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Retardation effect in microstrips and microwave detection of spatial dispersion in superconductors

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ABSTRACT

Effect of significant retardation of the phase velocity in a microwave microstrip resonator has been found and utilized for detection of spatial-dispersion phenomena in superconductors, which should be pronounced when the phase velocity became less than the Fermi velocity. The effect is explained by the influence of the fine fringes of a strip near of which the high values of curvature can appear for the system of coordinates introduced to find solutions. This leads to a spatial dependence of the phase velocity on the Lamé coefficients (metric coefficients) of the curvilinear system of coordinates and can decrease the velocity significantly. Comparative estimates of the spatial effects for single-crystal high-T_c (YBaCuO), Nb, and Cu samples were obtained from measurements of the resonant frequency depending on a position of the sample in the field.

1. Introduction

Pairs with a large quasi-momentum and the presence of carriers with the effective masses of opposite signs are the characteristic features of a mechanism of high-T_c superconductivity developed recently by Kopaev et al. (see [1] for review), which is based on the Coulomb repulsion. These unconventional attributes found experimental evidence in our previous studies [2]. Temperature behaviors of the Hall effect and conductivity, as well as the microwave properties of high-T_c superconductors (HTSC), such as YBaCuO, are explained by the model containing these features. The Coulomb interaction, which leads to the instability to the Mott–Hubbard transition implemented by the charge-transfer mechanism, results in the formation of a new spatial structure in the ground state [2]. A period of this structure is order of the doubled lattice parameter of an HTSC. The wave functions of boson-like pairs formed by the transfer of a charge from one lattice cell to an adjacent cell and consequently possessing the effective masses of opposite signs in the occupied and empty adjacent cells, should be modulated in space with a new doubled lattice parameter that correspond to pairing with a large quasi-momentum.

According to this model, the pronounced spatial dispersion associated with the Mott–Hubbard instability should be present in HTSC materials: the instability results in the dependence of the frequency of propagating electromagnetic waves on the wave number $\omega(k)$, which can considerably differ from a linear dependence $\omega \sim k$ (which is valid in the dispersion-free case) deviating to lower frequencies. Retardation of the phase velocity ω/k associated with deflecting the dispersion curve to lower frequencies must be accompanied by an increase in permittivity inversely proportional to the square of the phase velocity. Near the instability point, the permittivity must become very large and demonstrate noticeable spatial dependence. In this study, we used high sensitivity and accuracy of microwave measurements to study the effects of spatial dispersion. The phase velocity of electromagnetic wave was probed in a microwave microstrip resonator and it was found that the phase velocity depends on places on a microstrip. From a measured resonant frequency, spatial dependence of the resonant frequency, permittivity, and permeability was determined. The results of resonant frequency shift for Nb sample show an oscillation in real space, which is explained by a boundary effect at the edge of sample on the basis of a theoretical analysis and leads to the retardation of the phase velocity even below the Fermi velocity. It is also found that the spatial oscillation of the resonant frequency for HTSC is rather small than that for Nb in agreement with a theoretical model.

2. Effect of significant retardation

The resonant frequency $f_p \sim 9$ GHz was measured at 4.2 K depending on the position of a sample in a microstrip Nb resonator, described in details early [3], with the 11.35-mm-long

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strip placed between teflon discs. Samples with dimensions $\approx 1.5\times 1.4\times 0.5$ mm were made of $YBa_2Cu_3O_7$ single crystal, Nb, or Cu, and fastened in the hole drilled in the upper disc. From the value and stepwise shift of the resonant frequency when cooling helium transforms from the liquid state to the gaseous state [4], we obtained comparative dependences of the spatial effects in behavior of $f_p^{-1}\sim(\mu_{ef}\,\varepsilon_{ef})^{1/2}$, the effective length of the resonator $l_{ef}\sim\mu_{ef}^{1/2}$, and the square root of the permittivity $\varepsilon_{ef}^{1/2}$ for these samples. The sample position was varied by turning the upper teflon disc with a sample in its hole around the center of the disc. It is found that when a sample shifts just over the strip width the measured parameters oscillate, as it is shown in Figs. 1 and 2, in accordance with preliminary results [3]. The absence of ohmic and tunnel contacts between a sample and a niobium resonant strip was thoroughly verified in each measurement. The oscillations are produced obviously by perturbations of the small-scale modulated resonant field by a sample surface [3]. Note that positions of the oscillation extrema reveal the regular, repeatable behavior for all measured samples (Fig. 2) in spite of small uncertainties in the size and position of the samples, as well as for different resonators (cf. data in Fig. 2b for $z/\lambda<0.08$).

The small-scale modulation has been obtained in the numerically calculated dependences early and is especially well pronounced for distribution of the longitudinal current component I_z across the strip width (see Fig. 1). The data of these numerical calculations [5,6] are compared with the results of our measurements of a shift of the resonant frequency (Δf_{res}) of a superconducting microstrip resonator (SMR) dependent on the position of a side face of the Cu sample nearest to the strip. The frontal size of the sample is order of the strip width W. Fig. 1 shows that the oscillations of the resonant frequency correlate fairly well with the calculated spatial small-scale structure of the current distribution in the strip.

From the numerical calculations [5,6] performed for particular configurations and sizes of microstrip lines it is difficult to discover a mechanism responsible for the effect of significant retardation in the SMR, which corresponds to the short characteristic length of the small-scale spatial modulation. The mathematical model of a strip resonator was developed previously, in which the irregularities of the geometrical dimensions along the propagation direction of electromagnetic wave [7] were taken into account. To describe the mechanism of retardation in the SMR from the results of this model one can conclude that the found small-scale modulation is a consequence of features of the boundary conditions on the fine edges of the strip. Near these edges, the orthogonal curvilinear system of coordinates introduced to solve the problem for the boundary geometry has a high degree of curvature. This leads to a local dependence of the phase velocity on the Lamé coefficients (metric coefficients) of the curvilinear system of coordinates and can cause its significant decrease. The decrease of a phase velocity is equivalent to a local increase in permittivity or permeability in the region of high curvature. The model developed in [7] allows to illustrate the effect of strip edges if we consider the propagation of the curvilinear transverse wave (in the orthogonal curvilinear system of coordinates) in the radial direction. In this case, a resonator is a section of a regular stripline shortened on the ends Z_1 and Z_2 by metal boundaries (the fundamental curvilinear TM mode). Then the simple interchange of the radial and longitudinal coordinates in the equations obtained in [7] for the curvilinear system of coordinates of cylindrical type gives a dependence of the phase velocity on the curvilinear radial coordinate $\Re$:

$$v(\Re)=\left[\frac{\int_{Z_1}^{Z_2}\oint\delta(\Re,\Phi)\beta(\Re,Z)\,\mathrm{d}Z\,\mathrm{d}\Phi}{\mu\mu_o\varepsilon\varepsilon_0\int_{Z_1}^{Z_2}\oint h_{\Re}^2(\Re,\Phi,Z)\delta(\Re,\Phi)\beta(\Re,Z)\,\mathrm{d}Z\,\mathrm{d}\Phi}\right]^{1/2}, \quad (1)$$

where $h_{\Re}$ is the Lamé coefficient, δ and β are functions related to the Lamé coefficients [7], and μ and ε are the relative permeability and permittivity of the insulator, respectively. This expression indicates that the phase velocity depends on a degree of curvature (at a given value of $\Re$) via the Lamé coefficients. Also, we obtained a relation between the Lamé coefficients and, for example, a nonuniform permittivity $\zeta(r,\varphi,z)$ in a regular coaxial line where the similar wave solution would appear:

$$z\mathscr{E}(r,z)\oint\varsigma(r,\varphi,z)\,\mathrm{d}\varphi=\varepsilon\delta(\Re,Z)\oint\frac{h_\Phi h_\Re}{h_Z}\,\mathrm{d}\Phi. \quad (2)$$

This relation demonstrates equivalence between a local value of the permittivity and a degree of curvature of the system of

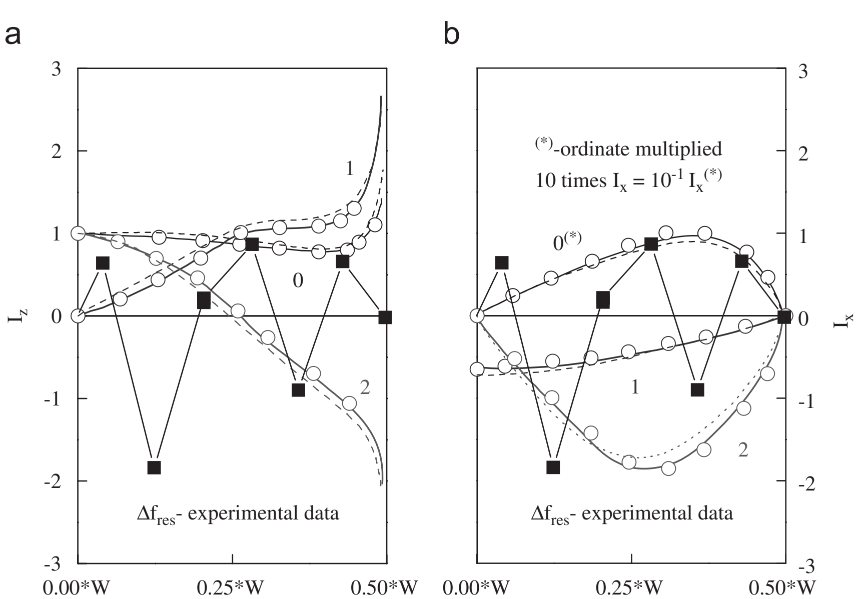

Fig. 1. Current distribution of the fundamental (0) and higher (1,2) types of the waves in the microstrip transmission line across the strip width (W) measured in the transverse direction (x) to the strip from its longitudinal axis (z), as calculated in [5,6], in comparison with the experimental shift of the resonant frequency (Δf_{res}) of the superconducting (Nb) microstrip resonator dependent on the position of the side face of the small (Cu) sample perturbing the SMR field.