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Features of the nonlinear interaction of electromagnetic waves in HTSC ceramics

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The nonlinear interaction of electromagnetic waves in an HTSC plate in the critical state is studied both theoretically and experimentally. The magnetic components of both waves are collinear and parallel to the plate surface. We have considered two radiowaves having different frequencies and have predicted and experimentally observed jumps of the electrical field $E(t)$ on the plate surface which take place owing to the nonlinear wave interaction. Besides, we have investigated the behaviour of the nonlinear surface impedance at low frequencies as a function of the radiowave amplitudes. The unusual non-monotonous dependence of the surface impedance (both real and imaginary components) on the radiowave amplitudes has been obtained. The character of the magnetic field dependence of the critical current density significantly influences the lineshape of the $E(t)$ curves. Therefore, one can obtain information on this dependence from the results of $E(t)$ measurements.

Consider a plane-parallel superconductor plate of thickness *2d* in an external magnetic field, oriented along its surface, of the form

$$H_s(t) = H_1 \cos(\omega_1 t) + H_2 \cos(\omega_2 t). \qquad (1)$$

The magnetic components $\vec{H}_1$ and $\vec{H}_2$ are collinear and parallel to the plate surface, the magnetic field in the superconductor is distributed symmetrically, whereas the electric field is distributed antisymmetrically, relative to the symmetry plane parallel to the plane sides

The Maxwell's equations for the spatial distribution of the electromagnetic field are essentially nonlinear due to the nonlinear relation between the critical current density and the electric field inside the superconducting sample We used an expression for the temporal dependence of the electric field $E(t)$ at the sample surface derived for an arbitrary form of the critical current density vs magnetic induction relation. The electric field $E(t)$ at the sample surface for an arbitrary form of the critical current density vs magnetic induction relationship $j_c(B)$ can be given in the form (see ref. [1]):

$$E(t) = \frac{\mu}{4\pi j_c(B)} |\dot{H}_s| (\bar{H} - H_s) \qquad (2)$$

The parameter $\bar{H}$ involved here is defined differently, depending on the values of the radiowave amplitudes and on time $\bar{H}$ is the value of the magnetic field in the planes which separate the region with the "frozen" flux from the region where the time derivative of the magnetic flux (and, consequently, the electric field) is not equal to zero. There are two such planes which are always parallel to the boundaries of the plate. The plot of the spatial distribution of the magnetic field $H(x)$ inside the sample exhibits an inflection in these planes. If the

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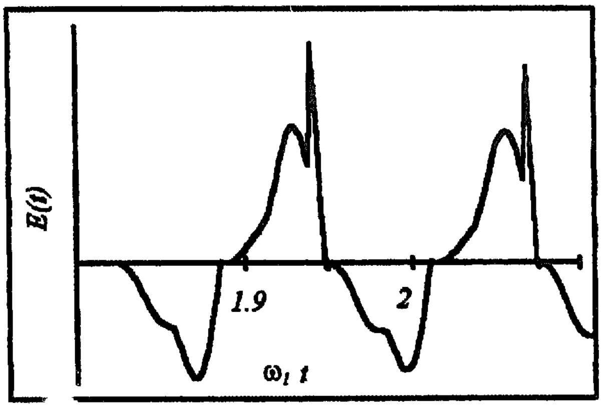

Figure 1. Jumps of the electrical field on the plate surface; $\omega_2/\omega_1 = 50$.

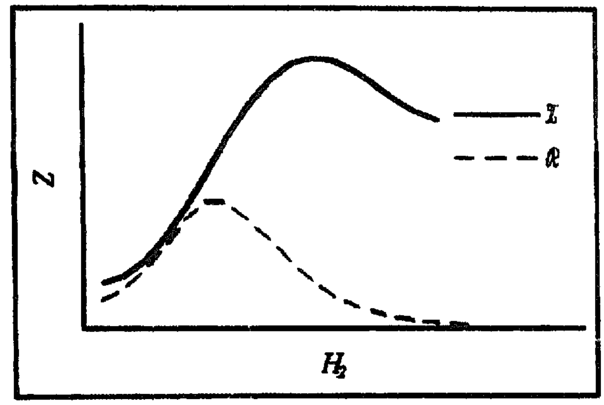

Figure 2. Low frequency surface impedance, $\omega_2/\omega_1 = 3.6$.

electric field is not equal to zero everywhere in the sample then the quantity $\bar{H}$ represents the magnetic induction in the middle of the sample.

The lineshape of the $H(x)$ curve (and, consequently, the value of $\bar{H}$) is extremely sensitive to the magnitude of the external field $H_s(t)$ at the sample surface. Under specific conditions, the function $\bar{H}(t)$ appears to suffer jumps at intervals of monotonicity of $H_s(t)$. These jumps are due to the intrinsic nonlinearity of equation (2) which gives us the spatial distribution of the magnetic induction in the sample. The value of these jumps is given by the relation

$$\Delta E(t) = \frac{\mu}{4\pi j_c(B)} |\dot{H}_s| \Delta \bar{H}. \qquad (3)$$

Here $\Delta\bar{H}$ is the magnitude of the jump of the function $\bar{H}(t)$. The quantity $\Delta\bar{H}$ is a function of the radiowaves amplitudes H_1 and H_2. The nature of the magnetic field dependence on the critical current density also considerably affects the value of $\Delta\bar{H}$. A section of the $E(t)$ plot is presented in Fig. 1 (the frequency ratio $\omega_2/\omega_1 = 50$).

Nonlinear interaction of the radiowaves in a hard superconductor leads to an unusual nonmonotonous dependence of the low frequency impedance Z_{ω_1} vs. amplitude of the high frequency radiowave H_2. Typical profiles of the dependence of the real $\Re$ and imaginary $\Im$ components as a function of H_2 are shown in Fig. 2. Note, that the shape of the electrical field $E(t)$ dependence and, thus, the low frequency impedance Z_{ω_1} is sensitive to the magnetic-field dependence of the critical current density. For computations, we used the explicit expression

$$j_c(\bar{B}) = \frac{j_0}{1+|\bar{B}/B^*|^{3/2}}, \qquad (3)$$

which consistently describes the $j_c(\bar{B})$ dependence in ceramics with inter-grain contacts of the elliptic type [2],[3]. Here B^* is the characteristic scale of the critical current density and j_0 is its value in zero magnetic field.

Analytical calculations were performed under the assumption that the higher frequency ω_2 equal to $3\omega_1$. In the other cases we used numerical calculations.

The effects treated here are sensitive to the values of amplitudes, frequencies, and phases of the interacting waves.

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