Performance of a fully superconducting microwave cavity made of the high $T_c$ superconductor $\text{Y}_1\text{Ba}_2\text{Cu}_3\text{O}_y$

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We report the successful fabrication and characterization of a high $T_c$ superconducting microwave cavity. The cavity made of bulk $\text{Y}_1\text{Ba}_2\text{Cu}_3\text{O}_y$ ($T_c = 93$ K) and dielectrically loaded with sapphire was resonant at 8.00 GHz in the TE$_{011}$ mode. At 77 K the $Q$ was $10^4$, which represents an improvement of a factor of 11 from the normal state. At 4.2 K the $Q$ was nearly $10^5$. The temperature dependence of the $Q$ correlates extremely well with the microwave surface resistance of a test sample measured independently, clearly showing that the $Q$ was limited by the intrinsic materials preparation and not by extraneous factors.

A major area where the low-loss properties of superconductors may potentially be exploited is in devices at rf, microwave, and mm-wave frequencies. The recent discovery of superconductors with transition temperatures above liquid nitrogen (77 K) has raised the possibility of a new class of microwave devices operating at temperatures well above liquid $^4$He (4.2 K). In order to examine the feasibility of such devices, to assess their operation at high temperatures, and to understand the nature of superconductivity in these new superconductors, we have been studying the microwave response of the oxide superconductors over a wide temperature range. In addition, we have also studied the fabrication of actual devices using the new superconductors.

In this letter we report the successful fabrication and characterization of a superconducting cavity resonant at 8.00 GHz. The body of the cavity was made out of bulk $\text{Y}_1\text{Ba}_2\text{Cu}_3\text{O}_y$ with a transition temperature of 93 K. The $Q$ of the cavity was measured as a function of temperature from 300 to 4.2 K. Starting from a value of $Q = 909$ above the transition temperature, the $Q$ increased by a factor of 11 to $Q = 10^4$ at 77 K and, upon further cooling, to nearly $10^5$ at 4.2 K. The data for the $Q$ correlate extremely well with independent measurements of the surface resistance $R_s$ of a test sample, thus confirming that the $Q$ of the cavity was determined by intrinsic material properties of the superconductor and not by extraneous effects such as joint losses.

Superconducting microwave cavities may be considered fundamental devices whose operation exemplifies the performance of bulk microwave structures. Cavities have potential applications for energy storage devices, particle accelerators, resonant filters, and ultrastable clocks.

The superconducting cavities were designed to be resonant in the TE$_{011}$ mode at around 8.0 GHz. Sapphire was used to dielectrically load the cavities, in order to reduce the cavity dimensions. Sapphire is well known to be an extremely low-loss material and has been used in cavities with $Q$ 's as high as $2 \times 10^5$ at 2.69 GHz.

Large batches (up to 0.5 kg) of high-purity (99.999%) $\text{Y}_2\text{O}_3$, $\text{BaCO}_3$, and $\text{CuO}$ were mixed, ground, and reacted at 900 °C for 12 h. The reacted mixture was pulverized, reground, and sintered at 900 °C for another 12 h, and again pulverized and ground. The resultant black powder was then cold pressed into solid and hollow cylindrical forms, using an isostatic press at pressures of 40 000 psi, and then sintered at 900 °C in pure $\text{O}_2$ atmosphere for 12 more hours. Characterization of test samples by four-point dc resistance measurements indicated a $T_c$ onset of 94 K with transition widths of less than 2° and the density was measured to be 83% of the theoretical value.

The cavity was cold pressed in two pieces as shown in Fig. 1. One piece is a hollow cylindrical piece with one closed end of dimensions 1.0 in. o.d. $\times$ 0.6 in. i.d. $\times$ 0.95 in. long with an indented bottom (base) for seating the sapphire (Fig. 1). The second is a top plate in the form of a disk 1.2 in.

FIG. 1. Top: Cavity pieces fabricated of the high $T_c$ superconductor Y-Ba-Cu-O. Bottom: Low temperature Dewar insert for the $Q$ measurements.
diam. × 0.5 in. thick, which contains two coupling holes of diameter 0.159 in. (to permit coupling using 0.141 in. semirigid coaxial cable) placed symmetrically at a distance of 0.125 in. from the cylinder axis. The pieces were sintered in O₂ atmosphere and then machined to a uniformly thick cylinder by machining the outside surface only (the inner surface was not touched). We have found that the cold-pressed material machines quite nicely, although extreme care is needed to avoid unwanted cracking. We have drilled holes of various sizes (0.125–0.6 in.), as well as faced, bored, and turned the cylindrical forms. No coolant was used during machining. The resultant forms are quite sturdy and can be assembled into the cavity structure. An indium seal between the top plate and closed-end cylinder was used.

A special low-temperature assembly was designed and constructed for testing the cavity (Fig. 1). Coupling to the cavity was provided via two 0.141 in. semirigid coaxial cables terminated by loops. The loops "look into" the cavity and couple to the cavity magnetic fields. One useful feature of the coupling design is the ability to vary the coupling by moving the probes with a fine micrometer, enabling weak or critical coupling over a wide range of Q's (10³–10⁷).

A stainless-steel jacket surrounds the cavity, and both the cavity and jacket interior can be independently evacuated. Usually, a small amount of He gas is let in to provide thermal exchange with the cryogenic liquid for efficient cooling. The cryogenic liquid (liquid N₂ or liquid He) surrounds the jacket, to allow cooling down to 77 or 4.2 K. A Si diode thermometer was mounted on the cavity to monitor its temperature from 4.2 to 300 K.

The bare cavity (without the sapphire dielectric) was calculated to have a TE₀₁₁ mode at 24.78 GHz. The sapphire crystal had the c axis parallel to the cylinder axis, and the appropriate dielectric constant used is 9.5. If the sapphire were to fill completely the cavity, the reduction in frequency would be a factor of \(\sqrt{\varepsilon} = 3.08\), leading to a frequency of 8.04 GHz. In reality, the sapphire is slightly smaller than the cavity dimensions. Also, sapphire is a pure dielectric with negligible magnetic properties, so that only the mode electric fields are affected and not the magnetic fields. Consequently, the reduction in frequency is slightly greater, and the resultant frequency for the TE₀₁₁ mode is 8.00 GHz.

For a particular mode \(m\) of a cavity, the mode \(Q\) is related to the surface resistance of the walls of the cavity by the relation

\[
Q = \frac{\Gamma}{R_s},
\]

where \(\Gamma\) is a geometric factor of the mode. The \(Q\) of the cavity was measured by the decay method, in which the input power to the cavity is pulsed, and the output power (the cavity is operated in a transmission mode) is observed. The decay time constant \(\tau\) of the output power is related to the \(Q\) by \(Q = 2\pi f\tau\). The electronics for measuring \(\tau\) and hence \(Q\) are described in Ref. 4.

The results for the measured \(Q\) as a function of temperature for the Y, Ba₂Cu₃O₇ cavity are shown in Fig. 2. The \(Q\) was measured with probes adjusted for weak coupling. For the data of Fig. 2, the \(Q\) is independent of input power. The \(Q\) is weakly temperature dependent between 300 and 100 K, attaining a value of about 909 at 100 K. A sharp increase is observed as the cavity is cooled below 100 K. (This suggests that the cavity material may have regions which superconducting onsets of 100 K.) The \(Q\) increases steadily, attaining a value of \(10^4\) at 77 K (liquid N₂). The increase appears to slow down at lower temperatures, below 60 K. The \(Q\) at 4.2 K was nearly \(10^5\).

We have also examined the cavity characteristics at high fields (high power inputs) at 4.2 K. This was done by adjusting the input probe for critical coupling. For input power levels of 100 mW, corresponding to a maximum field level of 4.58 T at the midplane of the cylindrical side, the \(Q\) decreased by a factor of 2. However, we believe this was due to heating, and not due to the destruction of superconductivity, since the cavity amplitude was dependent on pulse length. Because the only cooling path is through a small amount of He exchange gas at 4.2 K, the cooling is only adequate at low power levels. Further experiments exploring high-field effects are planned, in which the cavity will be directly immersed in the cryogenic liquid. High-field effects on the absorption appear to occur at much higher fields.\(^{10,11}\)

It is useful to compare the (low power) \(Q\) results with independent measurements of the surface resistance \(R_s\). We have measured \(R_s\) at 9.58 GHz using a special technique from 4.2 K to above \(T_c\). The comparison is best done by comparing the improvement in \(Q\) in going from the normal to the superconducting state, i.e., \(Q_n/Q_s\), with the surface resistance ratio \(R_s/R_n\), since \(R_s/R_n(T) = Q_s(T)/Q_n\). This is done in Fig. 3, which shows that the improvement in \(Q\) compares well with the surface resistance data measured independently. In fact, the \(Q\) improvement exceeds slightly that expected from the \(R_s\) data, which may indicate that the material used in the cavity was slightly better, in that it had a lower residual resistance than the test sample on which the \(R_s\) data were taken. It is also possible that the difference is due to the different frequencies involved. The Bardeen–Cooper–Schrieffer theory implies \(R_s \propto \omega^{1/3}\), so that between 8
and 9.58 GHz, \( R_c / R_n \) should be reduced by a factor of 0.8 (assuming a classical normal state with \( R_n \propto \omega^{1/2} \)), which is consistent with the experimental results.

One may ask how improvements in \( Q \) can be effected. The comparison of Fig. 3, showing the excellent correlation between a test sample and the fabricated cavity materials, indicates that the cavity performance is determined by the intrinsic material parameters of the superconductor. Thus possible improvements in \( Q \) can only be effected by improvements in the material property of the superconductor, i.e., in \( R_n \). Based on several measurements of \( R_n \) and analysis of the data, we believe that the following three factors influence the microwave response: (1) the high dc resistivity in the normal state, (2) the change in \( R_c \) in the superconducting state, which is not as dramatic as one would expect for a pure, elemental superconductor for the same frequency and \( T_c \), and (3) the large residual resistance (\( \sim 5 \times 10^{-3} \Omega \)), which is most likely due to the polycrystalline aspect of the superconductors, in which weakly superconducting intragranular material dominates the superconducting properties (this also appears to affect other properties such as critical current). This aspect may also be improved by materials processing.

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