Anisotropy in the Transparency of HTS Films at Millimeter and Submillimeter Microwave Radiation

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***Abstract*— The propagation of microwave radiation through $YBa_2Cu_3O_{7-\delta}$ and $Tl_2Ba_2Cu_1O_6$ films deposited on Al_2O_3, MgO, $LaAlO_3$ and LaSrAlTaO single crystal substrates, as well as through the bare substrates, has been studied in the 60-600 GHz frequency range. The angular dependence of the transmitted radiation was found to have a rather complicated structure. The dependence is affected by anisotropy of the substrate due to birefringence, resonance in substrate modes, non-homogeneity and the granular structure of the HTS film. To reduce reflections from the surface of the substrate, quarter-wave matching layers were used at selected frequencies. After correction for stray effects, the common feature is the presence of four maxima with a period of $\pi/2$ with four minima in between that can be due to the energy gap anisotropy in d-wave superconductors.**

***Index Terms*—Energy gap anisotropy, high-Tc superconductors, microwave transparency, transparency anisotropy.**

I. INTRODUCTION

THE Microwave transparency and reflectivity of thin HTS films is important for the design of microwave devices like mixers, detectors, antennas, resonators, filters, etc. At present most RF applications of HTS films and structures are developed for frequencies up to a few Gigahertz. When the frequency is increased the problem of losses becomes important and often it is preferred to use normal-metal elements instead of high-T_c superconductors. On the other hand, at least in theory, the HTS materials with their energy gap over one order of magnitude above the gap for low-T_c materials could be advantageous at frequencies up to several Terahertz. When speaking about conventional low-T_c superconductors the limiting frequency corresponds to the energy gap $f_g=2\Delta/h$ and does not depend on the polarization of the radiation. In high-T_c superconductors the angular dependence can be rather complicated and modify the reflectivity and transmittance patterns. The temperature dependent superconducting energy gap in Nb films has been studied earlier in [1] by measuring the complex conductivity spectra in the 150-900 GHz frequency range. Even in such conventional superconductors the increased absorption below the superconducting transition temperature may be caused by grain boundaries. Similar experiments were performed with $YBa_2Cu_3O_{7-\delta}$ (YBCO) films in [2] at frequencies up to 18 THz indicating peaks attributed to orthorhombic and tetragonal phases in the sample. A very useful model for interpretation of the experimental results is the Perot-Fabry Interferometer (PFI) model developed in [3] for two MgO plates coated with a thin YBCO film. An experimental peak transmission $T_m \approx 45\%$ and a Q-factor about 30 is a good reference point at frequencies around 900 GHz. This means that a superconductor PFI can achieve a transmission and finesse as good as the best classical PFI made of gold wires deposited on two parallel quartz surfaces.

A. *d-wave superconductor model*

The frequency dependence of the photoconductivity of a superconductor film is dependant on the energy gap. For a low-T_c film with s-wave symmetry the dependence is quite clear: The film reflects radiation at frequencies below the energy gap $f<2\Delta/h$ and transmits/absorbs radiation at frequencies above the gap. Due to the isotropic gap in s-wave superconductors the transparency of LTS film is independent of the radiation polarization. It can be expected that this will not be true for d-wave superconductors in which the energy gap is strongly anisotropic with four definite maxima and four minima (see Fig.1). Straightforward measurements of the angular dependence in HTS materials performed in [4]

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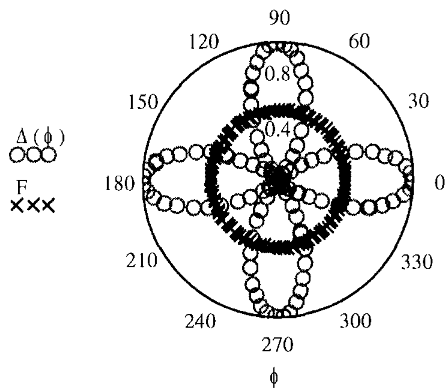

Fig. 1. The dependence of the energy gap on the angle for a d-wave superconductor (circles). Crosses show the energy corresponding to half of the maximum superconductor energy gap.

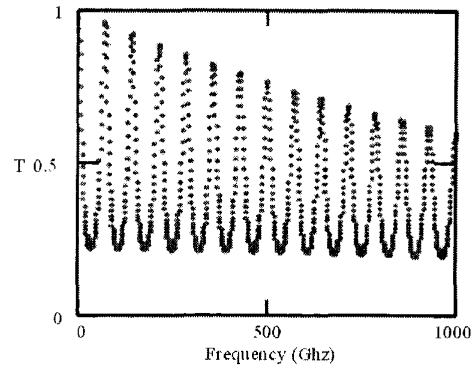

Fig 2. The dependence of the transparency on frequency for a Si substrate

by tunneling spectroscopy show a gap-dependence very similar to Fig. 1. This should modulate the dependence of reflection and transparency on the microwave radiation polarization angle. It should be mentioned that neither tunneling nor photoconductivity experiments can give us clear evidence of

the nature of this conductivity, because neither will show the difference in phase for different lobes of the superconducting order parameter. None of the methods can distinguish between anisotropic s-wave and d-wave symmetry [5].

B. Substrate resonator mode

The polarization dependence can be affected by anisotropy in the substrate material. This can further modulate the polarization dependence of the transparency coefficient of the film. One illustration of the influence of substrate resonance modes is the dependence of the propagation coefficient on the frequency in a pure substrate:

$$T_m = \frac{\left[(1-R_0)^2 + 4R_0(Sin\,\psi_0)^2\right]\cdot L(d)}{(1-R_0L(d))^2 + 4R_0\cdot L(d)\cdot\left(Sin\left(\psi_0 + 2\pi n\frac{d}{\lambda_m}\right)\right)^2}$$

In which d is the dielectric thickness, n=n'+ik the refraction index,

$$L(d) = \exp\left(-4\pi k_0\frac{d}{\lambda_m}\right),\quad R = \frac{(n-1)^2+k^2}{(n+1)^2+k^2},$$

and

$$\psi = \arctan\frac{2k}{n^2+k^2-1}$$

An illustration of this relation is given in Fig. 2 for a pure silicon substrate. One can see a periodic dependence that makes it possible both to estimate the real and imaginary parts of the dielectric constant of the substrate material.

For birefringent substrates the equivalent path distance varies with the angle between n_nd and n_ad, which gives an angular dependence for the transmitted signal for pure substrates and masks the angular dependence of HTS film transmittance.

II. Experimental Setup

One suitable detector for measurements with superconducting films is a Josephson detector that can be placed very close to the film to reduce losses. We use our quasioptical Josephson detector [6] that is placed just behind the film under test. The detector is operated in wideband mode, which means that the properties will be similar to an ordinary square-law detector. The detector temperature is kept close to 4.2 K even when we raise the temperature of the YBCO film. To avoid the influence of any anisotropy in the characteristics of oscillator, feedhorn, planar antenna or detector we designed and fabricated a rotation stage that allows us to rotate the sample under test without changing anything else. To reduce losses due to reflection quarter-wavelength antireflection layers were used at selected frequencies. At about 100 GHz a thin quartz substrate was used, and at 500 GHz a specific scotch tape serves as antireflection coating. A schematic drawing of the setup is presented in Fig. 3a and a photo of the inner parts of the cryostat in Fig. 3b. A thin-wire grid polarizer produces a high-Q polarized beam. For radiation focusing we use Teflon, Si and MgO lenses.

III. Samples

We have studied YBCO and $Tl_2Ba_2Cu_1O_6$ (Tl-2201) thin films deposited on Al_2O_3 (sapphire), MgO and LaSrAlTaO (LSAT) crystal substrates. Laser deposition give high-quality films with a critical temperature close to the bulk material. The morphology of the film is granular as one can see in Fig. 4. This means that for the dc and microwave currents there are regions of enhanced resistance at the grain boundaries.

The Josephson detectors were fabricated of similar films and contain a series array of Josephson bicrystal junctions integrated in log-periodic and double-slot planar antennas.

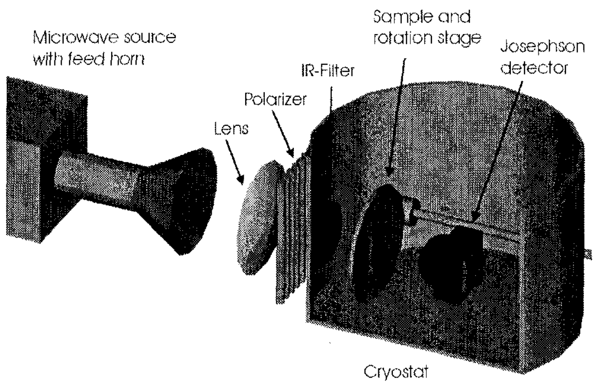

Fig. 3a. Schematic drawing of the experimental setup.

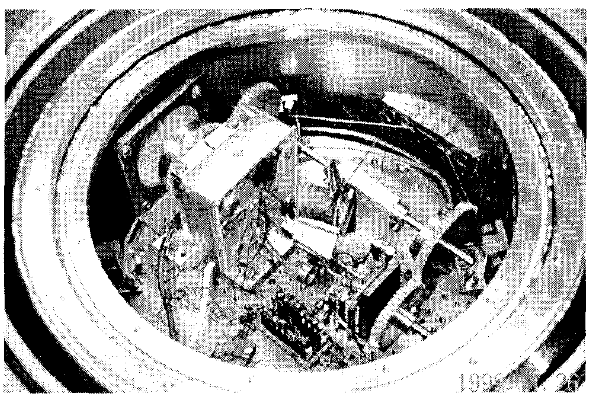

Fig. 3b. A photo of the opened cryostat with a rotation stage for substrate rotation and a quasioptical Josephson detector.

IV. Experimental Results

To estimate the influence of the substrate we first measured the transparency of the bare substrate without any film. Two typical cases are the LSAT substrate, which has a cubic lattice without anisotropy, and sapphire, which is a strongly anisotropic crystal with clear birefringence.

The next step was to measure the YBCO films on the same substrates. We measured 50 nm, 100 nm, 150 nm thick films at temperatures between 4.2 K and 100 K. When the film is deposited on an anisotropic crystal we will have a combination of two effects: Birefringence and energy gap anisotropy (see Fig. 5). Varying the substrate thickness, temperature and frequency one can extract the relatively clear dependence (see Fig. 6) with four maxima and four minima.

Sometimes it is not so easy to make a clear conclusion on the actual anisotropy; in some cases (see Fig. 7) the positions of maxima and minima at superconducting temperatures are rather complicated.

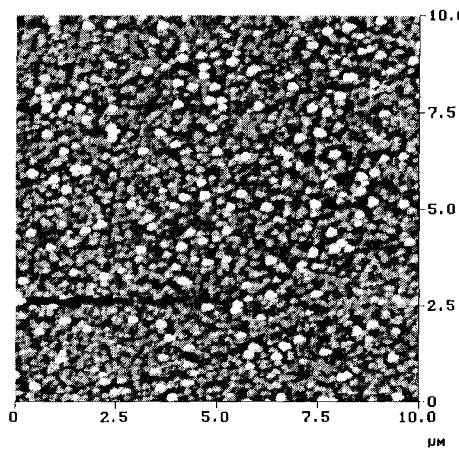

Fig. 4 Atomic Force Microscope image of a YBCO film deposited by laser ablation on a LAO substrate

This can be a result of the non-homogeneous structure of the film itself. The common feature for all samples was that with cooling down below the critical temperature of the sample the average signal goes down and the pattern becomes less uniform with pronounced maxima and minima. In general one can separate four main orthogonal maxima and four main minima between them. For comparison we measured a sample with several parallel scribes made on the YBCO film by a diamond scriber. Such artificial defects gives rise to a clear maximum in the detected signal for the polarization perpendicular to the scribes. A textured film with definite directions will show a similar dependence. The polarization measurements can also reflect the quality of the film. For example in our measurements on Tl-2201 films for a sample with a sharp R(T) dependence with ΔT_c about 1 K we observed a well pronounced angular dependence, while for a sample with a ΔT_c about 10 K the dependence was very smooth.

V. Discussion

The observed dependencies demonstrate the complicated nature of the transparency of YBCO films deposited on single crystal substrates. The YBCO film deposited on LSAT has a dependence that is in reasonable agreement with the assumed d-wave symmetry of the energy gap. However, when the YBCO is deposited on MgO the dependence is quite complicated although one can still see four maxima. This could in part be explained by a more complicated structure of the film itself (e.g. the presence of domains with in-plane misorientation). Finally, when using LAO substrate the dependence is even more complicated and asymmetry remains even at higher temperatures.

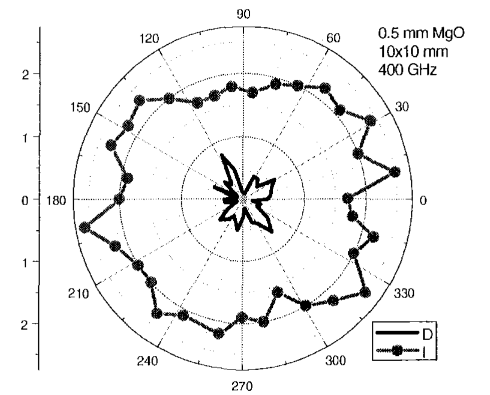

Fig. 5. The dependence of the transparency on the polarization angle for YBCO film on MgO substrate at two temperatures (D =4.2K, and I = 30K).

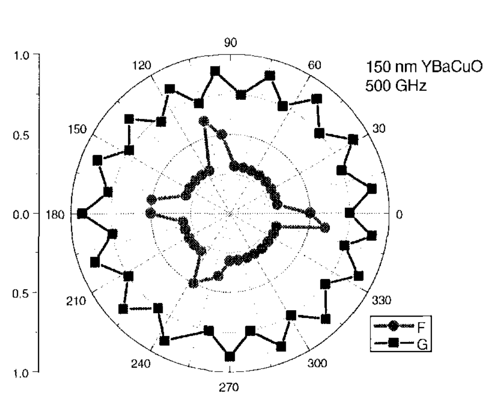

Fig. 6. Transparency of LSAT substrate with 150 nm YBCO film (curve F) and without film (curve G) at 500 GHz and 4.2 K.

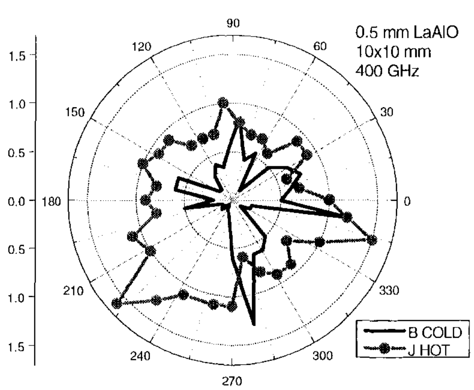

Fig. 7. Transparency of a YBCO film on LAO substrate at two temperatures (B=4.2K and J=30K).

The main features common to all measured samples are:
1. The YBCO films are partially transparent for microwave radiation in the frequency range 60-600 GHz.
2. The transparency is polarization dependent.
3. The dependence on polarization angle has, at least, four maxima and four minima.
4. The transparency can be affected by non-homogenous film structure.
5. Measuring the dependence of the transparency on the polarization can be an informative method for HTS film and crystal substrate characterization.

Reasons for polarization anisotropy could be energy gap anisotropy, irregularities in film structure, variations in penetration depth, interferometer effects in substrate modified by thin film, birefringence in dielectric material of substrate, etc.

VI. Summary

A high-T_c superconducting thin film deposited on a low-loss crystal substrate is transparent for microwave radiation at temperatures below the superconducting transition. The transparency varies in the range 0.01-0.3 depending on the polarization of the incoming radiation. The dependence on polarization angle has, at least, four maxima and four minima. One origin of such anisotropy can be the energy gap anisotropy that is predicted by theory for the d-wave high-T_c superconductors. Another reason can be the resonances in the substrate that can be affected by birefringence, imperfect alignment, etc. The transparency of the film is also sensitive to the granular structure of the film and to any irregularities and defects that change the conductivity between the grains.

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