/j_J + \omega^2/\omega_0^2 + ((j_c/j_J - \omega^2/\omega_0^2)^2 + (\omega\tau)^2)^{1/2}]^{1/2}}{[(j_c/j_J - \omega^2/\omega_0^2)^2 + (\omega\tau)^2]^{1/2}}. \tag{20}$$

If the pinning is so weak that the relation $j_c/j_J \ll \omega\tau$ is satisfied, turning on the pump leads to an insignificant increase of the surface resistance:

$$\frac{R_{Jmax} - R_{Jsat}}{R_{Jmax}} \approx \frac{j_c}{2j_J\omega\tau}. \tag{21}$$

Using the above parameters, we obtain the estimate

$$\frac{R_{Jmax} - R_{Jsat}}{R_{Jmax}} \sim 0{,}04.$$

Experiment yields for this ratio a value ≈ 0.01.

CONCLUSION

The model considered explains, at least qualitatively, most experimental facts on the microwave interaction in a granulated YBaCuO superconductor. What remains unclear is the stronger action on the superconductor by the alternating field than by the corresponding dc field. It seems to us that this is due to the different distributions of the dc and ac currents in the sample. This is clearly seen using as an example the concentrated junction considered in Refs. 13 and 14. In this approximation Eq. (9) is replaced by the relation

$$\frac{1}{R}\frac{\hbar}{2e}\frac{d\theta}{dt} + I_c \sin\theta = J_0 + \tilde{J}\cos\omega t + J_1 \cos\omega_1 t. \tag{22}$$

The current J_0 corresponds to the dc magnetic field, $\tilde{J}$ to the test microwave field, and J_1 to the pump. R and I_c are the total resistance of the junction and the critical current through the junction, respectively. Calculation of the contribution due to J_0 and J_1 to the absorption at the frequency ω shows that at small J_0 and J_1 the absorption is proportional to J_0^2 and J_1^2 with identical proportionality coefficients. It is easy to posit, however, that under realistic conditions a microwave field of amplitude H_1 produces in the region of the junctions responsible for the absorption a larger current than the dc field H_0.

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[11] It must be noted that the critical current obtained in ceramic samples is determined by the current's own magnetic field and is therefore much smaller than j_J (see, e.g., Ref. 12).

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