Use of high T_c superconductors for far-infrared Fabry–Perot resonators

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(Received 12 July 1990; accepted for publication 5 September 1990)

In this letter we report on the application of high T_c superconductors for fabrication of far-infrared Fabry–Perot resonators. Thin films of $YBa_2Cu_3O_{7-\delta}$ deposited on MgO substrates by the laser ablation technique were used as reflectors. Two films on two different MgO plates were arranged parallel at a distance determining the lowest order resonance. We demonstrate operation of a resonator in a frequency range (up to about 300 cm^{-1}) in which MgO is transparent at low temperature.

Far-infrared Fabry–Perot resonators have been realized by use of metallic mesh[1] and are successfully applied in submillimeter astronomy[2] and far-infrared laser spectroscopy.[3] In this letter we demonstrate operation of a far-infrared Fabry–Perot resonator with reflectors of high T_c superconducting material; at zero temperature and at frequencies smaller than the gap frequency ideal superconductors are free of absorption and therefore superconductors at temperatures small compared to the superconducting transition temperature should be suitable for almost lossless Fabry–Perot resonators of ultrahigh finesse.

We have prepared $YBa_2Cu_3O_{7-\delta}$ thin films on (100) MgO crystal plates by laser ablation. The films grown *in situ* at a substrate temperature of 750 °C and an oxygen pressure of 0.25 mbar were oriented with the c axis perpendicular to the film plane. The resistivity ($\sim$300 $\mu\Omega$ cm at room temperature) showed a linear temperature dependence above T_c. Zero resistivity was reached at $T_c \approx 89$ K; the critical current was 10^5 A/cm^2 at 4 K. We constructed a Fabry–Perot resonator (Fig. 1) consisting of two MgO plates (thickness 1 mm, size 10×10 mm^2), each covered on one surface with a $YBa_2Cu_3O_{7-\delta}$ film (thickness $\sim$1000 Å). The films were separated by an aluminum distance ring and adjusted parallel by observing interference patterns in the beam of helium-neon laser light reflected from the film surfaces; there remained a deviation from parallelism of few μm.

For a discussion of properties of a Fabry–Perot resonator we neglect the substrate and consider two parallel, identical films of infinite lateral dimensions. For radiation of perpendicular incidence the transmissivity of the resonator is given by Airy's formula

$$\tau = \tau_{max}[1 + (4/\pi^2)F^2 \sin^2(\tfrac{1}{2}\delta)]^{-1}, \tag{1}$$

where τ_{max} is the maximum transmissivity, F the finesse, and $\delta = 4\pi\nu d + 2\Theta$ the phase shift of the radiation for one round trip in the resonator, Θ the phase shift for reflection at a film, d the distance between the films, and ν the frequency. The characteristic properties of the resonator depend on absorptivity A, transmissivity D, and reflectivity R of the single films, namely, $\tau_{max} = (1 + A/D)^{-2}$ and $F = \pi R^{1/2}/(1-R)$. Resonances occur for $\delta = z\times 2\pi$ where $z = 1,2,...$ is the order of resonance. The half-width of the zth resonance is $\Gamma_z = \nu_z/zF(\nu_z)$, where ν_z is the resonance frequency.

$YBa_2Cu_3O_{7-\delta}$ may be suitable for the fabrication of far-infrared Fabry–Perot resonators up to 400 cm^{-1}; up to this frequency very high reflectivity (R near 1) and small absorptivity have been observed for not too thin films[4–7] and single crystals,[8,9] so that low-loss Fabry–Perot resonators of high finesse seem to be feasible. At higher frequencies the reflectivity drops strongly because of onset of absorption; this may be either due to pair breaking,[9] corresponding to an energy gap $2\Delta(0)/k_BT_c \approx 6.4$,[4,5] or due to other absorption processes[7,10] of yet unknown origin.

We have measured far-infrared transmissivity with a Fourier transform infrared spectrometer at a resolution of 0.3 cm^{-1}. Samples were cooled with helium exchange gas in a temperature variable cryostat with polyethylene windows. Radiation was focused to a diameter of about 5 mm, the beam divergence was 15°, in a part of the measurements reduced to 7°. The transmissivity was determined from the ratio of the spectral intensities with and without sample in the spectrometer beam.

The transmissivity of a MgO plate at low temperature [Fig. 2(a)] is large and almost constant at small frequencies—it is mainly determined by reflection at the surfaces according to the static dielectric constant $\epsilon_s \approx 10$—and decreases at high frequencies according to the reststrahlen behavior due to an infrared active phonon at 400 cm^{-1}. The transmissivity of the plate covered with a $YBa_2Cu_3O_{7-\delta}$ film of about 1000 Å thickness [Fig. 2(b)] is about half a percent at small frequencies and decreases at high frequencies; the frequency dependence is determined by both film and plate. For conventional superconductors

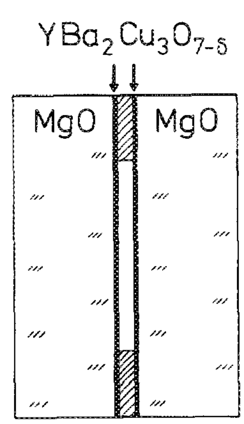

FIG. 1. Fabry–Perot resonator with $YBa_2Cu_3O_{7-\delta}$ thin-film reflectors.

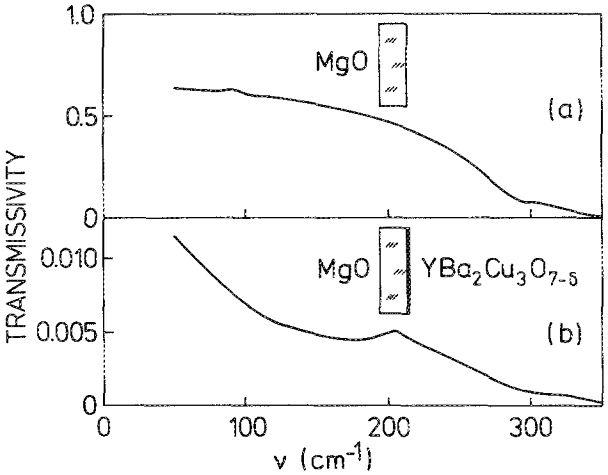

FIG. 2. Low-temperature transmissivity of a MgO plate of 1 mm thickness (a) without and (b) with $YBa_2Cu_3O_{7-\delta}$ film.

the transmissivity decreases towards low frequencies[11] while we found an increase (Fig. 2). The increase turned out to be sample dependent and seems to be connected with film quality.

The transmissivity of a Fabry–Perot resonator (Fig. 3) shows sharp resonances, corresponding to a film distance $d \approx 44\ \mu m$ and $\phi \approx \pi$. Each resonance consists of a series of modes (insert of Fig. 3) that are due to coupling of the main resonance (between the films) and the resonances in each MgO plate; the resonances in the MgO plates are of high order (~ 65) and low finesse (~ 4).

From the half-widths of the main resonances we find a finesse $F(100\ cm^{-1}) \approx 30$ and $F(200\ cm^{-1}) \approx 15$, while

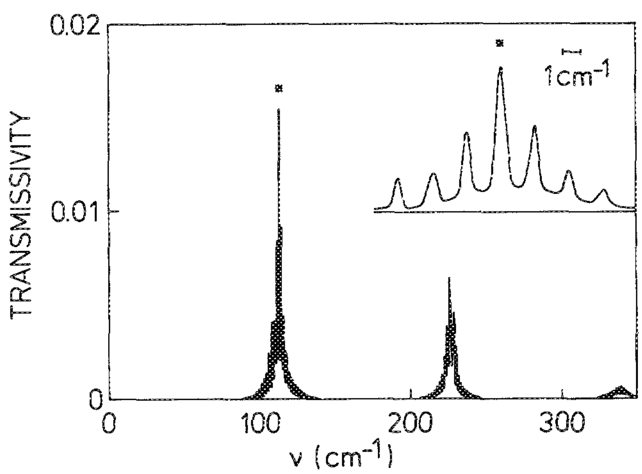

FIG. 3. Transmissivity of a far-infrared Fabry–Perot resonator consisting of two parallel $YBa_2Cu_3O_{7-\delta}$ films on MgO plates at 10 K; the mode structure (inset) is due to coupling of the resonances between the films and resonances in the plates.

direct reflectivity measurements give larger values. We suggest that nonparallelism of the reflecting surfaces is the main reason for a discrepancy for observed and expected finesse. The finesse of our Fabry–Perot resonator is by a factor of 4 smaller than the highest value reported for metal mesh resonators[2,3] and the maximum transmissivity is still quite small, $\sim 2\times 10^{-2}$ compared to values near 1/2 for mesh resonators.[2,3] an improvement of the geometric quality should already markedly improve the property of the superconducting Fabry–Perot resonator.

Our results show that Fabry–Perot resonators with reflectors of high T_c superconductors are promising devices for far-infrared spectroscopy. In comparison to conventional metal mesh Fabry–Perot resonators[1–3] the superconducting resonators should allow us to reach higher finesse because of the lack of ohmic losses, supposing that residual absorption in the films[5,6] can sufficiently be suppressed. There is a further advantage: While metal mesh are transparent at high frequencies[1] and low-pass optical filters have to be used for suppressing high-frequency radiation, superconducting resonators are opaque because of the onset of absorption due to Cooper pair breaking or other absorption processes and need no further low-pass filters.

In conclusion, we have demonstrated the use of high T_c superconductors for fabrication of far-infrared Fabry–Perot resonators. We note that the large superconducting energy gaps of high T_c superconductors are essential for these new devices: Far-infrared Fabry–Perot resonators present first applications based on the large energy gaps of high T_c superconductors.

The work was supported by the Bundesministerium für Forschung und Technologie.

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