HIGH T_c SUPERCONDUCTOR-SAPPHIRE MICROWAVE RESONATOR WITH EXTREMELY HIGH Q-VALUES UP TO 90 K

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ABSTRACT

Several high temperature superconductor (HTS)-sapphire TE_{011} mode resonators were designed, fabricated and tested. At 5.552 GHz, Q_0 reached 2×10^6 at 90 K, 3×10^6 at 80 K, and 1.4×10^7 at 4.2 K with circulating power up to 500 kW. Formulas for calculating the resonant frequency and Q-value were derived. These theoretical results showed good agreement with the experimental measurements. Applications, such as frequency-stabilized oscillators, filters and the characterization of HTS films, are discussed.

INTRODUCTION

The need for frequency-stabilized oscillators, low loss filters and slow wave structures drives the search for resonators with ever higher Q. Resonators fabricated from low temperature superconductors such as niobium and lead have achieved extremely high Q [1,2], but they require liquid helium temperature operation. At higher cryogenic temperatures, sapphire resonators have fairly high Q [3], but they are bulky. HTS-sapphire TE_{011} mode resonators offer the potential for high Q and small size [4]. We have designed, fabricated and tested several such resonators. Their exceptional performance at temperatures up to 90 K and at high power levels demonstrates the potential for high temperature superconductors in microwave applications.

RESONATOR DESIGN

The resonator was formed in a HTS-sapphire-HTS sandwich held in an oxygen-free copper package by an array of springs (Figure 1). Low surface resistance $Tl_2Ba_2CaCu_2O_8$ films on 2-inch diameter (100) $LaAlO_3$ wafers were used. These films have a superconducting transition temperature T_c of 106 K and surface resistance R_s at 10 GHz as low as 23 $\mu\Omega$ at 4.2 K and 130 $\mu\Omega$ at 77 K [5]. A dielectric cylinder of c-axis oriented high-purity sapphire from Union Carbide was centered between the films. Several pairs of films were tested using several cylinders of two different sizes, one size with dimensions of 1.000 inch diameter and 0.472 inch length, and the other 0.625 inch diameter and 0.552 inch length. Magnetic dipole coupling was achieved by a pair of copper coaxial cables with a loop at the end. The coupling was adjusted by changing the insertion depth of the cables.

MEASUREMENT TECHNIQUE

The measurements were made in a liquid helium storage dewar with a glass epoxy insert. The resonator assembly was mounted on a copper plate at the end of a stainless steel probe. The assembly was then evacuated and lowered into the insert. Temperature was controlled with a pair of 100 W heaters. A HP-8510 vector network analyzer with 1 Hz

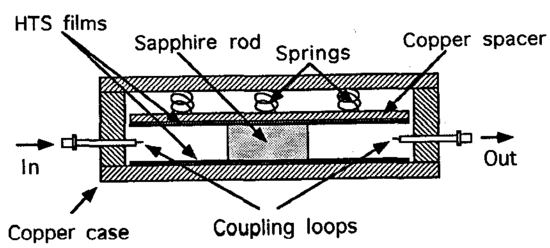

Figure 1. Schematic diagram of HTS-sapphire-HTS resonator.

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frequency resolution was used for the measurements. A HP-8449A preamplifier and a Hughes 8030H02F TWT power amplifier with output power up to 30 W were inserted at the input of the resonator for the high power measurements.

For a single mode resonator with unequal couplings at its input and output, the relationship between the loaded and unloaded Q-values, Q_L and Q_0, is

$$Q_0 = Q_L (1 + \beta_1 + \beta_2) , \quad (1a)$$

$$\beta_1 = \frac{1 - S_{11}}{S_{11} + S_{22}} , \quad (1b)$$

$$\beta_2 = \frac{1 - S_{22}}{S_{11} + S_{22}} , \quad (1c)$$

$$S_{21} = \frac{2(\beta_1\beta_2)^{1/2}}{S_{11} + S_{22}} . \quad (1d)$$

where β_1, and β_2 are the coupling coefficients at port-1 and port-2, respectively, and S_{11}, S_{22}, and S_{21} are the magnitudes of the S-parameters measured at the resonant frequency. Equations (1a-c) were used for calculating Q_0 from the measured data and Equation (1d) was used for verification. The measurement was repeated three times at each temperature and power level, and the average value was determined. Then, port-1 and port-2 were interchanged and the measurements repeated for verification.

The loaded Q-values were measured with the 3-dB band width method. The Q_L data were measured with strong coupling ($S_{21} \cong 3$ dB). No severe degradation of Q_0 was observed even with very strong coupling ($S_{21} < 0.2$ dB).

THEORY AND EXPERIMENTAL RESULTS

The TE_{011} mode resonant frequency f_0 was measured to be 5.552 GHz for the 1.000 × 0.472 inch sapphire cylinder and 6.480 GHz for the 0.625 × 0.552 inch sapphire cylinder. Theoretical calculations of f_0 from electromagnetic field theory agreed with the experimental measurements to within 0.2%. All measurements reported below were obtained with the 5.552 GHz resonator.

Figure 2 shows the measured resonant curve

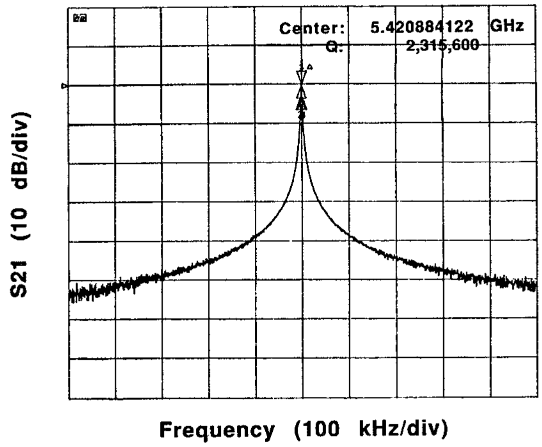

Figure 2. Measured resonant curve of a HTS-sapphire-HTS resonator at 82 K.

of a HTS-sapphire-HTS resonator fabricated with a pair of 2-inch diameter $Tl_2Ba_2CaCu_2O_8$ films at 82 K. The value of Q_L is 2.3×10^6 and that of Q_0 is 3.0×10^6.

The power handling of the resonator was determined by measuring Q_0 as a function of the circulating power P_c, which is defined as the rf power travelling along the length of the cylinder and reflected between the HTS films to form a resonant standing wave. P_c was calculated from the measured incident power at the input of the resonator P_{in} and the S-paramaters S_{11} and S_{21},

$$P_c = \frac{W_0 v_g}{2L} = \frac{Q_0 P_d v_g}{4\pi L f_0} , \quad (2a)$$

$$P_d = P_{in} (1 - S_{11}^2 - S_{21}^2) , \quad (2b)$$

where W_0 is the storage energy, P_d is the dissipated power in the resonator, L is the length of the sapphire cylinder, and v_g is the group velocity for the TE_{01} mode travelling wave in the cylinder.

The value of Q_0 is plotted in Figure 3 as a function of P_c at several temperatures. Q_0 was 2×10^6 at 90 K, 3×10^6 at 80 K, and 1.4×10^7 at 4.2 K.

The value of Q_0 was found to be very sensitive to parasitic coupling between the TE_{011} mode and case modes. A -50 dB case mode in the vicinity of the resonant frequency is sufficient to reduce Q_0 by as much as a factor

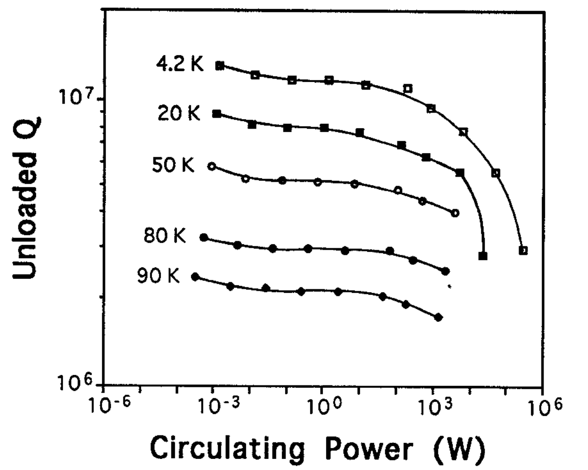

Figure 3. Unloaded Q-value Q_0 at 5.552 GHz vs. circulating power P_c for several temperatures.

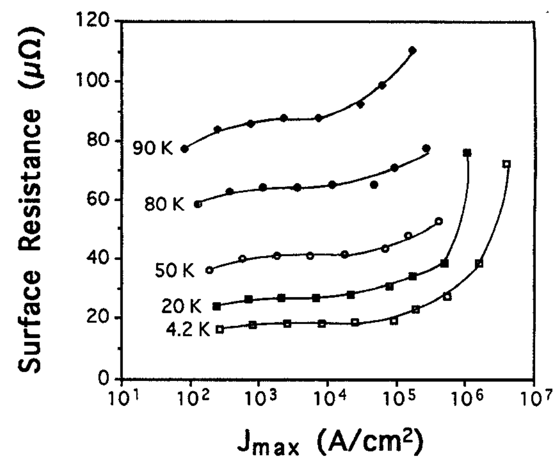

Figure 4. Surface resistance R_s at 5.552 GHz vs. maximum current density J_{max}.

of three. Mode selective damping was used to suppress the case mode, which resulted in a repeatable measurement of Q_0 upon temperature cycling or after re-assembling the resonator.

The resonator can be used to determine the surface resistance of the superconductor films. We assume that both films have identical, uniform surface resistance and that the radiation loss is negligible. According to the rf field distribution in the resonator, the Q_0 reflects contributions from both the conductor Q_{0c} and the dielectric Q_{0d},

$$\frac{1}{Q_0} = \frac{1}{Q_{0c}} + \frac{1}{Q_{0d}} , \quad (3a)$$

$$Q_{0c} = \frac{240\pi^2\varepsilon_r}{R_s} \left(\frac{L}{\lambda_0}\right)^3 \frac{1 + R}{1 + \varepsilon_r R} , \quad (3b)$$

$$Q_{0d} = \frac{1 + R}{\tan\delta} , \quad (3c)$$

$$R = \frac{1}{\varepsilon_r} \left[\frac{k_1 J_0(k_1 a)}{k_2 K_0(k_2 a)}\right]^2 \frac{\int_a^\infty K_1^2(k_2\rho)\rho \, d\rho}{\int_0^a J_1^2(k_1\rho)\rho \, d\rho} , \quad (3d)$$

where ρ is radius in polar coordinates, a is the radius of the sapphire cylinder, ε_r and $\tan\delta$ are the dielectric parameters of the sapphire cylinder, λ is the free-space wavelength, R is the ratio of energies stored outside and inside the sapphire cylinder, and k_1 and k_2 are the radial propagation constants inside and outside the cylinder, respectively. Values of the nth order Bessel function of the first and second kind, $J_n(x)$ and $K_n(x)$ (n = 0,1) were calculated numerically. Equation (3) can be used to calculate R_s from the measured Q_0.

For the TE_{011} mode, the rf current density J in the HTS films has a radial Bessel function distribution $J_1(k_1\rho)$ within the region $\rho \leq a$. The maximum current density J_{max} is present at $k_1\rho = 1.841$, and J_{max} can be calculated from the experimental measurements. Surface resistance R_s at 5.552 GHz for a pair of $Tl_2Ba_2CaCu_2O_8$ films is plotted as a function of J_{max} at several temperatures in Figure 4.

Similar measurements for $YBa_2Cu_3O_7$ and $Tl_{0.5}Pb_{0.5}Sr_2CaCu_2O_7$ films are in progress.

APPLICATIONS

The unique performance of the HTS-sapphire high Q resonator suggests many potential applications. Its extremely high Q can be utilized as the frequency stabilizer for a low phase noise oscillator. Preliminary measurements of an oscillator constructed from an amplifier and a high Q resonator operating at 80 K have indicated that the phase noise may be significantly reduced [6]. Phase noise measurements of the oscillator and the resonator are in progress.

The high Q resonator can also be used as a building block for filters with very low in-band insertion loss, high out-band rejection, steep skirts and extremely high power handling.

Another potential application would be to use the high Q resonator to measure surface resistance R_s and critical current density J_c of HTS films [7,8]. Preliminary data for R_s at low microwave power measured by this method show good agreement with measurements made with both a TE_{011} end-wall replacement cavity [9] and a parallel plate resonator [10]. The results will be published in a separate paper. The high Q resonator offers the advantage of being able to measure R_s at very high microwave power levels with moderate input power.

CONCLUSIONS

Using $Tl_2Ba_2CaCu_2O_8$ films, extremely high unloaded Q_0-values (> 10^6) were obtained from several C-band TE_{011} mode HTS-sapphire-HTS resonators above liquid nitrogen temperature (80-90 K). At liquid helium temperature (4.2 K), the measured Q_0 (> 10^7) was comparable to that of niobium cavities [1,3]. The power handling in terms of circulating power ranged from 500 kW at 4.2 K to 2 kW at 90 K. To our knowledge, these values represent the highest Q and power handling achieved for any HTS microwave devices at both 4.2 and 80 K. The results demonstrate that $Tl_2Ba_2CaCu_2O_8$ thin films can be used for high power microwave applications. Potential applications for the resonator include low phase noise oscillators, bandpass filters, and use in HTS film characterization.

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