Optical control of millimeter wave high T_c superconducting quasi-optical bandpass filters

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The optical response of $YBa_2Cu_3O_7$ high T_c superconducting quasi-optical millimeter wave bandpass filters operating at W band (75–110 GHz) has been investigated under various conditions of illumination. Radiation from a cw Ar^+ laser (514.5 nm) and a frequency-doubled Nd:YAG laser (532.8 nm, 120 ps) was used to induce a shift in the resonant frequency of the filter. A shifted Lorentzian line shape function model was used to estimate the magnitude of the light-induced changes. Shifts of the filter's resonance frequency on the order of 0. 1 MHz were induced by the laser effects on the superconductor pair population.

Since the discovery of high T_c superconducting materials, considerable work has been done on possible applications to microwave and millimeter wave devices. Experimentally successful devices fabricated from thin films include ring resonators,[1] transmission lines,[2] superconducting quantum interference devices (SQUIDs),[3] and tunnel junctions.[4] Recently, we reported the use of patterned high T_c superconducting thin films as quasi-optical millimeter wave bandpass filters.[5] These filters, fabricated from $YBa_2Cu_3O_7$ (YBCO), had a superior Q-factor at 90 GHz than similar filters fabricated using gold. Optical control of microwave propagation in superconducting devices has also attracted attention due to potential device applications such as microwave intensity modulators and phase shifters.[6] In this letter, we report the results of optical experiments performed on these quasi-optical bandpass filters. Our results show the effective millimeter wave response of the filter was modulated by laser radiation. The measurements indicated that the light increases the number of quasi-particles present when the film is illuminated. The effect of this increase in quasi-particle density is both to change the superconductor's kinetic inductance thus causing a shift in the filter's resonance frequency, and to increase the film's surface resistance thus causing a decrease in the filter's Q-factor. Recently, light-induced changes in the dc resistance of high T_c superconducting films were observed by applying a dc current to a high T_c superconducting stripline and measuring the light- induced change in the voltage drop across it.[7] A significant difference between our technique and other techniques is the fact that no electrical contacts are made to the film and as a result, fundamental film parameters at the millimeter wave frequencies can be measured directly.

The YBCO films (3000 Å to 5000 Å) were synthesized using the activated reactive evaporation (ARE) process onto $1'' \times 1'' \times 0.020''$ optically flat MgO substrates.[8] The surface resistance of these films was measured at 100 GHz using cavity measurement techniques[9] and showed that these films had a lower surface resistance than copper up to 60 K. Conventional photolithographic methods using phosphoric acid were used to pattern the filters, and a schematic of the crosses with associated dimensions is shown in Fig. 1. The asymmetry of the crosses is designed to allow for tuning of the filter transmission frequency by rotating the crosses with respect to the polarization of the incident electric field. A recording of the filter response at 15 K is shown in Fig. 2. Here, the center frequency and the FWHM of the filter is 91 and 0.85 GHz, respectively. As the temperature was increased from 15 to 85 K (T_c of the superconducting film), the Q-factor of the filter dropped from greater than 100 to less than 20. In addition, the resonance frequency of the filter shifted down 1.5 GHz when the temperature was increased from 15 to 85 K indicating a decrease of the kinetic inductance of the superconducting material. A full characterization of the quasi-optical filters will be described elsewhere.[5]

Figure 3 is a schematic of the current experimental setup. A computer controlled, 100 mW W-band backward wave oscillator was used as the millimeter wave source. Linearly polarized radiation was launched from a transmitting horn on the input side of the filter and collected by a second horn located behind the filter. The transmitted power was measured using either a thermal power meter or a millimeter wave silicon diode detector. Isolators were placed on both the input and output sides of the filter to prevent interference effects between the source and the filter, the filter and the detector, and the source and the detector. The horns and the filter were installed inside a vacuum chamber, and indium foil was used to make good thermal contact between the cold finger and the filter. A helium gas compressor was used to cool the filter, and temperature was measured using a thermistor located at a point on the filter mounting fixture furthest from the cold finger. Using this arrangement, temperature could be controlled to an accuracy of ± 0.5 K down to 15 K.

In an effort to observe optical control, a single line cw Ar^+ laser operating at 514.5 nm and having sufficient power to illuminate the large area high T_c filter was chosen

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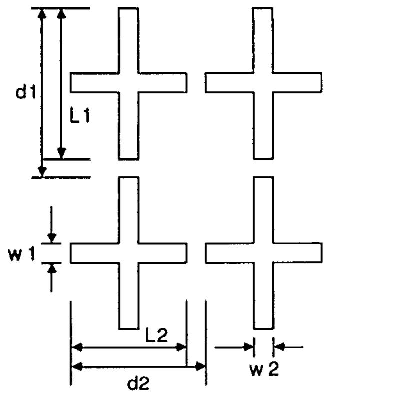

	L(mm)	d(mm)	w(mm)
1	0.713	1.435	0.020
2	0.617	1.243	0.020

FIG. 1. A schematic of the pattern and the associated cross dimensions.

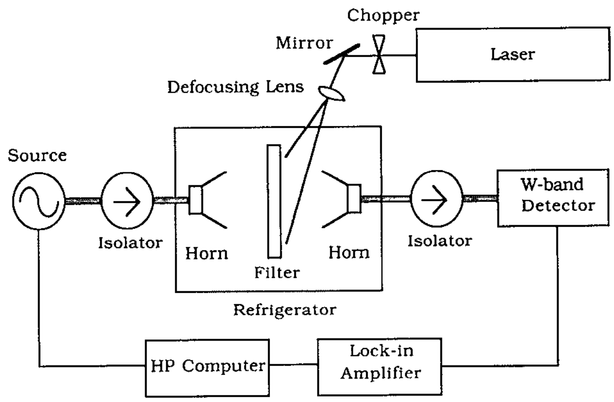

FIG. 3. Experimental arrangement used for optical response measurements.

(optical skin depth is about 1000 Å). Using an optical chopper and a lock-in amplifier in a phase sensitive detection scheme, small changes in the amount of millimeter wave power transmitted by the filter could be detected. A computer was used both to scan the source frequency and to record the light- induced changes in transmitted power. The Ar^+ laser radiation was defocused, using a lens, to a spot size of approximately 2 cm in diameter, and the beam was incident on the film at an angle of 45°. Figure 4 shows the phase-sensitive detection measurement of the light-induced change in the filter's transmittivity as a function of frequency. Taken at 17 K with a light intensity of 100 mW/cm^2, a lock-in time constant of 3 s, and a chopping frequency of 2 kHz, the data show the change in signal polarity and amplitude at the peak of the filter's transmittivity (Fig. 2). Measurements of the amplitude of the light-induced change were also performed. Asymmetric double-peaked curves with a well-defined minimum at the peak of the filter's transmittivity were observed as a function of laser power and temperature. Varying the laser power from 25 to 100 mW/cm^2 at 17 K established that the signal amplitude was a linear function of laser power. In addition, the temperature was varied from 17 to 90 K and the magnitude of the experimentally measured light induced response was found to increase as the temperature increased to T_c and decrease above T_c.

In order to quantify the magnitude of the shifts induced under various conditions of illumination, a shifted Lorentzian line shape function model was developed. Figure 5 is a plot of a Lorentzian fitted to the data of Fig. 2. Also shown is a second Lorentzian whose resonant frequency has been shifted down by an arbitrary 100 MHz, and whose peak amplitude and Q-factor are both reduced by an arbitrary 2%. Also shown is a plot of the difference between the two Lorentzians. Comparing this difference curve with Fig. 4 reveals that the shape of the experimentally measured curve can be interpreted using this model.

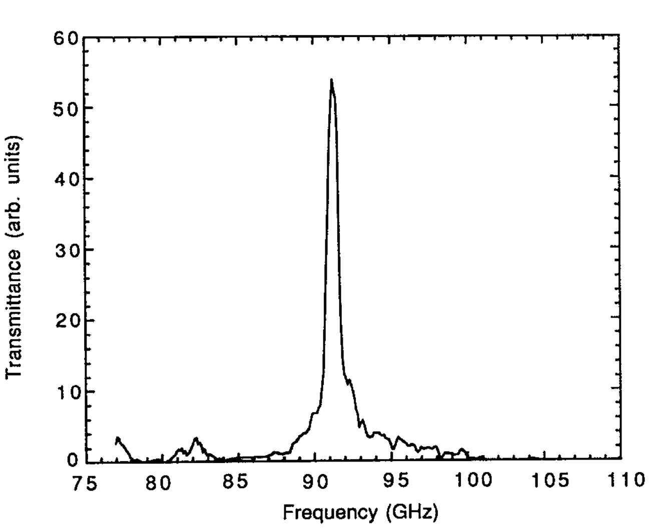

FIG. 2. Transmittance of the YBCO filter at 15 K. The center frequency is 91 GHz and the FWHM is 1 GHz.

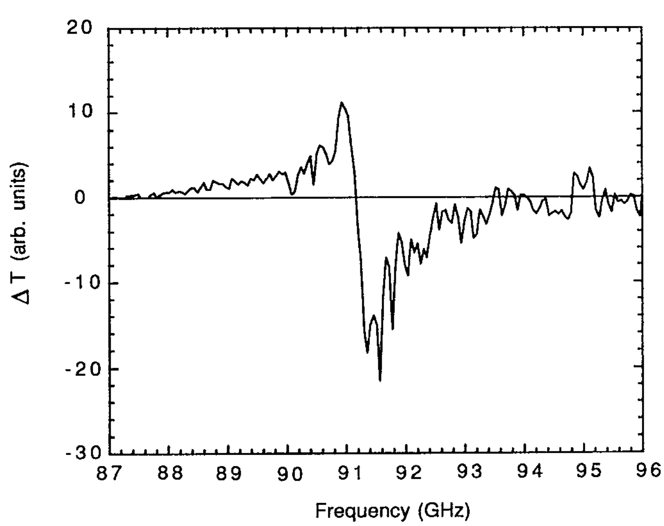

FIG. 4. A recording of the light-induced change in the filter transmittance.

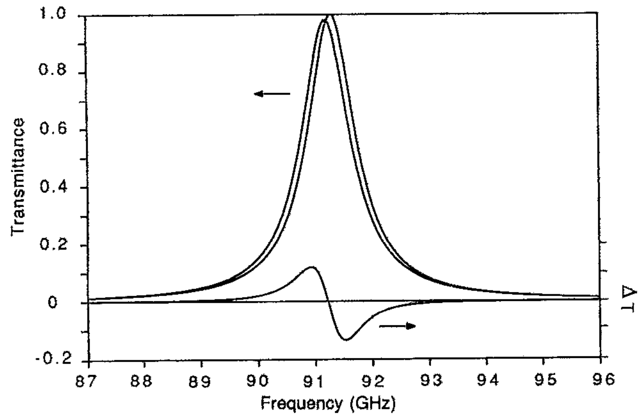

FIG. 5. A plot of a Lorentzian (fitted to experimental data of Fig. 2) and a shifted Lorentzian. In addition, the difference of the two Lorentzians is shown. The frequency shift depends only on the magnitude of the experimentally measured signal, but not on the separation of the peaks.

Using this simple model and neglecting a change in Q-factor, an estimate of the shift in resonant frequency can be obtained. This shift can be expressed in terms of the maximum amplitude of the frequency-dependent difference between the original and the shifted Lorentzians. In the limit that the shift is small compared to the halfwidth, the shift can be expressed as:

$$\nu_{\text{shift}} = 4/\sqrt{3}(\Delta\nu A/A_0) , \qquad (1)$$

where $\Delta\nu$ is the FWHM of the unshifted filter, A_0 is unshifted filter's maximum signal strength, and A is the maximum signal strength of the experimentally measured light-induced change. Based on this model, we estimate from the experimental data that the radiation (100 mW/cm^2) induces a shift of 0.1 MHz and an approximate decrease in Q-factor of 4×10^{-3} at 17 K.

In another set of experiments aimed at determining the speed of light-induced response, a pulsed laser source (having approximately the same wavelength as the Ar^+ laser) was employed. Here, the filter was illuminated by 120 ps long optical pulses from a mode-locked, frequency- doubled Nd:YAG laser (532.8 nm) operating at 76 MHz. Results similar to those observed using the cw Ar^+ laser were obtained when the filter's response was measured using phase- sensitive detection. Efforts to determine the filter's temporal response to pulsed excitation are currently in progress. Observations of Frenkel *et al.*[7] in related systems indicate that there are both thermal and fast components in the responsivity of similar superconductor films to pulsed light.

In conclusion, we have shown that high T_c superconducting films can be used to fabricate narrow-band quasi-optical millimeter wave bandpass filters. At millimeter wavelengths the dimensions of these filters are consistent with available materials and in addition the surface resistance is still lower than copper. The tunability of the filter's resonance frequency and Q-factor by optical laser radiation has also been demonstrated. In addition, these quasi-optical filters can be used in novel, contact free arrangements to study the interaction of light with high T_c superconducting thin films at millimeter wave frequencies.

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