SPATIAL DISPERSION AND NEGATIVE PERMITTIVITY EFFECTS IN SUPERCONDUCTORS

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ABSTRACT

Short-scale spatial modulation of the resonance field in a microstrip resonator revealed by experiment was used to study the spatial dispersion effects in dielectric properties of Nb and $YBa_2Cu_3O_7$ superconductors. The results show a negative sign of a real part of $\varepsilon(\omega,k)$ the dielectric permittivity, which absolute value drastically depends on configuration of the electric field, suggesting strong spatial dispersion effects in these materials.

1. INTRODUCTION

Early it was argued that superconductivity with a high T_c requires a negative value of $\varepsilon(0,\mathbf{k})$ the static dielectric permittivity at $\mathbf{k}\neq 0$ and that a positive sign of $\varepsilon(0,\mathbf{k})$ averaged over a wave vector $\mathbf{k}$ restricts T_c to a low value of order of 1 K [1-3]. It has been shown for the phononic pairing mechanism that the critical temperature can be expressed as

$$T_c = \Theta e^{-1/\lambda_{eff}} ,$$

where $k_B\Theta$ is the energy range near the Fermi level in which conduction electrons are attracted to one another, and λ_{eff} characterizes the attraction force. The index λ_{eff} can be written, following [1-3], as

$$\lambda_{eff} = \lambda - \mu^* = \lambda - \frac{\mu}{1+\mu \; ln\left(\Theta_F / \Theta\right)} ,$$

where Θ_F is the Fermi temperature, λ and μ are dimensionless coupling constants for the phonon (or exciton) attraction and Coulomb repulsion, respectively. Given this, in the simplest approximation (homogeneity and isotropy of the material, weak coupling)

$$\mu - \lambda = \frac{4\pi N(0)}{k^2 \varepsilon(0,k)} ,$$

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where $N(0)$ is the density of states at the Fermi level, and the factor $<1/k^2\varepsilon(0,\mathbf{k})>$ should be understood as a certain average of $k^2\varepsilon$ with respect to **k**. If this average is negative, the inequality $\lambda > \mu$ is possible and the parameter λ_{eff} can be positive, as reqired by the BCS model. The negative sign of $\varepsilon(0,\mathbf{k})$ may result from a contribution of the ionic (due to the electron-phonon coupling) component to the total static permittivity. It should originate from the presence of relatively strong local (acting) electric fields and spatial dispersion ($\mathbf{k}\neq 0$) effects in permittivity. From an experimental point of view, however, establishing the static dielectric properties in highly conducting systems is rather complicated, because the total permittivity is dominated by the conduction electrons. A method for a rigorous verification of spatial dispersion effects resulting in the change of sign of static dielectric permittivity in superconductors would be therefore of both fundamental and experimental interest.

2. PRINCIPLES OF EXPERIMENT

It seems to be possible to study these effects under quasistatic experimental conditions, namely when the characteristic wavenumber k of the spatial modulation of the external electromagnetic wave is high enougth to fulfil the relation to the Fermi velocity $v_F \geq \omega/k$ at the wave frequency ω. If this inequality is held, pronounced effects of the spatial dispersion may become visible in the electromagnetic response of a conducting medium.

In this work we observe for the first time that the dynamical fringing field effects in a microstrip resonator result in the short-scale (order of 100 times less than the wavelength) spatial modulation of the resonance field across the width interval of a resonant strip. We explore this fringing-field spatial modulation to look for and to compare the spatial dispersion effects in microwave permittivity of normal metal (Cu), low-T_c (Nb) and high-T_c ($YBa_2Cu_3O_7$ single crystal) superconductor samples.

3. EXPERIMENTAL TECHNIQUE

Experiments were performed in the Nb microstrip resonator schematically shown in Fig.1. We have measured the resonance frequency (f_p) of a microwave Nb microstrip resonator perturbed by Cu, Nb or $YBa_2Cu_3O_7$ sample as a function of the spatial position of the sample relatively to the resonant strip at frequencies around 9 GHz, between 4.2 and 300 K. All investigated samples had the same rectangular shape and dimensions (1.5×1.4×0.5 mm) and were measured at the same set of positions in a resonator. The sample position was characterized by the angle α (Fig.1) measured in a plane of the resonant strip off the polar axis, directed along the transverse axis of the strip, as described in detail previously [4].

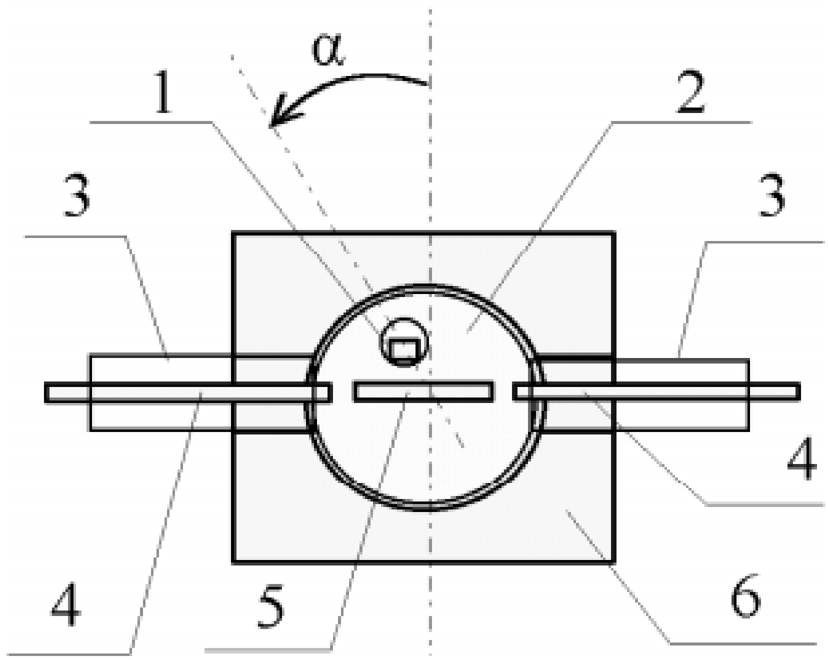

Figure 1. Scheme of the measuring symmetric microstrip Nb resonator. Top view without of the upper cap of Nb shielding: 1 - sample, 2 - teflon disks, 3 - teflon laminae, 4 - Nb-strip coupling lines, 5 - Nb-strip half-wave resonator , 6 - lower part of Nb-shielding cavity. A sample is inserted in a hole drilled in the upper teflon disk. Teflon parts are shown as if these would be light transparent.

4. SHORT-SCALE SPATIAL MODULATION OF THE MICROSTRIP RESONATOR FIELD

Intense oscillations of f_p are observed as the Cu sample moves across the width (1.5 mm) interval of a strip that corresponds to values of α over 40° in Fig.2. A sample can affect f_p via the contribution of its magnetic and/or electric dipole to the effective permeability (μ_{ef}) and permittivity (ε_{ef}) of a resonator according to the relation f_p^{-1}~$(\mu_{ef}\,\varepsilon_{ef})^{1/2}$. Experimental values of $\varepsilon_{ef}^{1/2}$ and l_{ef} (the effective length l_{ef} ~$\mu_{ef}^{1/2}$) of a resonator [5] show (Fig.3) the strong correlation of the l_{ef} and f_p^{-1}, indicating to the dominant contribution of the Cu sample magnetic dipole which affects the short-scale (~300 μm) spatial modulation of the unperturbed resonance field. The highest amplitudes of the oscillations correspond to the sample positions in which the side-wall of a conductive sample crosses the loop of the unperturbed resonant electric field which is tangential to the side-wall surface.

5. SPATIAL DISPERSION OF PERMITTIVITY IN SUPERCONDUCTORS

The f_p behavior (Fig.2) and associated variations of the $\varepsilon_{ef}^{1/2}$ and l_{ef} (Fig.3) exhibit remarkable difference in dielectric properties between superconductor and non-superconductor samples, as well

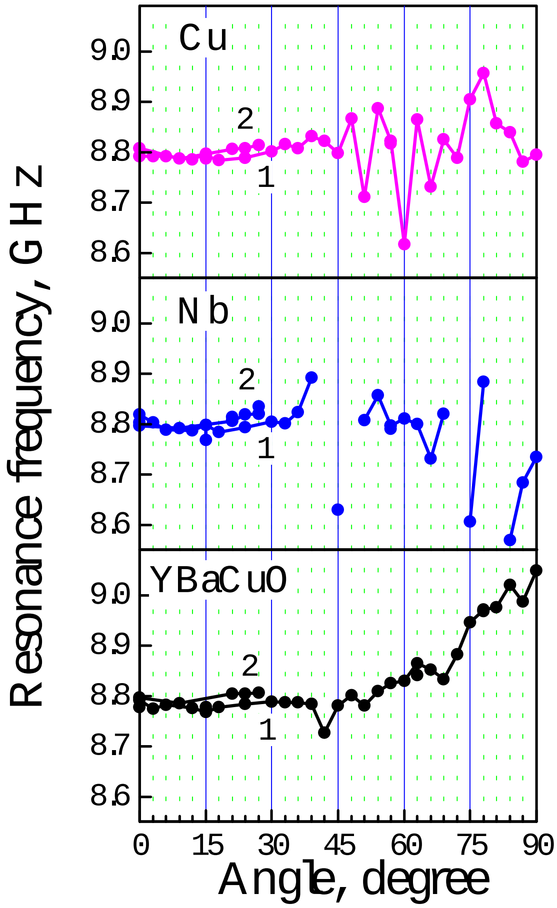

Figure 2. Center frequency for different positions of Cu, Nb and $YBa_2Cu_3O_7$ sample in microstrip resonator measured at T=5 K for two (1, 2) resonators.

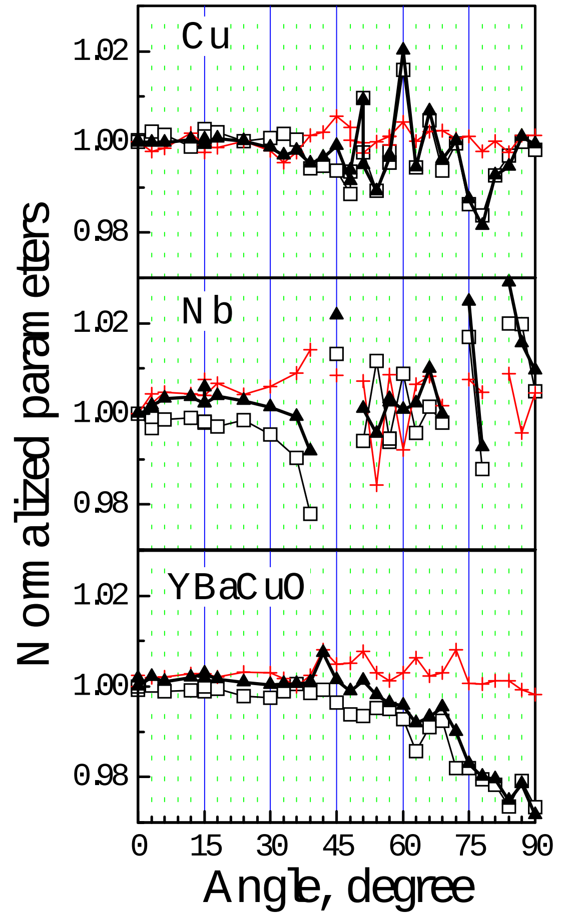

Figure 3. Normalized values of f_p^{-1} (triangle), $\varepsilon_{ef}^{1/2}$ (cross) and l_{ef} (square) corresponding to Fig.1.

as between low-T_c and high-T_c superconductors. Data of Fig.3 demonstrate the significant effect of the superconductor electric dipole ($\varepsilon_{ef}^{1/2}$) on f_p^{-1}, which depends strongly on the spatial position of samples. The results reveal a negative sign of the real part of $\varepsilon(\omega,\mathbf{k})$, which absolute value drastically depends on local configuration of the electric field, suggesting strong spatial dispersion effects in Nb and HTSC. Rather smooth $f_p(\alpha)$ dependence for the $YBa_2Cu_3O_7$ sample compared with the divergent behavior of the Nb sample (Figs.2 and 3) points to the nonlinear material properties of HTSC [4].

REFERENCES

1. “High temperature superconductivity” ed. by V.L. Ginzburg and D.A. Kirzhnits, Consultants Bureau, New York - London (1982).
2. O.V. Dolgov, E.G. Maksimov, Uspehi Fiz. Nauk [Soviet Phys. Uspekhi], v.138, No.1 (1982) 95.

3. V.L. Ginzburg, Contemporary Physics, v.33 (1992) 15.
4. E.M. Golyamina, V.A. Dravin, B.G. Zhurkin, A.L. Karuzskii, A.N. Lykov, and V.N. Murzin, Kratk. Soobsh. Fizike FIAN, Nos.5-6 (1993) 17 [Bulletin of the Lebedev Phys.Inst., No.5 (1993) 13].
5. V.A. Dravin, A.L. Karuzskii, A.E. Krapivka, A.V. Perestoronin, N.A. Volchkov, B.G. Zhurkin, Proc. 5th Int. Symp. Rec. Adv. Microwave Technol., ed. by B.S. Rawat and K.S. Sunduchkov, Kiev, Ukraine (1995), Pt.2, 725.