Comparison of High-Temperature-Superconductor and Metal-Based Resonators

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***Abstract*—A 50 Ω coplanar waveguide (CPW) resonator designed for a fundamental frequency of about 4.75 GHz was fabricated on $LaAlO_3$. Two versions were fabricated: the first using 1.9-μm-thick gold and the second using a high-temperature superconductor (HTS), $YBa_2Cu_3O_7$, 0.6 μm thick. The devices were identically packaged and tested at 77 K. It was found that the HTS resonator had a surface resistance, R_s, about six to nine times lower than the Au one. At 45 K, the R_s of the HTS resonator decreases by another factor of 4 compared with its 77 K value. For the HTS resonator, (i) R_s varies as f^2 and (ii) R_s degrades with resonator power density as the RF current density, J_c, approaches typical dc measured values. Five identical HTS resonators were fabricated. At 77 K, mean and standard deviations on R_s were $\mu = 1.42$ and $\sigma = 0.46$ mΩ/sq., respectively. The measured σ/μ ratio of 0.3% on the fundamental suggests that narrow passband filters can readily be implemented.**

I. Introduction

The advent of high-temperature superconductors (HTS's) with transition temperatures, T_c, above 77 K has led to intensive developmental activities at research laboratories worldwide. These activities have centered on improving the material's quality and in finding applications for its use. Because it is not yet possible to reproducibly make active electronic HTS devices, most investigators have focused their efforts on applying HTS's to passive devices, such as in resonators and filters. For such applications, the most important material parameter is the surface resistance, R_s. As expected, HTS materials proved to be superior to the best metals for such applications. The objective of the present work was to determine, on a one-to-one comparison basis, (i) the extent of this superiority and (ii) the limitations of HTS materials, if any, vis-à-vis metals.

It is important to mention that the cost of cooling such devices to 77 K and below has to be considered in any system application. Since such cooling costs may be significant, HTS passive devices will find application where their use makes a system feasible at a lower cost than alternative approaches. Examples are more efficient use of communications satellite spectrum by finer partitioning; reconfiguring the partitioning of the satellite's spectrum as needs change; and channelization at the front end of radar or communications receivers to counter jamming. (For papers of general interest discussing microwave applications, see [1]–[5].) In addition, should HTS devices be used, then the benefits of significant performance improvement of semiconductor devices (as well as superconductive interconnects [6]) can be obtained with negligible incremental cost.

II. Resonator Design

The coplanar waveguide resonator structure was selected for the test vehicle because only a one-sided film is required. It was also decided to use $LaAlO_3$ as the substrate because good YBCO films could be deposited thereon and because of its low loss tangent. Fig. 1 shows a photograph of the resonator; its pertinent parameters and dimensions are shown in the figure legend. Usually Au, but sometimes Ag, was used for the bond pads. A 50 Ω resonator design was selected to minimize reflections. Using Supercompact [7], a microwave software design package, the resonator was designed for a center frequency of 4.75 GHz. The most difficult aspect of resonator design is the excitation gap size. This gap must be large enough so that the resonator is adequately isolated, but small enough so that sufficient energy can be coupled into and out of it. Since the optimum gap size is dependent on the Q, its size was determined experimentally.

III. Material Growth

A. YBCO Deposition and Annealing

YBCO resonators were fabricated using thin-film YBCO deposited on single-crystal (100) $LaAlO_3$ substrates. The films were deposited by the coevaporation of Y, BaF_2, and Cu in an oxygen pressure of 8×10^{-5} torr. The evaporation was performed at ambient temperature, with the substrates attached to 22-cm-diameter rotating

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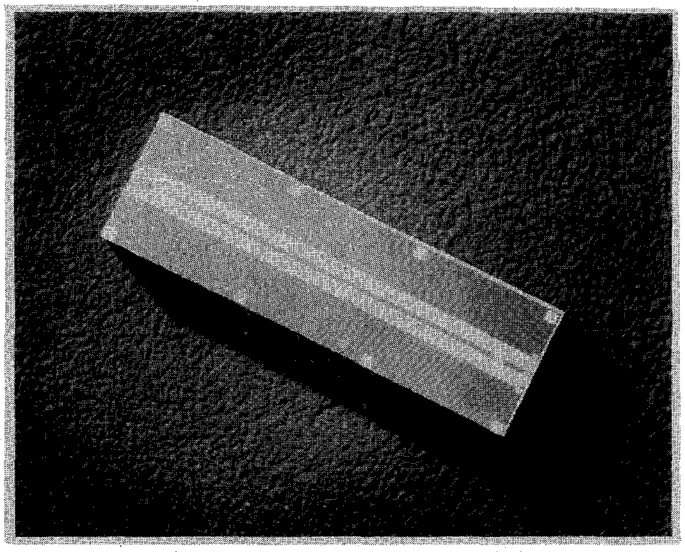


Fig. 1. Coplanar waveguide resonator. The resonator was designed for a center frequency of 4.75 GHz. Substrate is 0.5-mm-thick $LaAlO_3$; material is 0.6-μm-thick YBCO. Resonator width: 142 μm; length: 8.66 mm; gap to ground: 0.32 mm; resonator impedance: 50 Ω. Input/output gaps: 254 μm; this results in an insertion loss of about -6 dB for a high-Q resonator.

plates; rotation allows YBCO deposition over large areas. The Y was evaporated by an electron beam, and the BaF_2 and Cu by resistive heating. Collimated quartz crystal monitors mounted above each source and approximately at the height of the substrates provided automatic feedback to maintain constant and independent evaporation rates of the three sources. For this study, 2.5-cm-diameter $LaAlO_3$ wafers were used, and a YBCO film thickness of 0.6 μm was employed.

Annealing is required to convert the deposited material into a superconducting one and is performed in a tube furnace with flowing oxygen. The temperature is ramped up to 850°C in about 1 h, and then maintained at this temperature for 3.5 h, during which time oxygen is bubbled through water prior to its entry into the furnace. Temperature ramp-down is done over several hours in dry oxygen, which includes a 30 min dwell at 550°C.

These processing conditions typically produce epitaxial YBCO films on $LaAlO_3$ with sharp resistive transitions, zero-resistance transition temperatures (T_c) between 89 and 90 K, and a dc J_c around 10^5 A cm^{-2} at 77 K [8].

B. Processing

Resonators are fabricated using standard photolithographic processing. Photoresist, patterned by the first mask level, defines the resonator structure (see Fig. 2(a)). YBCO patterning is performed by etching in dilute nitric acid (1000:1 by volume). After resist removal (Fig. 2(b)), the sample is subjected to a low-temperature anneal (defined as 30 min at 550°C in oxygen, followed by a slow cool). Next, photoresist is patterned with the second mask level to define the metal contact pads (Fig. 2(c)). A 1 μm layer of Au or Ag is evaporated and patterned by lift-off; this is followed by a low-temperature anneal. The YBCO

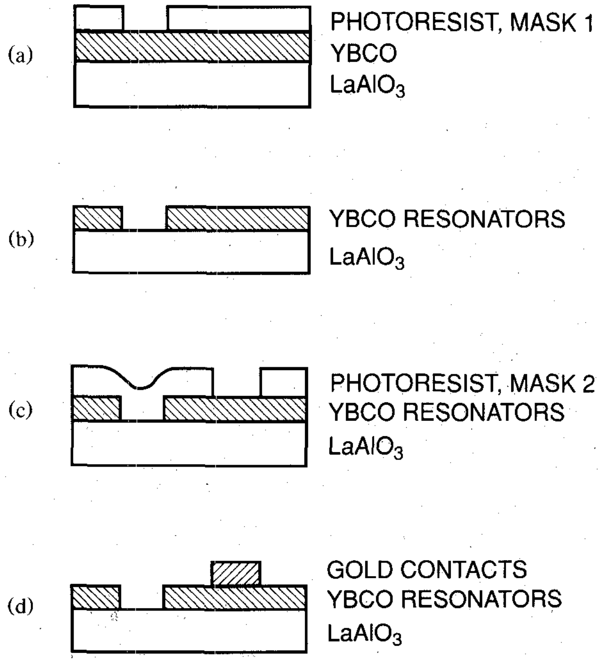


Fig. 2. Process sequence. Schematic representation of the main steps in resonator processing. Drawings are not to scale.

resonators with metal contacts are now complete (Fig. 2(d)). The final step, sawing the wafer to obtain individual resonator chips, is accomplished with a diamond saw, and with a coating of resist to protect the resonators. After resist removal, a final low-temperature anneal is performed. The samples subjected to the above processing exhibited no degradation in either T_c or J_c.

C. dc Characterization

Resistance versus temperature and J_c measurements are done using the conventional four-point-probe method on sample pieces. Contact is made by pressure in the T_c measurements. For J_c measurements, a photolithographically patterned bridge 20 μm wide and 400 μm long is used. Silver contact pads are evaporated and annealed at 550°C for 30 min for low-resistance contacts to the YBCO. A 1 μV criterion is used to define J_c.

A typical resistance-versus-temperature plot is shown in Fig. 3. The material used was made in the same YBCO run that produced the resonators reported in Table I. It is seen that T_c is 90 K, the 10% to 90% transition width is 1 K, and the resistance at room temperature is a factor of 3 higher than that at 100 K. J_c for this sample run at 77 K was determined to be 4×10^4 A cm^{-2}; this value is within a factor of 2 of that typically measured for films fabricated in the above manner [8], [9].

IV. Packaging and Test Procedure

Fig. 4 shows the resonator in its package. The coaxial-to-coplanar transitions on either side of the resonator are fabricated on Al_2O_3. Its length is optimized to minimize reflections at 4.75 GHz. The initial coax-to-microstrip transition is gradually transformed into a grounded copla-

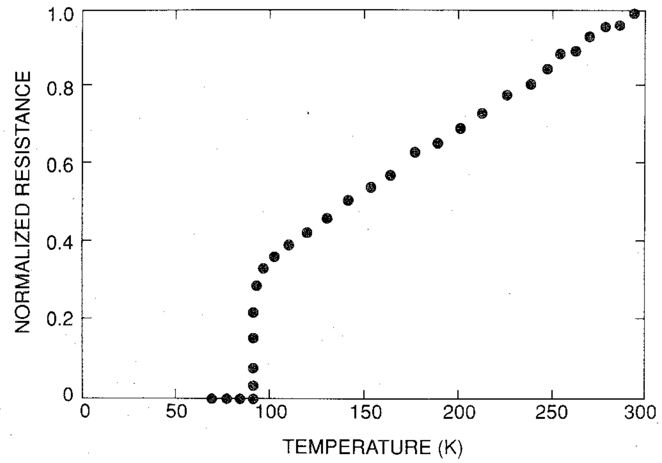


Fig. 3. Normalized resistance. The resistance is normalized to that at 295 K. The sample used here was made in the same YBCO run that produced the resonators reported in Table I. Also, the 77 K J_c for this sample run was determined to be 4×10^4 A cm^{-2}.

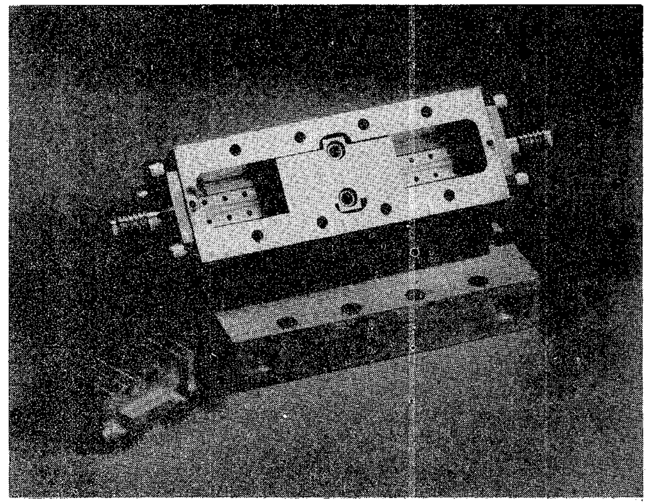


Fig. 5. Partially assembled package. The cavity suppressor breaks up the internal air cavity, thereby suppressing package-related resonances below 12 GHz.

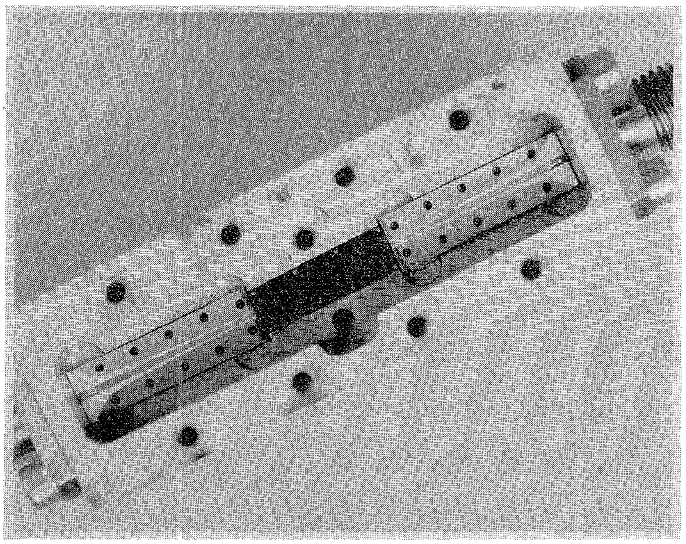


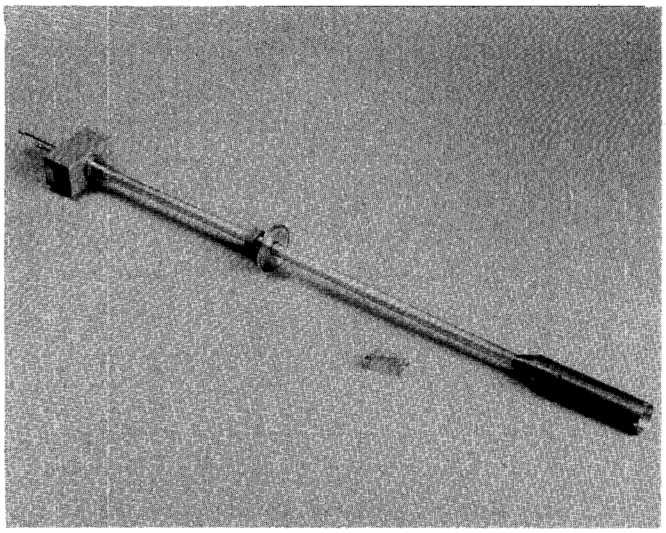
Fig. 4. Internal view of package. The coaxial-to-coplanar transitions are designed to minimize reflections. A 1.27 mm cavity, which cannot be seen, exists under the resonator.

nar transmission line. The transitions are attached to the package with AuSn eutectic. A 1.27 mm cavity, which cannot be seen, exists under the resonator; the resonator is supported only along its periphery. The main ground connections are adjacent to the transitions; the larger grounding pads on the sides are backups. Low-temperature ($< 200°C$) thermocompression bonds are used to contact the resonator with 25 μm Au wire. The transition and the resonator surfaces were made to be nearly coplanar and their dimensions were made to be comparable so as to reduce reflections at this interface.

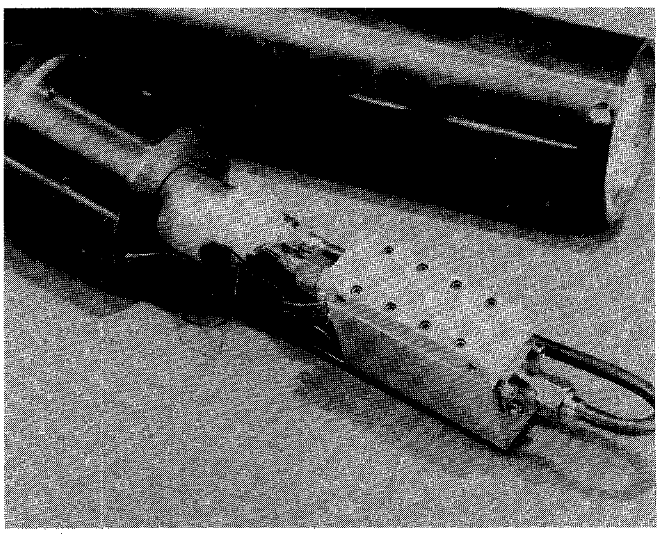
The partially assembled package is shown in Fig. 5. A cavity suppressor is used to break up the internal air cavity into three smaller cavities, each of somewhat different size, effectively suppressing package-related resonances below 12 GHz. This allows resonator behavior at the fundamental and the second harmonic to be accurately measured. The air space above the resonator is 1.27 mm high. A 50-μm-thick indium gasket was to be used to hermetically seal the package. Initial experiments suggested that In may react with YBCO; thus its use was discontinued. (Gold or silver gaskets have not yet been tried.) Since the package is not hermetic, the devices are stored in a dry N_2 ambient when not being tested. The threaded holes on the side of the cover plate allow mounting the package on a laboratory cold finger or insertion of a temperature sensor therein. Standard K-type connectors complete the package.

The resonators are characterized using an HP8510B microwave network analyzer. For 77 K characterizations, short sections of semirigid coax are attached to the package and the whole assembly is inserted into a Dewar containing liquid nitrogen (LN_2). Scalar calibration is done before each measurement session. The HP8510B was also calibrated in terms of its output power before resonator characterization began. It is worth mentioning that the packaged resonator withstands multiple (> 10) temperature cycles, at a cooling or heating rate of about 100 K per minute, without any noticeable change in its characteristics.

For characterization of the resonator at temperatures below 77 K, the arrangement shown in Fig. 6 was devised. It consists of (i) a thin-wall stainless steel tube through which pass semirigid coaxial lines and wires to the temperature sensors, (ii) a box at the top for electrical terminations, (iii) an adapter that mates to a LHe Dewar and allows the penetration of the apparatus into the Dewar to be adjusted, (iv) a copper "black body" enclosure to reduce temperature gradients, and (v) a platform to which the packaged device is attached. Fig. 6(b) shows details of the package mounted into this apparatus. (A swage-lock arrangement on the top box permits the semirigid coax lines to slide when desired.) Two temperature sensors are used: a calibrated Pt resistor accurate to about 50 K and a



(a)



(b)

Fig. 6. (a) Experimental apparatus for insertion in a helium Dewar. The depth to which the apparatus can be inserted into the Dewar is adjustable. Radiation coupling to the He surface determines the thermal exchange rate which can be adjusted to <1 K/min. Measurements are made "on the fly." (b) Package mounted into LHe apparatus.

calibrated Si diode accurate to below 4 K. A Dewar with a neck diameter of 5.7 cm was used. Typically, the apparatus is lowered into the Dewar until there is LHe boil off, and then retracted a few cm. Radiation coupling determines the thermal exchange rate, which can be adjusted to <1 K/min. Measurements are made "on the fly" on cool-down and confirmed during the warmup cycle by extracting the apparatus from the LHe surface. Scalar calibration is done before each use of the apparatus.

V. Experimental Results

Fig. 7 shows the response of a YBCO resonator and compares it with that of a Au one at 77 K. The resonators are identical in terms of substrate used, packaging, and test conditions, except that the input/output gap for the Au resonator is 85 μm, while it is 254 μm for the YBCO one. (Note, nevertheless, that the insertion loss of the YBCO resonator is smaller than that for the Au resonator.) The thickness of the metallization of the Au resonator is about four skin depths at 77 K. The fundamental resonance is seen to be close to the design value. The 3 dB points are used to determine the loaded Q. The unloaded Q in Fig. 7 is calculated by assuming that the energy couples out of both resonator ports equally since the input/output gaps are identical. The unloaded Q of 1625 compares favorably with the Q of 1300 at 8.8 GHz reported by Valenzuela and Russer [10] using a similar structure but made with a laser-ablated YBCO film. The Q of this particular HTS resonator at its fundamental is seen to be about six to nine times greater than that of the Au one.

A resonator using Nb metallization was also fabricated. Its excitation gap was adjusted until an insertion loss of about 7 dB was obtained. A value of $Q_L = 5570$ was measured, with a Q_u of 8150 and a Q_c (due to conductive losses only) of 44 000 determined for the Nb resonator at 4 K.

To compare our results with those of others, a relationship between Q and the surface resistance, R_s, has to be determined. Since R_s is inversely proportional to Q_u, the relationship

$$R_s(\text{YBCO}) = R_s(\text{Au}) \cdot Q_u(\text{Au}) / Q_u(\text{YBCO})$$

is used, where $R_s(\text{Au}) = 9.1$ mΩ/sq. [11], to get $R_s(\text{YBCO}) = 1.01$ mΩ/sq., both at 77 K and 5 GHz. Casting this relationship into a form similar to that determined by Oates *et al.* [12], [13], one obtains for our resonator

$$R_s = 0.33 f / Q_u \ \Omega/\text{sq.} \tag{1}$$

where f is the frequency in GHz.

Fig. 8 shows R_s of an early resonator at its fundamental and first three harmonics. Also shown are the data for the best of our resonators at its fundamental. In addition, R_s of Cu at 77 K and that of unpatterned GE films measured by the cavity end wall replacement method are included for comparison. The data point for the Nb resonator at 4 K is included as well; its R_s compares within 25% with that reported elsewhere [12], [13]. Also included are representative data by Inam *et al.* [14] and Klein *et al.* [15]. The data show (i) the best of our YBCO's R_s values is about an order of magnitude lower than that of high purity bulk Cu at 77 K and at 5 GHz; (ii) R_s values close to those of our unpatterned films, indicating that the processing used does not significantly degrade film quality; (iii) R_s values within a factor of about 4 of patterned, laser ablated films; and (iv) f^2 behavior. Note that both the Inam data and the Klein data are for films deposited by laser ablation, a small-area deposition method. By contrast, the deposition technique used for this work is suitable for large areas.

Fig. 9 shows the behavior of R_s of two resonators as a function of temperature. R_s decreases rapidly as the temperature is reduced in the vicinity of T_c. For example, R_s is about three times smaller at 60 K than at 77 K.

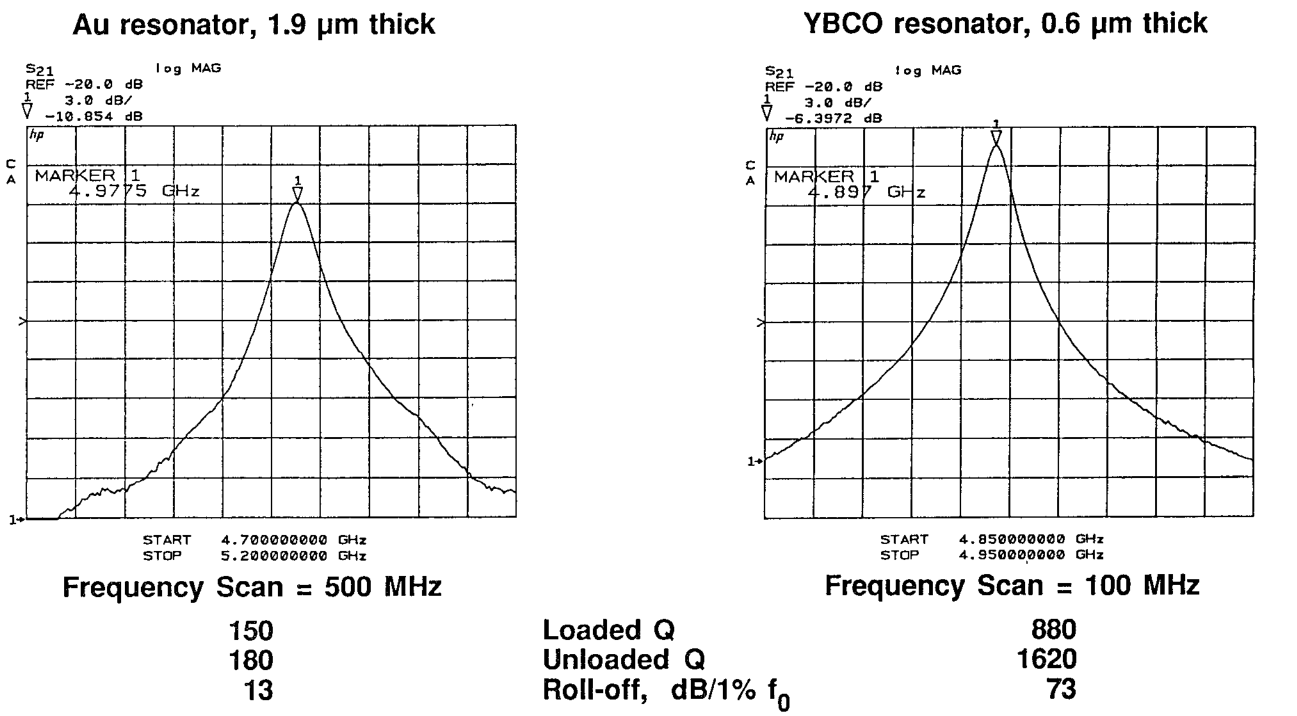


Fig. 7. Performance comparison of Au and YBCO CPW resonators at 77 K. The resonators are identical in terms of substrate used ($LaAlO_3$), packaging, and test conditions.

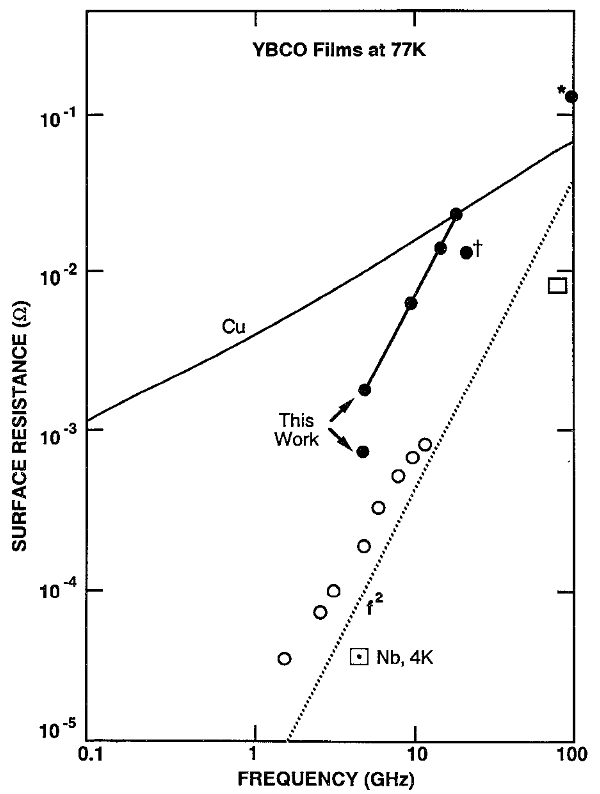


Fig. 8. Comparison with the results of other laboratories. ● Coevaporated, postannealed YBCO films deposited at GE; unpatterned films measured at STI (*) and at Los Alamos (†) [9] by the cavity end wall replacement method. ○ Patterned laser-ablated films reported by Inam *et al.* [14]. □ Unpatterned laser-ablated film reported by Klein *et al.* [15]. ⊡ Nb resonator at 4 K.

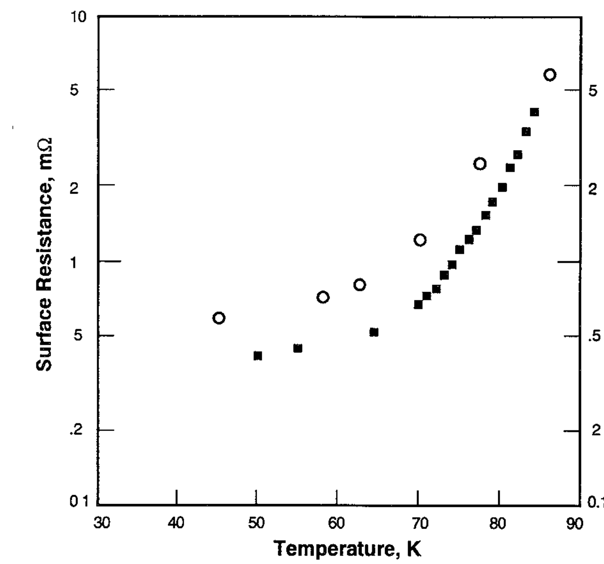


Fig. 9. Temperature behavior of R_s.

Below 60 K, reduction of R_s with temperature is more modest. Measurements below 45 K were not made because the insertion loss becomes quite small and measurement error increases. In Fig. 10, R_s for our best resonator is shown as a function of the average power density stored, P_{resav}; the maximum surface magnetic field, H_s; and the maximum current density, $J_{\max}$, in the resonator. Recalling that the J_c measured for this sample run was 4×10^4 A cm^{-2}, it is seen that R_s begins to increase rapidly as that value is approached. It is clear that these

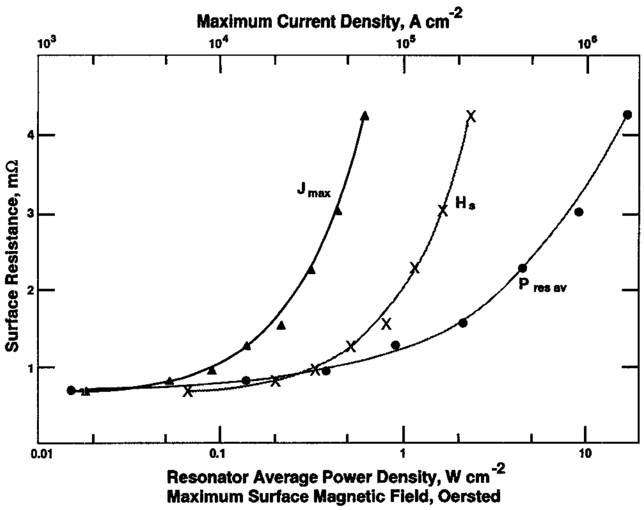


Fig. 10. Relationship of R_s to power, magnetic field, and current density. The dc J_c for this sample was measured to be 4×10^4 A cm^{-2}, which correlates well with the sharp increase in R_s that occurs as the RF current density approaches that value.

TABLE I
SUMMARY OF RESULTS ON FIVE IDENTICAL RESONATORS AT 77 K

Device Identification	f (GHz)	Q_L	Q_U	R_s (mΩ/sq.)
HTSO2	4.857	540	810	1.98
HTSO3	4.876	590	925	1.74
HTSO4	4.894	780	1440	1.12
HTSO5	4.883	645	1140	1.41
HTSO6	4.897	880	1915	0.84
$\langle\mu\rangle$	4.881	687	1245	1.42
σ	0.016	140	444	0.46
σ/μ, %	0.3	20	35	32

films are presently suitable only for low-power applications.

Table I shows a summary of results, at 77 K, of five identically fabricated devices. Here, the unloaded Q was determined by detailed balance including the input power reflected (S_{11} measurement), the dielectric loss ($\tan\delta = 0.0001$), and the cavity loss (estimated at 6×10^{-7}). (Typically, this method yields Q_u values that are about 20% larger than those obtained with the simpler method used earlier.) The mean value for R_s is 1.42 mΩ, with a standard deviation of 0.46. The standard deviation-to-mean ratio on the frequency is seen to be 0.3%. This is because the etchant used is more active at the periphery of the wafer than at the center, causing the resonator lengths to differ slightly. For filters with bandwidths less than about 1%, such variability must be reduced.

VI. SUMMARY AND DISCUSSION

It is clear that our current typical HTS films offer superior performance to metal ones for microwave applications of about 20 GHz and below. Can more improvement be expected in the future, particularly for films produced by large-area deposition techniques? At 77 K and 5 GHz, Inam reports an R_s of 0.2 mΩ while Klein's result of 8 mΩ at 86.7 GHz projects to 0.03 mΩ at 5 GHz (both these films being deposited by laser ablation). Laderman *et al.* [16] report an R_s of 0.016 mΩ at 4.2 K and 10 GHz for a YBCO film produced by off-axis sputtering. It is reasonable to expect that improvements in the coevaporation deposition method used in this work will also continue. Thus, HTS R_s values 50–100 times lower than those offered by metals can be reasonably expected at 77 K and at 5 GHz. If operation at under 50 K is considered, the performance gap between HTS and metals can be expected to widen to more than two orders of magnitude.

The YBCO films used in this paper are suitable for low-power applications. Laser-ablated films on $LaAlO_3$ are reported to exhibit J_c values of 5 MA cm^{-2} at 77 K [14], [15], and coevaporated films with J_c exceeding 1 MA cm^{-2} have been reported recently [17]. Such films may be suitable for medium-to-high power applications. It is worth mentioning that at the highest power densities, appreciable power will be dissipated in the HTS film (>10 W cm^{-2}); thus good thermal design will be essential.

Microwave filters constructed with HTS films can provide performance that is also satisfied, at present, by cavity filter structures. The small size and weight of HTS filters, as well as the ability to fabricate them in batches, will have to be weighed against their need for cooling and the attendant size, weight, power requirement, and reliability of the cooler. HTS filters are likely to be used when the application requires several filters. In such applications, the size, weight, and power requirement of the cooler are shared.

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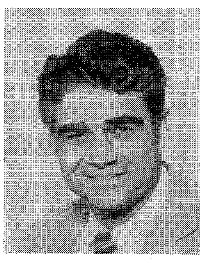

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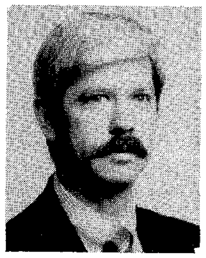

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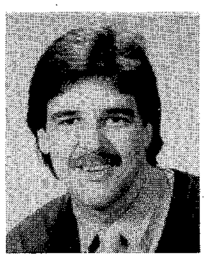

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