Measured Performance at 77 K of Superconducting Microstrip Resonators and Filters

Michael S. Schmidt, Roger J. Forse, Robert B. Hammond, *Member*, *IEEE*, Michael M. Eddy, and William L. Olson

Abstract —**Results on three types of passive microwave devices fabricated and tested using epitaxial thin films of $Tl_2CaBa_2Cu_2O_8$ grown on $LaAlO_3$ are reported. A microstrip ring resonator with unloaded Q of 2740 at 77 K and 33 GHz is described. A superconducting 4.6 GHz band-reject filter with unloaded Q greater than 15000 when operated at 77 K is reported. In addition, results on a multipole microstrip band-pass filter are presented.**

I. Introduction

The first demonstration of superconductivity above liquid nitrogen temperature, 77 K, was nearly four years ago. The microwave performance of the new high-temperature materials has improved dramatically during this time [1], [2]. In addition, the performance of these films in passive microwave devices has surpassed that of normal metals by orders of magnitude. High Q has been seen in stripline and microstrip thin-film resonators at temperatures up to 77 K and above [3], [4], [8]. In addition, there have been recent reports of superconducting thin-film multipole band-pass filters with attractive performance up to these high temperatures [5], [6]. Finally, these materials offer a number of advantages in microwave antennas [7].

We report here the development of microstrip resonators at millimeter-wave frequencies and describe a thin-film single-pole band-reject filter operating at 77 K. In addition, we describe a five-pole, interdigital band-pass filter that operates at X band.

II. Thin-Film Synthesis

The films for the microstrip devices were made by our production process for $Tl_2CaBa_2Cu_2O_8$ thin films on $LaAlO_3$. Substrates were either 1-cm-square or 2-in.-round and were either 0.5 mm or 0.25 mm in thickness. Microwave thin films are produced in high yield (> 80%). Tl-Ca-Ba-Cu-O thin films were prepared by laser ablation deposition followed by postdeposition thermal processing. The amorphous precursor deposits were prepared by laser ablation because it is an effective method of retaining the stoichiometry of the target in the deposited film. The oxides were ablated at room temperature using a KrF excimer laser (249 nm) onto chemically polished $LaAlO_3$ substrates. A laser pulse repetition rate of 10 Hz was maintained during the deposition and the deposition time was varied to give the desired film thickness. The amorphous films were heated to high temperature (830°–900° C) under controlled thallium and oxygen pressures to prevent excessive loss of Tl_2O_3. Final film thicknesses were ~ 9000 Å. X-ray diffraction showed the films to be oriented with the c axis of the superconductor perpendicular to the substrate; in addition, sharp rocking curves (as sharp as 0.30°) indicated an epitaxial orientation. Epitaxy was substantiated by selected area electron channeling, which showed electron channeling over the whole of the substrate, with the 100 orientation of the superconductor aligned with the 100 of the substrate.

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III. Device Fabrication

High-temperature-superconductor thin films were patterned using a wet chemical etch process. The films were rinsed with a series of organic solvents (toluene, acetone, methanol, isopropanol) and dried at 135° C for 30 min immediately prior to photoresist deposition. A positive photoresist (Shipley 1713) was spun onto the 1 cm^2 wafer using a spin rate of 5000 rpm for 30 s to give a photoresist thickness of 1.3 μm. The resist was oven-baked at 95° C for 30 min to remove casting solvents.

A Kasper mask aligner was used to perform the contact lithography. The photoresist layer was exposed for 30 s and developed by soaking for 60 s in an aqueous hydroxide solution (Shipley MF 319). The etched resist was then examined optically for pinholes/defects. If defects were observed, the photoresist was removed using acetone and the photoresist was redeposited. Otherwise, the uncoated film surfaces were chemically removed by etching for 20–30 s in a dilute HCl solution (1:150 dilution of concentrated HCl in 18 MΩ deionized water). The film was then rinsed with DI water and dried using dry, hepafil-

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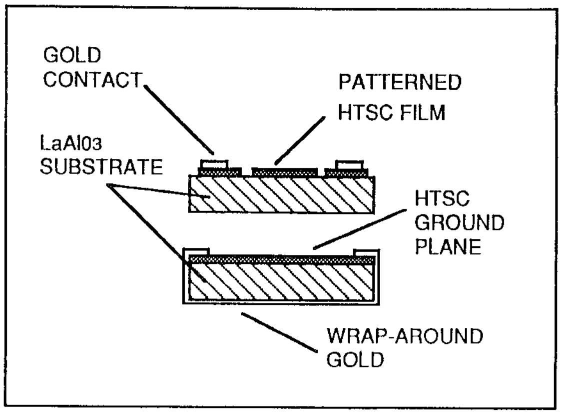

Fig. 1. Microstrip construction using two separate superconducting films, one for the center conductor and one for the ground plane.

tered nitrogen. Residual resist was removed using acetone.

Gold metallization was used to provide low-loss microwave contact to the superconducting films. Coaxial to microstrip transitions were made using Ag epoxy to the gold-covered superconducting film surface. Gold metallization of the film was accomplished using a combined sputtering, lift-off process. Shipley 1713 photoresist was patterned for lift-off using the process described above. The exposed HTSC film surfaces were coated with 2000 Å of gold using a 1-in.-diameter US sputtering gun. The target Au purity was 99.99%. The sputtering gun was located 3.5 in. from the substrate and operated using a gun current of 0.5 A and an Ar partial pressure of 2×10^{-2} torr. The gun was presputtered for 15 s behind a closed shutter prior to deposition on the substrate. A gold deposition rate of 30 Å/s was typically observed. Lift-off of the undesired Au film and photoresist was performed by soaking the wafer in acetone for 10–20 min. Unannealed contacts gave contact resistances less than 10^{-4} $\Omega\cdot cm^2$.

A. 35 GHz Ring Resonator

To measure the microwave properties of high-T_c superconductor thin films at millimeter-wave frequencies, we developed a microstrip ring resonator. The outer diameter of the ring was 0.044 in. and the line width was 0.006 in. We varied the input and output capacitive coupling gaps from 0.005 to 0.020 in. and performed measurements using the third-harmonic response of the ring resonator at 35 GHz. The substrates were lanthanum aluminate, 1.0 cm$\times$1.0 cm$\times$0.010 in. thick. Three types of resonators were tested: an all-gold resonator, an HTSC center conductor with gold ground plane, and all-HTSC resonators. The resonators were mounted in a test package with APC-2.4 connectors. The all-HTSC resonators used the geometry detailed in Fig. 1 while the other resonators used a single substrate with a sputter-deposited gold ground plane on the back. As illustrated in Fig. 1, for the fully superconducting resonators, a patterned HTSC resonator was stacked on top of an HTSC ground plane, with gold wraparounds providing a ground connection to the package. Table I lists the test results at 77 K and -10 dBm input power for each of these 35 GHz resonators.

TABLE I
HTSC RING RESONATOR SUMMARY

Resonator Type	Insertion Loss (dB)	Loaded Q	Unloaded Q
All Gold	9.3	360	550
HTSC/Gold	8.6	900	1440
All HTSC #1	18.8	2360	2670
All HTSC #2	26.9	2610	2740

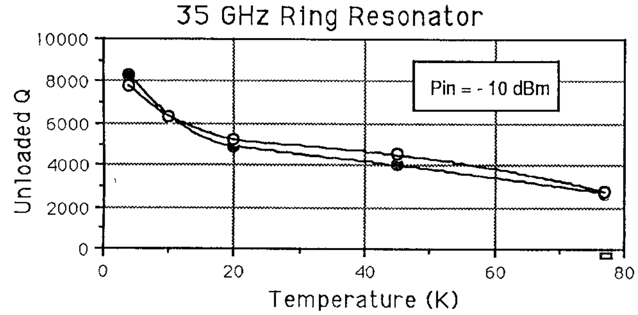

Fig. 2. Measured unloaded Q plotted versus temperature for two all-superconducting 35 GHz resonators.

The two all-HTSC resonators were mounted in a cryostat and characterized over the 4 K to 77 K temperature range. Fig. 2 shows the effect of temperature on the unloaded Q of the resonators. We extracted surface resistance of the superconducting films from the measured unloaded Q's using the Sonnet electromagnetic modeling program. We ignored the effect of loss in the substrate. At 77 K the inferred surface resistance of the superconducting films was 6 mΩ and at 4 K it went down to 2 mΩ. If we assume that the surface resistance of the superconductor is proportional to the square of the frequency, this extrapolates to $R_s = 0.5$ mΩ at 10 GHz and 77 K.

B. 4.6 GHz Band-Reject Filter

In addition to work described above on capacitively coupled resonators (that perform as single-pole band-pass filters), we have also developed inductively coupled resonators that perform as single-pole band-reject filters. The device we report here is a single-resonator band-reject filter designed to be as steep as possible while maintaining low loss near the band edges. It is an inductively coupled half-wavelength resonator that provides a reflective short at its resonance but has no effect off resonance. The circuit is designed to be close to critical coupling to give it a large shape factor.

The band-reject filter structure is shown in Fig. 3. It consists of a 0.006-in.-wide center conductor patterned on a 0.020 in. lanthanum aluminate substrate. The line impedance is 50 Ω. The device was constructed with a superconducting ground plane as shown in Fig. 1. As seen

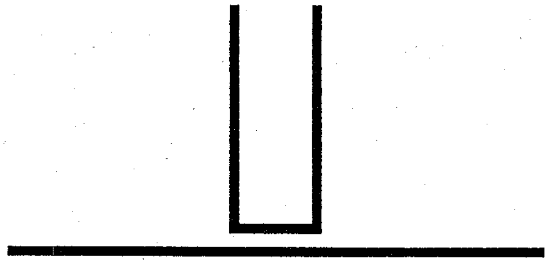

Fig. 3. Mask layout for the 4.6 GHz band-reject filter.

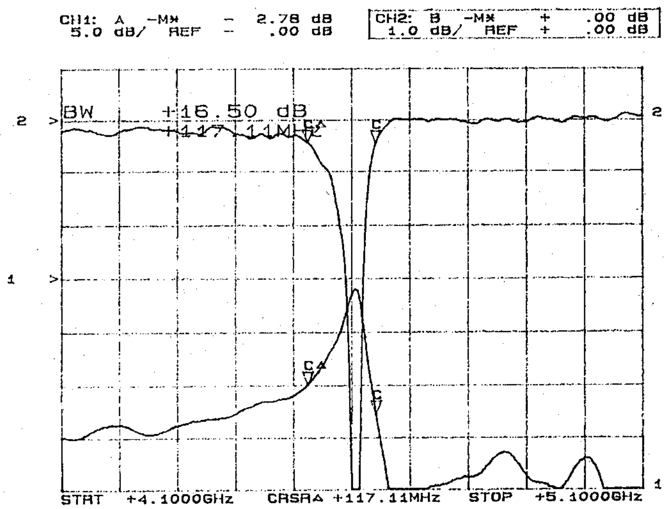

Fig. 4. Measured S_{21} and S_{11} for the 4.6 GHz band-reject filter. Channel 2, the upper plot, is insertion loss at 1 dB/div. Channel 1, the lower plot, is return loss at 5 dB/div.

in the device layout in Fig. 3, the coupling length is a small percentage of the total resonator length and may be adjusted to raise or lower the bandwidth of the filter. It is inductively coupled in the middle of the resonator to make the analysis more accurate than would be possible with end-coupled resonators. If the resonator had infinite Q the depth of the null would be infinite. The real finite Q of the resonator gives a finite depth and width, which gives a useful measure of microwave loss in the superconducting film. The measured data, shown in Fig. 4, show the good out-of-band performance and the sharp in-band rejection expected. The resonator loaded Q was 12422 and it provided 17 dB of rejection 1% from the band edge. The extracted unloaded Q from this measurement combined with a knowledge of the loss tangent of the lanthanum aluminate substrate can be used to calculate the surface resistance of the superconducting film at 4.6 GHz. Using 3×10^{-5} for the loss tangent [9] of lanthanum aluminate at 4.6 GHz and 77 K and an unloaded Q of 16500, we infer a surface resistance for the film of 80 $\mu\Omega$. Ignoring loss in the substrate yields a surface resistance of 160 $\mu\Omega$.

The through line also gives a good measure of the interconnect and general connector losses of the package, which is useful in troubleshooting as well as in measuring the transition temperature and width of the HTSC material. We used this structure to measure loss in our HTSC

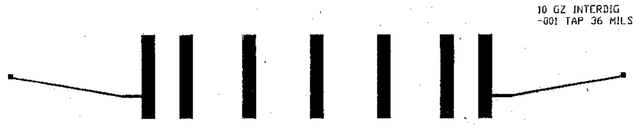

Fig. 5. Five-pole, interdigital microstrip filter layout. The device was fabricated on a 1 in.$\times \frac{1}{4}$ in. die, 0.010 in. in thickness. The center conductor was superconducting and the ground plane was Au.

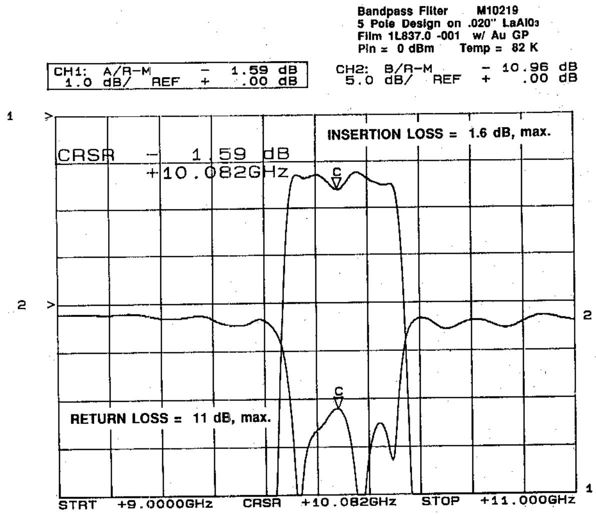

Fig. 6. Typical measured insertion loss and return loss for five-pole, interdigital microstrip filter. Channel 1 is insertion loss, 1 dB/div, and channel 2 is return loss, 5 dB/div.

material and have seen good agreement with the more traditional end-coupled resonator measurements. This topology would be ideal for applications requiring the filtering of a strong interfering signal near the desired band or rejecting a fixed local oscillator from a frequency conversion device. We are currently exploring applications in receiver protection.

C. 10 GHz Band-Pass Filter

A five-pole interdigital HTSC band-pass filter was designed and fabricated on a 1.00 in.$\times$0.25 in. lanthanum aluminate substrate. The ground plane was 3.0 μm of sputtered gold, and the substrate thickness was 0.020 in. The filter was designed using proprietary software, and was verified by electromagnetic analysis using Sonnet Software's "em" program. The filter layout is shown in Fig. 5.

Three filters were fabricated and mounted in aluminum housings with SMA connectors. The filters were fabricated simultaneously on the same 2 in. round lanthanum aluminate wafer. Each filter was tested separately at 82 K and 0 dBm input power using an HP8340 synthesized sweeper and an HP8757 scalar network analyzer. The response of one filter is shown in Fig. 6. Typical test results are summarized in Table II.

Performance of the three filters tested was very consistent. Fig. 7 compares passband responses of the filters at 82 K. Variations in bandwidth were less than 5%, and the center frequency error was less than 0.2%.

TABLE II
TYPICAL BAND-PASS FILTER PERFORMANCE AT 82 K

Center Frequency:	10.10 GHz	1 dB Bandwidth:	430 MHz
Insertion Loss:	1.5 dB	Passband Ripple:	0.2 dB
VSWR:	< 2.0 : 1	Out-of-Band Rejection: at 500 MHz from CF	30 dB

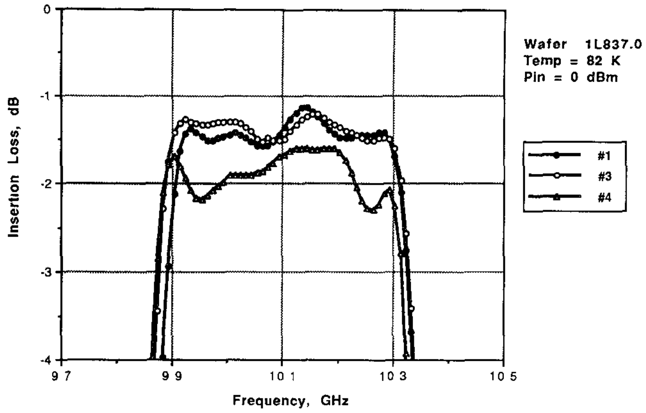

Fig. 7. Overlay of measured insertion loss and return loss for three five-pole interdigital microstrip filters. Devices were fabricated from a single 2-in.-diameter wafer.

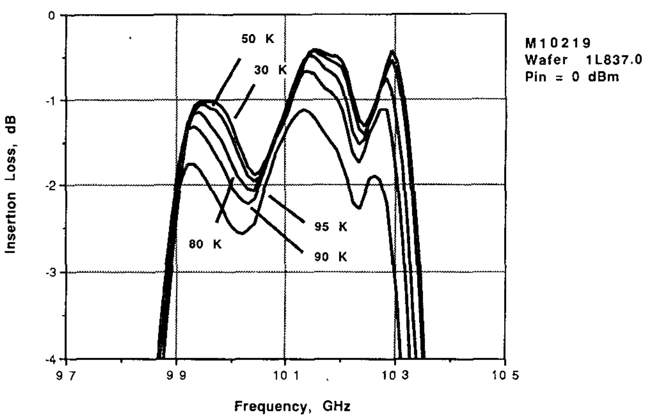

Fig. 8. Filter performance versus temperature.

One of the filters was placed in a cryostat and tested over a temperature range from 30 to 95 K. The results of this testing are presented in Fig. 8. (The passband variations are due to cable mismatches in the cryostat.) The filter showed very little temperature effect up to 90 K. Insertion loss increased with increasing temperature, as expected, but the center frequency and the bandwidth remained relatively unchanged. This temperature stability is of major importance in systems applications where cryogenic cooling systems are employed.

IV. SUMMARY AND CONCLUSIONS

The three superconducting passive microwave devices reported here demonstrate that performance significantly better than that of gold can be achieved in devices operated at practical power levels at liquid nitrogen temperature, 77 K. They demonstrate this in a microstrip configuration, an open transmission line structure that allows easy access to the circuit for tuning. These results show the potential for the application of HTSC films in complex passive microwave structures that can reduce the size and weight and improve the performance in satellite communications systems and other high-performance microwave systems.

Perhaps the most significant progress shown in our program is that these devices were made with a *production film process* and fabricated by *production patterning and metallization techniques*. The overall device yield of these processes is higher than 50%. This overall yield permits us to offer these devices on the commercial market.

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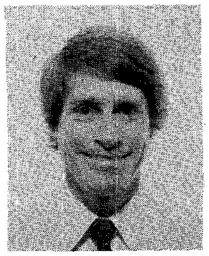

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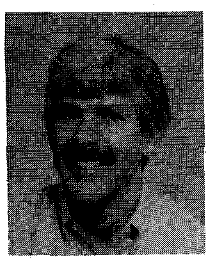

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