Microwave Fabry-Pérot Transmission through YBaCuO Superconducting Thin Films

H. E. Porţeanu, K. Karraï, R. Seifert, F. Koch, P. Berberich, and H. Kinder
Physik Department, Technical University of Munich, 85747 Garching, Germany
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Transmission measurements of 35 GHz microwaves through two 200 nm YBaCuO films are performed in the temperature range between 7 and 100 K. The films are facing each other parallel in such a way that resonant Fabry-Pérot transmission is made possible. From the amplitude and the frequency width of the resonance, the values of the London penetration depth and the Ohmic losses are obtained independently for the first time in an absolute way over the whole temperature range below T_c.

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The electron pairing mechanism responsible for high T_c superconductivity is to date unexplained and remains one of the most challenging problems of this end of the century in solid state physics. One important step toward sorting between possible mechanisms is to determine the symmetry of the probability amplitude of finding a Cooper pair with a quasimomentum k, namely, the order parameter $\Delta(k)$. In particular, if Δ does not have the symmetry $k_x^2 - k_y^2$ (i.e., the d-wave symmetry), spin fluctuation pairing mechanisms are then unlikely [1]. The most convincing test for d-wave pairing relies on the measurement of the phase of Δ rather than on its amplitude. A quantum interference experiment carried out by Kirtley *et al.* [1] and Tsuei *et al.* [2] on YBaCuO demonstrated convincingly that more than 97% of the order parameter has a d-wave symmetry. d-wave pairing implies the existence of nodes in the superconducting energy gap, since $\Delta = 0$ for $k_x^2 = k_y^2$ (i.e., along the lines 45° away from the Cu-O bonds).

A direct consequence resulting from the existence of such nodes is that thermal breaking of Cooper pairs into normal carriers does not follow an exponential activation at temperatures $T \ll T_c$. The London screening length λ_L reflects directly the fraction of paired carriers. A test for the evidence of nodes Δ can be, in principle, obtained by measuring the temperature dependence of λ_L. Microwave measurements on $Nd_{2-x}Ce_xCuO_{4-y}$ single crystals (a high T_c electron doped superconductor) show that λ_L is exponentially activated at $T \ll T_c$ [3]. This result is consistent with $\Delta(k)$ of s-wave symmetry with a constant superconducting energy gap. In contrast, microwave cavity perturbation measurements performed on small pure YBaCuO twinned single crystals show a linear temperature dependence of λ_L [4] at $T \ll T_c$. On the other hand, measurements obtained on high purity $Bi_2Sr_2CaCu_2O_8$ single crystals [5], on thin YBaCuO films [5], on polished YBaCuO crystals, and on Zn doped twinned single crystals [4] show that, at $T \ll T_c$, λ_L has a quadratic dependence with T.

Most of such results are based on microwave cavity perturbation measurements providing most often the relative changes in the real and imaginary parts of the dynamical conductivities $\sigma_1(\omega)$ or $\sigma_2(\omega)$ relative to their lowest temperature counterpart. In this work we present a new sensitive experiment allowing us to measure in an absolute way both $\sigma_1(\omega)$ and $\sigma_2(\omega)$ down to the lowest temperatures. From $\sigma_1(\omega)$ and $\sigma_2(\omega)$, the absolute values of $\lambda_L(T)$, as well the Ohmic losses expressed in terms of the surface resistance $R_s(T)$, are determined at microwave frequency $\omega = 2\pi f$.

In light or microwave transmission experiments, the measured signal rides over a zero background, making it possible to characterize the electrodynamical properties of the probed sample in an absolute way. This contrasts with the usually measured reflected microwave intensity which rides over an unknown and undesired reflection background. The basic idea of this proposed experiment is to measure the phase and amplitude of the electromagnetic radiation transmitted through a superconducting layer in order to obtain σ_1 and σ_2. One way of doing it is to perform an interferometric transmission measurement in which the wave transmitted through the film is mixed with the reference electromagnetic wave impinging on the film (i.e., homodyne detection) [6]. The problem related to such measurements is that, at microwave frequencies, the low temperature screening properties of a superconductor σ_2 overwhelms the lossy part of the conductivity σ_1. As a result of this, the transmittance which is a function of $\sigma_1 - i\sigma_2$ is mostly dominated by σ_2. This makes it difficult to measure the low temperature values of σ_1 [6–8]. The route we are taking instead is to measure the microwave power transmitted through two superconducting films placed in a Fabry-Pérot configuration. Because in their superconducting ground state the films have very little losses, a resonant transmission is expected when both films are placed parallel to each other and separated by a distance d for which the standing wave conditions are fulfilled [9]. In particular, when no losses are present in the film (i.e., $\sigma_1 = 0$), this Fabry-Pérot interferometer transmits on resonance 100% of the impinging radiation and the frequency bandwidth of the transmission is determined by σ_2, the screening properties of the superconducting mirrors. When Ohmic losses are present, and this even when $\sigma_1 \ll \sigma_2$, the transmitted power reduces

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dramatically. This indicates that with such a Fabry-Pérot interferometer σ_1 and σ_2 can be, in principle, determined independently and accurately from the measurement of both the amplitude and the frequency bandwidth of the resonant transmission peak. This is particularly well illustrated when the transmission (i.e., the transmitted power) is calculated in the case of an idealized model in which the film thickness δ is thin compared to the London penetration depth λ_L (i.e., $\delta \ll \lambda_L$) and for the low temperature condition $\sigma_1 \ll \sigma_2$. Within such a model, the resonant transmission peaks at f_0 and has a Lorentzian shape in frequency. Its amplitude on resonance is given by $T_{\max} = 1/(1 + Z_0\delta\sigma_1)^2$, while its full frequency width at half maximum Δf is given by the resonance quality factor $Q = f_0/\Delta f = (P\pi/4)(Z_0\delta\sigma_2)^2$, where $P = 1, 2, 3, \ldots$ is the order of the resonance and $Z_0 = \mu_0 c = 377\,\Omega$ is the vacuum impedance. An advantage of Fabry-Pérot resonant transmission measurements is the large signal levels compared to the transmission measured through a single film. This present technique is to be clearly distinguished from the dielectric waveguide Fabry-Pérot [10], where the wave is transmitted solely through a dielectric medium. The single superconducting layer transmission $T_{\rm SL}$ is easily calculated in the case of a lossless superconductor, where $Z_0\delta\sigma_2 = (\delta\lambda_{\mu W}/\lambda_L^2)/2\pi$. In the present experimental situation, for which λ_L is of the order of δ, and the microwave length $\lambda_{\mu W} \gg \lambda_L$, the result is $T_{\rm SL} = [4\pi(\lambda_L/\lambda_{\mu W})/\sinh(\delta/\lambda_L)]^2$. For a lossless 200 nm thin YBaCuO film for which $\lambda_L = 150$ nm at $T = 0$, we calculate that $T_{\rm SL} = 1.14 \times 10^{-8}$, which is 8 orders of magnitude smaller than the lossless resonant Fabry-Pérot transmission. As seen from the above formula, such a small value of $T_{\rm SL}$ is essentially due to the ratio $(\lambda_L/\lambda_{\mu W}) = 2\pi|Z_S/Z_0| \approx 10^{-4}$, which represents the mismatch between Z_0 and the wave impedance $Z_S \approx i39\,{\rm m}\Omega$ in the superconductor.

The simplified analysis we presented up to this point is derived for an unbound plane wave falling on infinitely extended films. In a real microwave experiment, film sizes are comparable to $\lambda_{\mu W}$. In order to avoid undesired transmission through diffraction around the films, it is necessary to confine the wave to an area smaller than the sample's diameter. Moreover, in order to reach optimal Fabry-Pérot constructive interference conditions, the impinging microwave should be prepared with a homogeneous phase front parallel to the films. In the present setup, the Fabry-Pérot resonator is bound laterally by cylindrical copper walls. The incoming (outgoing) microwave radiation is coupled from (to) a rectangular waveguide into (out of) the cylindrical sample space through appropriately placed coupling holes. Within the copper walls confinement, the electrical fields are circulary distributed in the plane of the sample (i.e., $\rm TE_{01}$). This in-plane field distribution ensures a homogeneous phase front. Furthermore, with such a $\rm TE_{01}$ field distribution, the electric fields are shorted at the plane of contact between the confining walls and the film inhibiting this way possible radiative electric dipole leakage through channels outside the films. Unfortunately, the copper confining walls are lossy and contribute not only to a dramatic reduction of the resonant transmission $T_{\max}$ below normal detection limits, but also to a saturation of Q, which would no longer depend on σ_2. Such a reduction in signal results from the large impedance mismatch between the vacuum and the superconducting samples as discussed above. In order to overcome this difficulty, a greater amount of microwave energy is stored before (and after) the Fabry-Pérot interferometer, inside two identical cylindrical side cavity resonators. The net effect of such a configuration is to obtain a better impedance matching of the waves at the superconductor interface, where now $|Z_S/Z_0|$ is replaced by $|Z_S/Z_M|$. With the present setup, we worked somewhat close to the matching condition by having the impedance of the side cavities $Z_M = 0.83\,\Omega$.

The measurements were performed on pairs of YBaCuO films with δ ranging between 100 and 300 nm. The samples were grown on 30×30 mm MgO substrates at 600 °C using a coevaporation method described in Ref. [11]. A T_c of 85 K was measured with a critical current density of $J_c \approx 3 \times 10^6$ A/cm^2. Both films were placed parallel to each other and separated by a 4.87 mm thick copper spacer ring confining the wave in a cylinder of $2r_0 = 21.7$ mm in diameter. Resonant transmission conditions are obtained for the first order Fabry-Pérot interference around $f_0 \approx 35$ GHz. Figure 1 shows a typical low temperature microwave transmission peak measurement, with $Q = 10^5$ and $T_{\max} = 0.3\%$, rising above a zero signal. Since the frequency width of the impedance matching cavities is about 2 orders of magnitude broader than that of the Fabry-Pérot resonance, its effect on the measured transmission peak can be safely neglected. The temperature dependence of the measured $T_{\max}$ and Q is plotted on Fig. 2 for a pair of YBaCuO films with $\delta = 200$ nm. Similar plots were obtained for

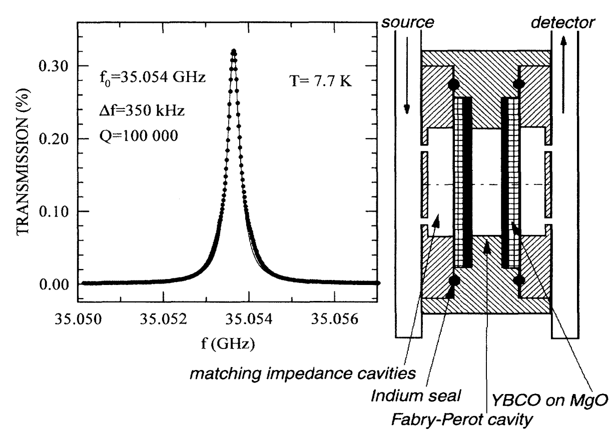

FIG. 1. Right: schematics of the Fabry-Pérot interferometer. Left: a typical resonant transmission peak for a pair of 200 nm YBaCuO films.

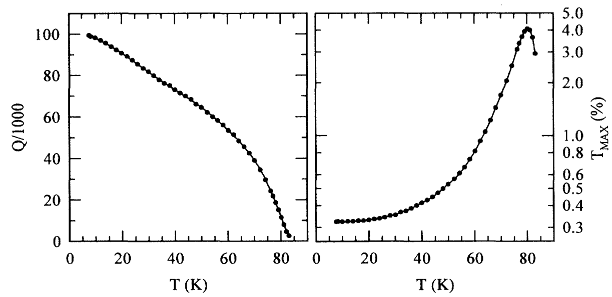

FIG. 2. The temperature dependence of Q and $T_{\max}$.

film thicknesses ranging between 100 and 300 nm. It is worth pointing out that contrary to what is normally expected for Fabry-Pérot interferometers with normal half silvered mirrors, the amplitude of the resonance reduces when the quality factor of the interferometer increases. This is simply due to the fact that, as the temperature decreases, the wave impedance Z_S in the superconducting films (which is dominated by σ_2) reduces, increasing consequently the impedance mismatch $|Z_S/Z_M|$.

In order to model the measured transmission, we have calculated the electric and magnetic field amplitudes of the radiation transmitted through a layered system comprising in the following order: the first film, the lossy copper wave confining spacer, and the second film. The spacer ring can be thought of as an effective homogeneous layer with losses. In the approximation of plane electromagnetic waves, the optical properties of a layered system is given by the product of transfer matrices of the type

$$\begin{pmatrix} \mathbf{E}_{N-1} \\ \mathbf{H}_{N-1} \end{pmatrix} = \begin{pmatrix} \cos(k_N d_N) & iZ_N \sin(k_N d_N) \\ iZ_N^{-1} \sin(k_N d_N) & \cos(k_N d_N) \end{pmatrix} \begin{pmatrix} \mathbf{E}_N \\ \mathbf{H}_N \end{pmatrix},$$

where for our three layer system the subscript N runs from 1 to 3. Such a matrix equation relates the electromagnetic field components (E_N, H_N) in the layer N at the interface between the layer N and $N + 1$ to their counterparts in the layer $N - 1$ at the interface between the layer $N - 1$ and N. The product of the three layer matrices relates the fields (E_0, H_0) at the input face of the interferometer to (E_3, H_3) at its output side. It is convenient to relate such fields to the electric field component of the incoming wave E_i using the wave amplitude transmittance t and the reflectance r of the layered system. This writes $E_0 = (1 - r)E_i$, $H_0 = E_i(1 + r)/Z_M$, $E_3 = tE_i$, and $H_3 = E_i t/Z_M$, where Z_M is the wave impedance of the matching cavities. The power transmitted through the Fabry-Pérot structure is then simply obtained computing $T_{\mathrm{FP}} = |t|^2$.

The electrodynamic properties of each layer N of thickness d_N is entirely defined through the wave vector k_N and its wave impedance $Z_N = \omega\mu/k_N$. The wave vectors in the pair of superconducting films are given by $k_1 = k_3 = (-i/\lambda_L)[1 + 2iR_s/\omega\mu_0\lambda_L]^{1/2}$, where R_s accounts for their Ohmic losses in terms of surface resistance. In order to obtain the above relation for k_1 and k_3 we have made use of the usual expressions for the dynamic conductivity of a superconductor $\sigma(\omega) = \sigma_1 - i\sigma_2 = 2R_s/\omega^2\mu_0^2\lambda_L^3 - i/\omega\mu_0\lambda_L^2$. The wave confining spacer copper ring acts as a waveguide with a cutoff frequency of $f_c = 1.68$ GHz. As a consequence, the TE_{01} microwave mode confined in the spacer layer is almost transverse electromagnetic and behaves as a plane electromagnetic wave propagating in a medium of effective index $\gamma = [1 - (f_c/f)^2]^{1/2} \approx 0.88$ and of effective thickness $d_2 = d/\gamma$. This indicates that the standing wave condition in this Fabry-Pérot interferometer is given by d_2 and not by d. The wave vector in this effective spacer medium is given by $k_2 = -i\alpha + \gamma k_0$. The losses in the spacer ring walls are characterized by the attenuation $\alpha = R_{\mathrm{s}1}(f_c/f)^2/\gamma Z_0 r_0$, where $R_{\mathrm{s}1}$ is the surface resistance of the copper walls and r_0 the inner radius of the spacer ring.

The resonant transmission peak calculated using this model is found to have a Lorentzian shape as shown by the fit obtained in Fig. 1. The values of R_s and λ_L are determined by using the measured values of $T_{\max}$ and Q in the model as input parameters. The resulting $R_s(T)$ and $\lambda_L(T)$ for a pair of 200 nm YBaCuO films are shown in Figs. 3 and 4. Since $R_{\mathrm{s}1}$ and the impedance Z_M of the matching cavities were used as parameters in the model, both were independently measured. The surface resistance $R_{\mathrm{s}1} \approx 48$ mΩ of the copper ring spacer was measured by replacing the pair of superconducting films by two copper plates with known surface resistance, each having a 1 mm coupling hole placed at $r_0/2$ from the axis. $T_{\max}$ in this setup, in contrast with the superconducting films, increases together with Q, as expected from a more traditional Fabry-Pérot interferometer. We estimate the uncertainty on the measured value of $R_{\mathrm{s}1}$ to be of about 10%, which corresponds to a 0.04 nm error on the 7 K value of λ_L and to 0.2 mΩ error on R_s. The impedance Z_M of the impedance matching cavities was also determined by measuring their quality factor which varies between 2000 and 3000 over the whole temperature range of interest. The uncertainty on the value of the measured matching impedance corresponds to a 3 nm

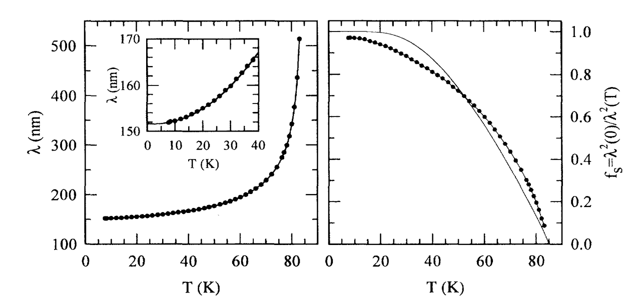

FIG. 3. The temperature dependence of λ_L and f_s. The thin line in the right panel is calculated using the BCS model. The data in the inset of the left panel are fitted to a parabola.

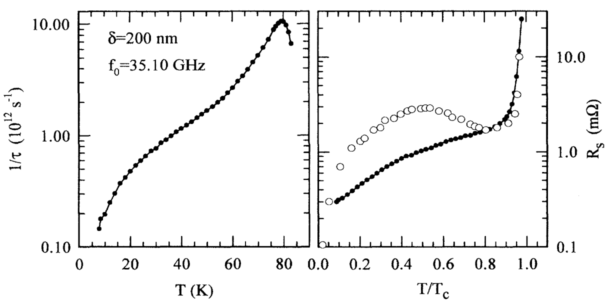

FIG. 4. The temperature dependence of $1/\tau$ and R_s. The pure single crystal R_s data [4] are plotted as open circles.

error value of λ_L and to 0.05 mΩ on R_s. We note that the dielectric function of the substrate is implicitly included in the measured value of Z_M.

A calibration point of the signal in terms of absolute transmission was also necessary. Since the resistivity of the normal state YBaCuO at 100 K is of the order of 100 $\mu\Omega$m or even larger, the calculated resonant transmission is found to be $T_{\max} \geq 0.98$. Therefore the $T_{\max} = 1$ was calibrated against the signal measured at $T > T_c$.

The uncertainty on the absolute transmission calibration obtained this way corresponds to a 2 nm error on the 7 K value of λ_L and to 0.03 mΩ on R_s. The accumulated uncertainties give an absolute error of ± 5 nm on the determined λ_L and of ± 0.3 mΩ on R_s. At this point we are confident that both R_s and λ_L are measured to a good level of accuracy down to the lowest temperatures.

The low temperature dependence of λ_L plotted in Fig. 4 is found to be quadratic in T and follows $\lambda_L(T) = (151.2 + 0.00979T^2)$ nm. This contrasts with the behavior reported in pure YBaCuO single crystals for which λ_L is linear in T [4]. However, Hardy *et al.* [4] have found that doping the YBaCuO single crystal with 0.31% Zn leads to a quadratic dependence of λ_L quantitatively similar to the one measured in the present work. This would suggest that the low temperature behavior of λ_L in YBaCuO thin films is dominated by defects. On the other hand, microwave measurements reported on pure $Bi_2Sr_2CaCu_2O_8$ single crystals [5] show a much stronger quadratic dependence of λ_L on T. The surface resistance R_s is shown in Fig. 4 together with the results obtained on a pure YBaCuO single crystal measured in a similar frequency range. However, in this case too, our results for R_s are found to be in better agreement with data obtained on 0.31% Zn doped YBaCuO crystals [4].

The resonant transmission data are also analyzed in terms of a general two fluid model. In such a model, we define the dynamic conductivity $\sigma = f_s\sigma_s + (1 - f_s)\sigma_n$, where σ_s and σ_n are the conductivities of the superconducting and of the normal fluid, respectively, and f_s is the fraction of electrons condensed in the superconducting ground state. The real and imaginary parts of σ are simply given by $\sigma_1 = \sigma_0(1 - f_s)\omega\tau/[1 + (\omega\tau)^2]$ and $\sigma_2 = \sigma_0\{f_s + (1 - f_s)(\omega\tau)^2/[1 + (\omega\tau)^2]\}$, where $\sigma_0 = 1/\omega\mu_0\lambda_L^2(T = 0)$ and $1/\tau$ is the scattering rate of the normal state carriers. Using σ in the transmission model described above, we obtain the temperature dependence of f_s and $1/\tau$ as determined from the best fit to the transmission data. The results are plotted in Figs. 3 and 4. The dependence of f_s on the temperature shows an obvious deviation from the theoretical predictions for an isotropic s-wave model (i.e., the BCS theory) and this over the whole temperature range below T_c. The scattering rate $1/\tau$ of the normal fluid component decreases by 2 orders of magnitude with decreasing temperatures over the whole temperature range below T_c. This is a yet unexplained property of the normal state observed in YBaCuO single crystals [4] and in BiSrCaCuO crystals [12].

In conclusion, we have developed a novel high precision transmission measurement in order to study the low temperature dynamic properties of thin superconducting films over a wide temperature range. The results show that YBaCuO films have intrinsic losses much smaller than what is commonly reported in the literature [13], and their magnitude is comparable to the results obtained on single crystals. We have also performed an accurate measurement of the absolute value of the London screening length giving an upper value for YBaCuO of $\lambda_L(T = 0) = 151 \pm 5$ nm. This value could be possibly smaller for better quality YBaCuO films. The sensitivity of the Fabry-Pérot transmission interferometry to small changes in σ_1 and σ_2 shows that it is also suitable for magnetic field experiments such as vortex dynamic studies and the search for cyclotron resonance of the superconducting ground state.

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