Giant absorption of an rf electromagnetic field in conducting ceramics

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A giant absorption of power from an rf field ($\nu \sim 1$ GHz) has been observed in La_2CuO_4 and in systems with a metallic conductivity, $La_{2-x}Sr_xCuO_{4-y}$ and $YBa_2Cu_3O_{7+\delta}$. The observed effects are interpreted as ferroelectric anomalies at finite frequencies, caused by the low-frequency lattice dynamics. A phenomenological model is offered to describe the coexistence of ferroelectric anomalies and a metallic conductivity.

In this letter we report a study of the absorption of power from an rf electromagnetic field in the ceramic materials La_2CuO_4 (LCO), $La_{2-x}Sr_xCuO_{4-y}$ (LSCO) with $x = 0.175$, and $YBa_2Cu_3O_{7+\delta}$ (YBCO) at room temperature. The samples were prepared by the technique of Ref. 1. The conductivity $\sigma(\nu)$ was studied over the frequency range 10^8–10^{10} Hz by measuring the loss in a resonator.[2] The details of the experimental procedure are given in Ref. 3.

Figure 1 shows the results of the measurements of the absorbed power, $P(\nu)$, for the semiconductor LCO, divided by the eddy-current loss [its static conductivity is[4] $\sigma(0) = 4$ S/cm at the two points in the resonator corresponding to antinodes of the magnetic field **H** and the electric field **E**]. We see that while the absorbed power corresponds precisely to the eddy-current loss at $\nu < 10^8$ Hz and $\nu > 10^{10}$ Hz it increases sharply in the frequency range 10^8–10^{10} Hz (the increase is by more than two orders of magnitude at $\nu \approx 0.9$ GHz). This increase is of a resonant nature. Near the resonance, $P(\nu)$ at the E-point exceeds $P(\nu)$ at the H-point (Fig. 1).

In a nonferromagnetic system, rf field power can be absorbed either by conduction electrons (the eddy-current loss) or dipole moments (as in ferroelectrics). Both the scale of the effect and its behavior as a function of the position of the sample in the resonator rule out the first of these possibilities. The absorption of P at high frequencies should therefore be attributed to dipole moments. We are talking here about a very peculiar "ferroelectricity," which is manifested only at finite frequencies, well below the characteristic phonon frequencies $\nu_{\text{ph}} \sim 10^3 - 10^4$ GHz.

The possible existence of a low-frequency dynamics in solids has been discussed in connection with the observation of a "central peak" in neutron scattering.[5,6] Some specific mechanisms which might lead to a low-frequency dynamics were examined in Ref. 7. The results in Fig. 1 lead to the conclusion that a low-frequency dynamics occurs in LCO. Furthermore, the data show that the low-frequency dynamics may be

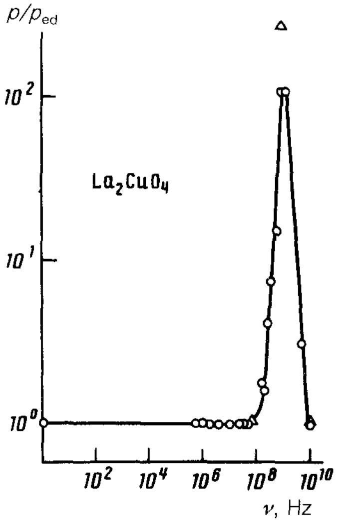

FIG. 1. Frequency dependence of the absorbed power in an LCO sample. ○ — At the H-point; △ — at the E-point (P_{ed} is the eddy-current loss).

manifested in the form of the ferroelectric anomalies at finite frequencies. Of all the known "central-peak" theories, only the model of a "nonlinear resonance"[7] predicts a maximum in the absorption of finite ν. According to Ref. 7, in systems which exhibit a "central peak" there can be displacements of atoms with characteristic $\sim \nu_{ph}\kappa^2 \sim 1$ GHz (κ is the adiabatic parameter).

A study of $P(\nu)$ for LCO thus revealed a new phenomenon: ferroelectric anomalies at finite frequencies. The compound LCO is not an ordinary ferroelectric, since it gives no indications of anomalies of any sort in the dielectric constant $\epsilon(\nu)$ at $\nu < 0.1$ GHz. The data from structural studies[1] also seem to rule out an ordinary ferroelectricity, because of the presence of an inversion center in the structure of LCO.

Figure 2 shows the results of $\sigma(\nu)$ measurements for LSCO (also shown in this figure are the data from Fig. 1 for LCO, expressed in units of an effective conductivity). We wish to stress that in terms of its static properties the LSCO sample is a metal [$\sigma(0) \approx 4500$ (S/cm), and the temperature coefficient of the resistance is positive, as is characteristic of a metal]. In this compound we observe a resonant decrease in the effective conductivity $\sigma(\nu)$ (an increase in the absorbed power), in the same frequency region as in LCO. This resonant decrease is by two orders of magnitude in comparison with $\sigma(0)$ (Fig. 2). In this samples, however, the absorption at the H-point is significantly stronger than that at the E-point of the resonator; i.e., the relaxation of the rf-field energy goes through conduction electrons. The compound YBCO exhibits a corresponding behavior $\sigma(\nu)$ [Fig. 3; in YBCO we find $\sigma(0) = 1330$ (S/cm) and a positive temperature coefficient of the resistance]. The agreement of the resonant frequencies in LCO and LSCO (Fig. 2) indicates that the anomalous absorption in LSCO is also caused by dipole moments. In this case, however, as in YBCO (Fig. 3), we are dealing with the coexistence of ferroelectric anomalies and a metalic conductivity.

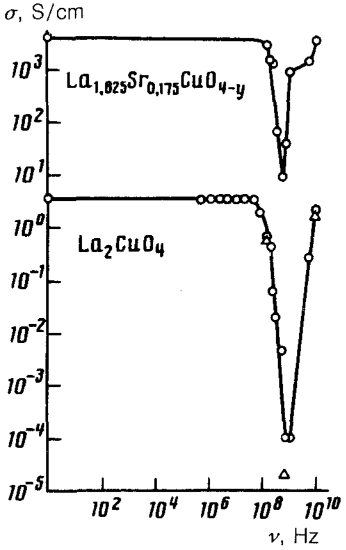

FIG. 2. Frequency dependence of the effective conductivity of LSCO (upper curve) and of LCO (lower curve).

Phenomena associated with the simultaneous existence of a static ferroelectric polarization and conduction electrons were discussed in Ref. 8 for semiconductors, where the Debye screening length satisfies the condition $\lambda \gg a$ (a is the lattice constant). In order to reach an understanding of the results shown for LSCO and YBCO in Figs. 2 and 3, we must assume that the same relation, $\lambda \gg a$, holds in these materials. An important feature of these systems is the extremely short mean free path of the conduction electrons, $l \sim a$ (in metals, the relation $l \gg a$ usually holds, and an electron "senses" only the average electric field **E** and does not interact with the local field).

To describe the observed dielectric anomalies in LSCO and YBCO, we introduce phenomenological equations for the conduction current density **j** and the dielectric

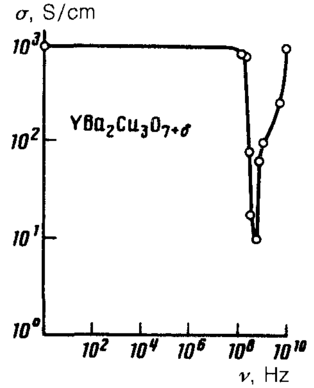

FIG. 3. Frequency dependence of the effective conductivity of YBCO. ○ — Room temperature.

polarization $\mathbf{p}$:

$$\frac{\partial \mathbf{j}}{\partial t} = \frac{\omega_p^2}{4\pi}\left(\mathbf{E} - \frac{4\pi}{3}\hat{b}\,\mathbf{p}\right) - \mathbf{j}/\tau_D, \tag{1}$$

$$\frac{\partial \mathbf{p}}{\partial t} = \frac{\partial}{\partial t}(\hat{\alpha}\mathbf{E}) - \frac{\mathbf{p}}{\tau^*} - \hat{\beta}\mathbf{j}, \tag{2}$$

where $\omega_p^2 = 4\pi ne^2/m$ is the square of the plasma frequency, n is the electron density, m is the effective mass of the electrons, and the caret means a coupling which is nonlocal in time. Equations (1) and (2) correspond to a local regime with $l \ll \lambda$, R, i.e., to the case in which the spatial irregularities are ignored. These irregularities are characterized by length scales λ and R, where R is the size of the "ferroelectric" regions. The first term in (1) includes the effect of the local field $(4\pi/3)\hat{b}p$ on the motion of the electrons ($b \to 0$ with $l \gg a$). The relaxation term in (1), $-j/\tau_D$, describes the ordinary Drude dissipation of momentum ($\tau_D \sim 10^{-14}$ s). The first term in the right side of (2) is standard, while the second describes the dissipation of the dipole moment ($\tau^* \sim 10^{-9}$–10^{-10} s). Finally, the last term in (2) describes a transfer of the momentum of conduction electrons to oscillating dipoles during a collision.

Transforming to the Fourier representation in (1), (2), we find, for the case $\omega\tau_D \ll 1, \omega \ll \omega_p, \tau^* \gg \tau_D$, $\beta \ll 1$,

$$\frac{\sigma(\omega)}{\sigma(0)} = \frac{1 - i\omega\tau^*\left[1 - \dfrac{4\pi}{3}\alpha(\omega)b(\omega)\right]}{1 - i\omega\tau^* + \dfrac{4\pi}{3}\sigma(0)\tau^*\beta(\omega)b(\omega)} \tag{3}$$

[here we have $\beta(0) = 0$ by virture of invariance under time reversal]. Here we have $(4\pi/3)\sigma(0)\tau^* \sim 10^7 - 10^8$ with $\sigma(0) \sim 1000$ (S/cm). We can therefore explain the experimentally measured values $\sigma(\omega_0)/\sigma(0) \sim 10^{-2}$ by setting $\beta(\omega_0)b(\omega_0) \sim 10^4$, which is a rather reasonable estimate.

The conductivity decreases at finite frequencies because of the existence of two interacting subsystems with relaxation times which differ by several orders of magnitude. Accordingly, a conduction electron will cause a rather strong polarization, even if the interaction with dipole moments is weak. The microscopic prerequisites for the observed effects are (1) the existence of a low-frequency dynamics (possibly in the form of a "nonlinear resonance" in a phonon subsystem[7]). (2) extremely short mean free paths of the conduction electrons, $l \sim a$, and (3) a rather large Debye screening length, $\lambda \gg a$.

The most unambiguous piece of evidence relating the observed anomalies in $\sigma(\nu)$ to the dipole moments in LSCO and YBCO is the presence of an absorption in the superconducting state, since Cooper pairing does not change the nature of the screening of a longitudinal electromagnetic field from that of the screening by "normal" electrons.[9] There is accordingly interest in studying $\sigma(\nu)$ at $T \lesssim T_c$.

In the ceramics which have been studied, by virtue of the existence of the low-frequency dynamics which has been observed in the present study, an anomalous increase of the ultrasonic absorption at the corresponding frequencies should be observed, and we should also observe a "central peak" in the neutron scattering, with a dispersion $\Gamma \sim \hbar\omega_0 \sim 10^{-2}$ meV. The associated quasistatic displacements might also be studied by experiments on the scattering of Mössbauer radiation by a procedure like that of Ref. 10.

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