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Andrei Pimenov, Artem V. Pronin, Bernd Schey, Bernd Stritzker, Alois Loidl

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Submillimeter-wave conductivity of $YBa_2Cu_3O_{7-\delta}$ film

A. Pimenov[a,*], A.V. Pronin[b], B. Schey[a], B. Stritzker[a], A. Loidl[a]

[a] *Institut für Physik, Universität Augsburg, Universitätsstr. 2, D-86135 Augsburg, Germany*
[b] *Institute of General Physics, Russian Academy of Science, Moscow, Russian Federation*

Since the discovery of the high-temperature superconductivity (HTSC) [1] the most intensively discussed question is concerned with the physical mechanism lying behind this phenomenon. The investigations of the dynamical conductivity of superconductors below the gap frequency may help to solve this problem because they supply informations about low-lying excitations in the superconducting state. The existence of the coherence peak in the temperature dependence of the real part of the low-frequency conductivity was one of the important predictions of the BCS theory of superconductivity [2]. This peak is a well-established feature of the conventional superconductors, such as Nb or Pb [3, 4]. The similar coherence peak-like behaviour is observed in the temperature dependence of the conductivity of high-temperature superconductors at frequencies to 1 THz [5–16]; for a review see Ref. [17]. The peculiar feature of the dynamical conductivity of HTSC, observed at low frequencies, is the two-peak structure [8–10, 16, 18]. The temperature dependencies of σ' reveals a narrow peak at $T = T_C$ and a broad maximum at lower temperatures. By now it is well established that two main effects are responsible for the existence of the narrow peak that is normally observed for a frequencies below 100 GHz: the fluctuation effects and the possible distribution of the superconducting transition temperatures in the sample [18]. Concerning the broad maximum at low temperatures, it is still a matter for discussion whether this effect corresponds to the BCS coherence peak and can be explained within the modified version of the theory [14], or using the d-wave

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* Corresponding author. Tel.: + 49-821-598-3605; fax: + 49-821-598-3649; e-mail: Andrei.Pimenov@Physik.Uni-Augsburg.DE.

symmetry of the pairing state [19]. The d-wave models predict the existence of the maximum in the temperature dependence of conductivity for some concrete set of parameters, but, in addition, the d-wave symmetry results in a few principal differences compared to the conventional s-wave theory: at first, the real part of the low-temperature conductivity saturates at low temperatures at a value $\sigma'_0 = (ne^2/m)(\hbar/\pi\Delta)$ [20] which is independent of the scattering mechanism and approximately a factor of $\xi/\ell \sim 0.1$ smaller than the conductivity in the normal state; and secondly, the penetration depth $\lambda(T)$, or, equally, the imaginary part of low-frequency conductivity $\sigma''(T)$ should reveal a power-law dependence at low temperatures: $\lambda(T) - \lambda(0) \sim T^{\alpha}$ with an exponent $1 \gtrsim \alpha \gtrsim 2$ depending upon the parameters of the theory [19].

In this paper, we present the results of our submillimeter measurements of a thin $YBa_2Cu_3O_{7-\delta}$ film on the MgO substrate. The experiments have been carried out in the frequency range 80 GHz $< \nu <$ 960 GHz and at temperatures 3 K $< T <$ 300 K.

The c-axis oriented twinned $YBa_2Cu_3O_{7-\delta}$ film with 85 nm thickness was prepared using pulse-laser deposition technique as described elsewhere [21]. The film was characterised employing an inductive 3ω-method [22] and shows the transition temperature $T_C = 85.9$ K and a critical current density $j_C = 5.6 \times 10^5$ A/cm^2 (77 K). The four-point DC resistivity shows a linear temperature dependence in the normal state with $\rho(300\ \mathrm{K})/\rho(100\ \mathrm{K}) = 2.8$ and $\rho(100\ \mathrm{K}) = 79\ \mu\Omega$ cm, which is quite typical compared to the literature data [23]. The resistive transition width (10–90% resistance) was 1.2 K. The slightly lower value of the transition temperature and approximately 1.5 times larger penetration depth ($\lambda = 230$ nm, see below) are possibly due to some oxygen deficiency of the film.

In the frequency range from 80 to 960 GHz transmission measurements were performed using a coherent source spectrometer [24] utilising a set of backward wave oscillators as monochromatic but continuously tuneable sources. The interferometer is set up in a Mach–Zehnder arrangement which allows for measuring both the amplitude and the phase of the transmitted signal. Compared to the microwave cavity technique this method provides the measurement of absolute values of the film properties and the results are obtained continuously in a certain frequency range. The optical parameters if the MgO substrate are determined by repeating the experiments on a blank substrate. Using the Fresnel's formulae for the two-layer system [25], the conductivity and the dielectric constant of the film are evaluated by simultaneously analysing the observed transmission amplitude and phase shift without assuming any particular model.

Fig. 1 shows the measured transmission and the phase shift of the film–substrate system at room temperature. The oscillations seen in the spectra arise due to the interference of the radiation, reflected from the opposite surfaces of the substrate. The substrate–film system thus resembles the asymmetrical Fabry–Perot resonator. The solid lines in Fig. 1 present the results of the fit assuming frequency-independent conductivity of $YBa_2Cu_3O_{7-\delta}$ film.

The frequency dependence of the complex conductivity of $YBa_2Cu_3O_{7-\delta}$ film is presented in Fig. 2. Far above the superconducting transition temperature, the real part of the conductivity (lower frame) is frequency independent and increases with the decreasing temperature. At temperatures near the superconducting transition (curve $T = 90$ K in the lower frame of Fig. 2) one observes a weak frequency dependence of $\sigma'(\nu)$. Below superconducting transition the frequency dispersion of the conductivity is stronger and increases with decreasing temperature. We were not able to investigate this frequency dependence in detail because of the relatively high imaginary part of the conductivity $\sigma''(\nu)$ below 50 K ($\sigma'/\sigma'' \sim 0.2$), which masks the influence of the real part of the conductivity in the transmission spectra. This explains the high error bars in the 6 K curve. The points at this temperature are the averaged values in the frequency range of one BWO-source.

The imaginary part of the conductivity $\sigma''(\nu)$, shown in the upper part of Fig. 2, equals zero within the experimental accuracy in the metallic state. Below the transition temperature σ'' increases sharply and shows a distinct frequency dependence. The simple relation $\sigma''(\nu) \sim \nu^{-1}$ is expected within the standard BCS theory. The solid lines in Fig. 2 indicate this power-law behaviour with an exponent $s = 1$, and the discrepancies with the

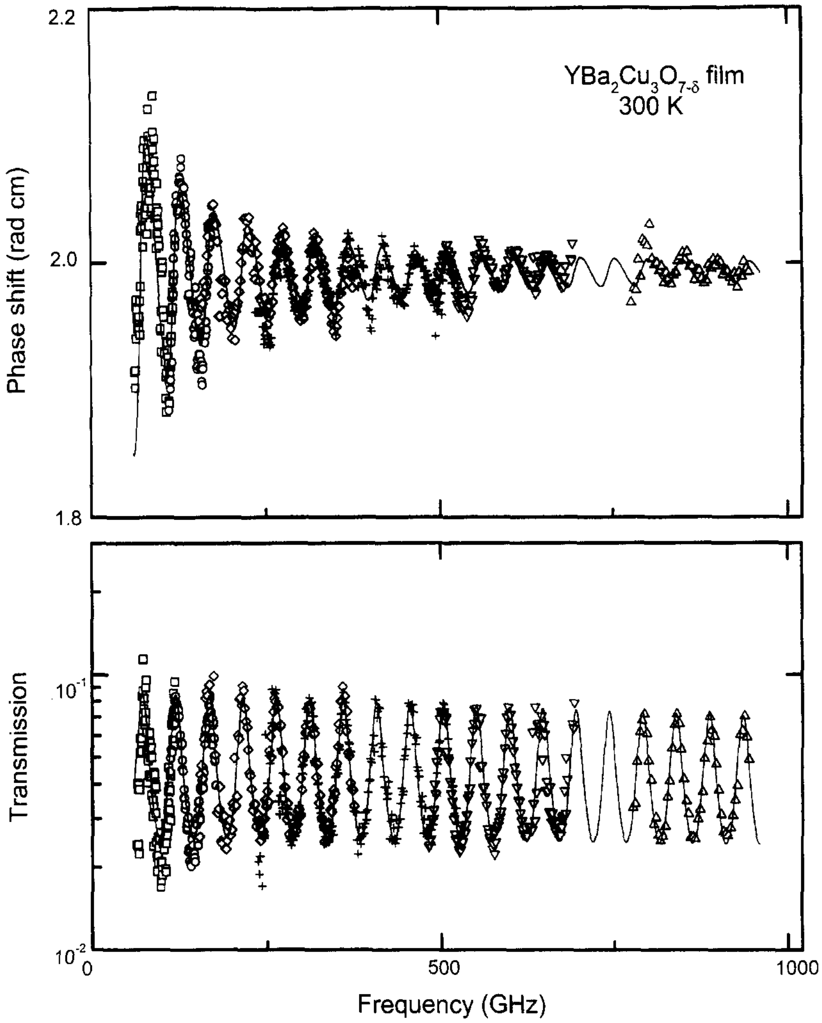

Fig. 1. Transmission and phase shift (φ/ν) of a $YBa_2Cu_3O_{7-\delta}$ thin film on a MgO substrate at room temperature. Different symbols correspond to the measurements with different BWO-sources. The fits are calculated assuming the frequency-independent film conductivity.

experimental data are evident. Better fits could be obtained with an exponent $s = 0.65 \pm 0.1$. Qualitatively, the discrepancies imply, that the effective density of the superconducting carriers decreases with increasing frequencies because $\sigma'' \sim n_s/\nu$ and the superconducting gap partially opens even in our frequency region ($\hbar\omega/\Delta(0) \sim 0.1$). Recently, Jiang et al. [26] have calculated the imaginary part of the complex conductivity of a d-wave superconductors. They have shown, that at small frequencies relative to the gap frequency, one expects an additional contribution to the conductivity. As a first approximation this term can be taken as a constant at low frequencies and becomes significant at frequencies above some hundred GHz [26] and may explain the observed deviations.

Fig. 3 shows the temperature dependence of the complex conductivity at 600 GHz. Also shown are the surface impedance, calculated according to the expression $R - iX = (\mu_0\omega/i\sigma^*)^{1/2}$ and the penetration depth, defined as $\lambda = \mathrm{Re}[\mu_0\omega\sigma^*/i)^{-1/2}]$. As mentioned above, in the metallic state σ' increases

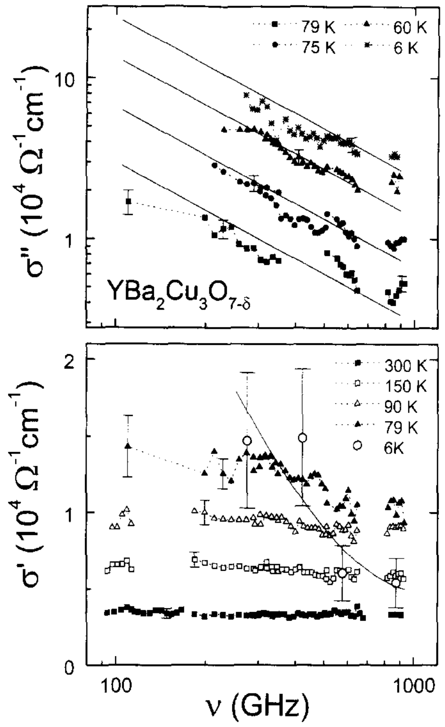

Fig. 2. Frequency dependence of the complex conductivity of $YBa_2Cu_3O_{7-\delta}$ thin film at different temperatures. Upper frame: Imaginary part of the conductivity. The lines indicate $\sigma'' \sim \nu^{-1}$ as expected from BCS theory. Lower frame: Real part of the conductivity. For the experimental data at 6 K the line is a guide to the eye.

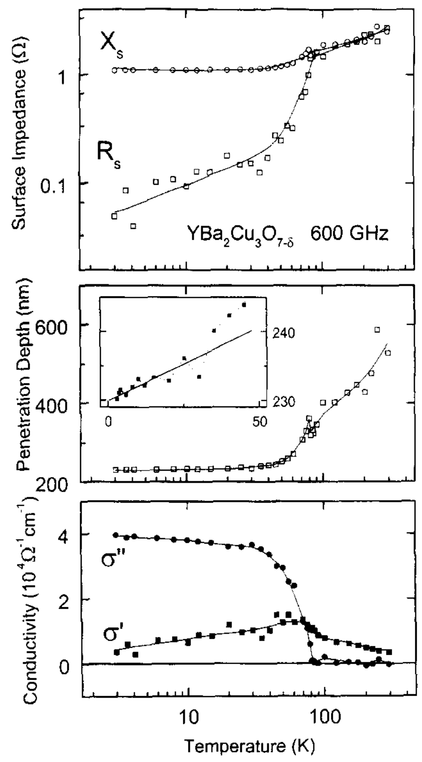

Fig. 3. Temperature dependence of the submillimeter-wave properties of $YBa_2Cu_3O_{7-\delta}$ film at 600 GHz. Lines are guide to the eye. Upper frame: surface impedance. Lower frame: complex conductivity. Middle frame: penetration depth, as defined in the text. The insert demonstrates the linear low-temperature behaviour of the penetration depth.

with decreasing temperature corresponding with the linear temperature dependence of the resistivity. In the superconducting state the real part of conductivity shows a maximum near 50 K and then slowly decreases. This maximum is qualitatively similar to the BCS coherence peak. The important difference is that the decreases of σ' is not an exponential function at low temperatures as in BCS theory and, in addition, we observe the nonzero values of σ' even at lowest accessible temperatures of about 3 K. The real part of conductivity seems to saturate at a value of $(3.5 \pm 1) \times 10^3\,\Omega^{-1}\text{cm}^{-1}$. This value is in good agreement with the theoretically expected limiting value σ'_0 [20]. The evaluation of σ'_0 can be done within the local clean approximation, because in that case the London penetration depth $\lambda(0)^{-2} = \mu_0 ne^2/m$. Using the experimentally obtained $\lambda(0) = 230$ nm, and the estimation $\Delta(0) \sim 2kT_C$ for our film, we obtain $\sigma'_0 \sim 2 \times 10^3\,\Omega^{-1}\,\text{cm}^{-1}$, which is in good agreement with the experimental value. The similar limit of the low-temperature values of σ' has been obtained for a $YBa_2Cu_3O_{7-\delta}$ single crystal at frequency of 34.8 GHz by Zhang et al. [11].

An estimate of the effective scattering rate in the metallic state can be obtained within the Drude model: using $\sigma = ne^2\tau/m = \tau/\mu_0\lambda(0)^2$ in the low-frequency limit, we get $\tau^{-1} = 12$ THz at $T = 90$ K. This value is in agreement with the data known from the literature [10, 12].

The temperature dependence of the submillimeter-wave penetration depth is shown in the middle frame of Fig. 3. The limiting low-temperature value of the penetration depth is $\lambda = 230$ nm.

The insert demonstrates, that at lowest temperatures $\lambda(T)$ is approximately linear ($\alpha \approx 1$) in contrast with the exponential behaviour, expected in BCS theory. This observation is quite common in the high-temperature superconductors [10, 11, 16], although other temperature dependencies have also been reported [9, 27].

In conclusion, we have measured the complex conductivity of $YBa_2Cu_3O_{7-\delta}$ thin film on MgO substrate at frequencies 80–960 GHz and at temperatures 3–300 K. The parameters of the film have been calculated from the measured complex transmission coefficient using the exact optical formulae for the two-layer system. At low temperatures we observe the saturation of the real part of conductivity, in agreement with the predictions for d-wave superconductors. The frequency dependence of the imaginary component shows deviations from the behaviour, expected from the BCS theory. These deviations can be qualitatively accounted for assuming the d-wave superconductivity.

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