Low- and High-Temperature Superconducting Microwave Filters

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***Abstract*—Stripline and microstrip filters at X-band were designed and fabricated using low- and high-temperature superconductors in quarter-wave, parallel-coupled section configurations. Low-temperature superconducting niobium thin films, deposited on single-crystal sapphire, were used to build two six-pole stripline filters with adjacent passbands and approximately 3 dB crossovers and 1.2% bandwidth. Four- and six-pole microstrip filters were made with *in situ* epitaxial $YBa_2Cu_3O_7$ (YBCO) films on $LaAlO_3$ substrates. All the YBCO filters showed 77 K passbands with clean skirts and high out-of-band rejection. The YBCO six-pole filters were made after some initial technology developments, together with a reasonably high degree of repeatability, were established with the fabrication of eight working four-pole filters. The six-pole filters had adjacent passbands with −28 dB crossovers and 1.5% bandwidth. The results obtained show the potential of high-temperature superconductors for filters with narrow bandwidths and low insertion losses. Furthermore, they show a very rapid rate of development of superconducting filter technology, leading to system demonstrations and subsequent production in the near future.**

I. Introduction

High-temperature superconductors (HTS's) are likely to find their first systems applications in passive microwave devices. Among these, planar band-pass filters are particularly attractive wherever a portion of the RF frequency spectrum is required to be partitioned into smaller bands. Wide-band radar and communication systems generally do not use their entire bandwidth at once. They typically frequency-hop with a much narrower bandwidth signal. While on a specific frequency, it is desirable that the rest of the available bandwidth be filtered out at the input to the receiver. The required filtering can be performed with a switched filter bank or a tunable filter that will track the hopping transmitter signal. Electronic warfare receivers use preselection to break the complete RF band into several bands, each with a width equal to that of the IF. Since preselection is at the very front end of the receiver it must have very low loss so as not to contribute significantly to the receiver noise figure.

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Low-loss and narrow-bandwidth (0.5–3%) switched filter banks are available using such technologies as waveguide and multimode coupled dielectric resonators, which result in the filter bank having a very large size. In satellite communications, for example, where filter banks are also needed, the problem of size and weight becomes of primary importance.

Microstrip filters, small in size but too lossy for this application when using normal conductors at room temperature, can provide the solution when using HTS's. In this paper we report the design, fabrication, and testing of X-band low- and high-temperature superconducting filters. Our results show a rapid rate of technology development, demonstrating the potential for low-loss, narrow-bandwidth filter banks requiring relatively inexpensive cooling to 77 K.

II. Low-Temperature Superconducting Filter Pair at X-Band

Before HTS films could be reliably produced in relatively large (e.g., $>1.5\ cm^2$) substrates, the design and fabrication of a microwave filter pair with contiguous passbands were undertaken using low-temperature superconducting (LTS) niobium thin films on sapphire substrates. The goal of this effort was to establish the major technological difficulties in producing very low loss microwave devices which were to operate at cryogenic temperatures. It must be kept in mind that most of the thermal and mechanical problems associated with cooling a device are the same at 77 K as they are below this temperature (4.2 K in the case of the LTS filters built). Furthermore, the use of sputtered niobium thin films for this project was viewed as risk free from the materials standpoint, as we could readily obtain films of good quality on relatively large (2.54 cm by 2.54 cm) single-crystal sapphire substrates.

The approach taken was to design a pair of parallel-coupled stripline resonator filters at X band. The filters were designed taking into consideration the fact that sapphire is an anisotropic dielectric material [1]. Nb films were deposited onto rectangular sapphire substrates (2.54 cm by 1.27 cm by 0.038 cm) cut with the c axis parallel to their long dimension. The parallel-coupled resonators were then defined photolithographically in the c-axis di-

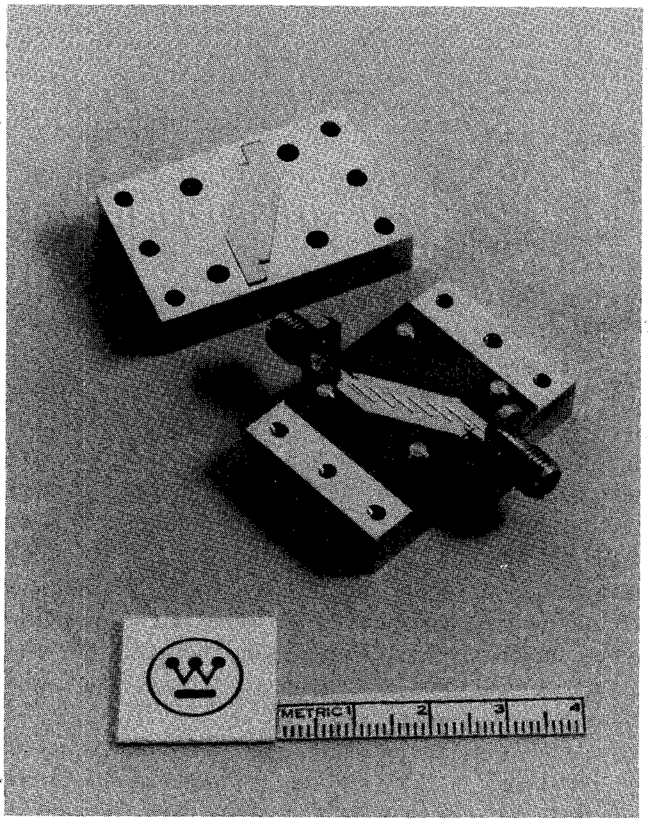

Fig. 1. Photograph of the interior of one of the low-temperature superconducting filters. Sputtered niobium thin films on single-crystal sapphire substrates were used. Operation temperature was 4.2 K (liquid helium).

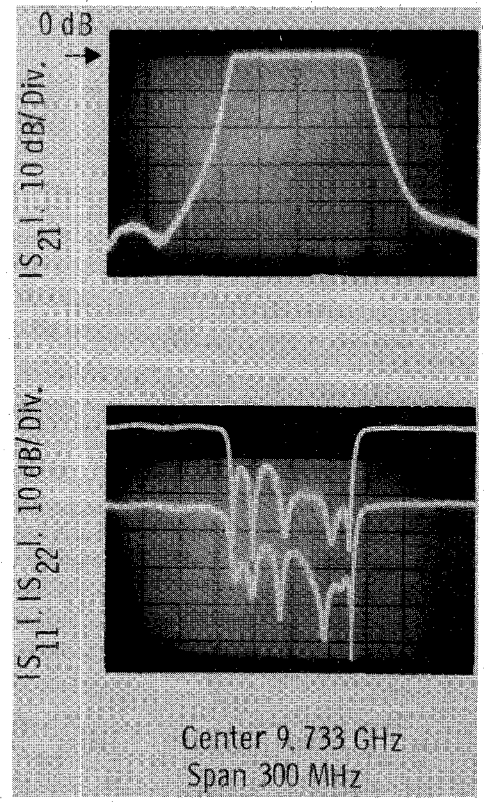

Fig. 2. Return and insertion loss response at 4.2 K for one of the low-temperature superconducting filters.

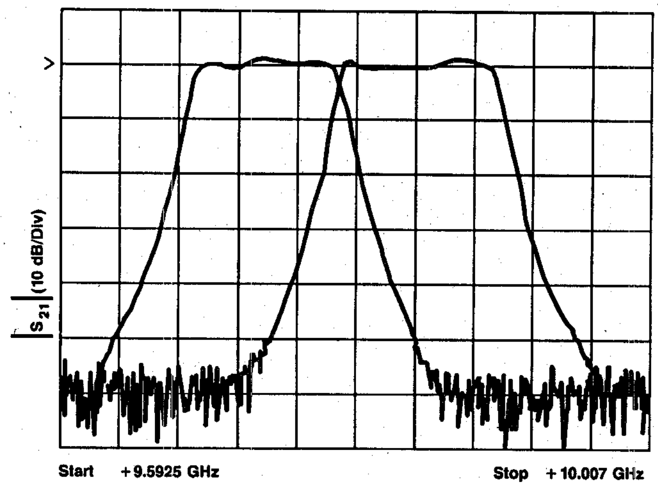

Fig. 3. Superimposed passbands at 4.2 K for the low-temperature superconducting filter pair.

rection. Thus, only the a-axis (ordinary) dielectric constant ($\epsilon_a = 9.4$) needed to be taken into account in the electrical design of the filter. The reason is that the electric fields were mostly confined to planes perpendicular to the c axis.

One advantage of our sputtered Nb films is that they could be deposited on both sides of a substrate. The quality of one of the films was degraded in the process, however. After a film was deposited the substrate had to be taken out of the sputtering chamber in order to turn it over to coat the back side. When the substrate was heated again for growth of the second film, a decomposition of the NbO layer ($\simeq$ 5 nm thick) that forms on the surface of the first film occurs. The oxygen then diffuses into this film, contaminating it. A way to prevent film degradation is to devise a mechanism to turn the substrate over inside the chamber, without breaking vacuum. We did not have this capability in place. Nevertheless, the degraded film was used as a ground plane, where current concentration is lower and its contribution to the total loss is several times smaller than that of the strips. This allowed us to have a relatively simple package configuration for the stripline filter.

Fig. 1 is a photograph of one of the units made. The substrates were given the shape shown in order for the structure to behave like a waveguide below cutoff at the two ports of the filter. This resulting in a large out-of-band rejection, as can be seen in the passband shown in Fig. 2 for the lower frequency filter. The figure also shows the return losses at both ports. Fig. 3 shows both passbands together, with crossovers at approximately 3 dB. The two filters were tested using a power divider outside the Dewar.

It was established from the outset that one of the main difficulties in this work was the packaging. Not only electrical but also thermal and mechanical considerations were important. The devices had to maintain their physical integrity in the face of repeated thermal cycling.

Therefore considerable effort was spent in developing a suitable packaging technique.

III. HTS Filter—Materials and Processing

A. Film Deposition and Processing

Four- and six-pole filters using microstrip parallel-coupled resonators were fabricated in HTS material. The high-temperature superconducting films used in this work were $YBa_2Cu_3O_7$ (YBCO) grown on $LaAlO_3$ substrates by off-axis magnetron sputtering. The target was a pressed and sintered disk of $YBa_2Cu_3O_7$ approximately 5 cm in diameter. The films grown were epitaxial with the crystallographic c axis oriented perpendicular to the plane of the film. The properties of these films are comparable to those of the best films produced by laser ablation, by coevaporation in activated oxygen, and by other sputtering techniques. In addition, uniform film properties across a 5-cm-diameter substrate holder have been demonstrated [2], [3]. Film uniformity over large areas is of great importance for integration of filters into filter banks on a single wafer.

The YBCO was patterned by conventional contact photolithography and wet etching with 15:1 $H_2O:H_3PO_4$ used as an etchant. Contact to the HTS filter was made through 200-nm-thick gold contact pads overlaying the 50 Ω input and output lines of the filter. These contact pads were patterned by lift-off from a gold layer deposited by evaporation. Annealing in one atmosphere of dry oxygen at 650°C ensured a low-resistance contact between the gold and the YBCO microstrip line [4].

B. Film and Substrate Electrical Characteristics

Of interest in the work presented here is the surface resistance of our films and the relative dielectric constant, ϵ_r, and loss factor ($\tan\delta$) of the substrate. From parallel-plate resonator measurements performed using the technique introduced by Taber [5], the typical (not the lowest) surface resistance of our films extrapolated to 10 GHz, assuming an f^2 dependence, is about 0.5 mΩ. This value was not corrected for film thickness. Our films are typically 500 nm thick, although some of the earlier four-pole filters reported on below were fabricated using thinner films. Films with a thickness comparable to the penetration depth (about 200 nm at 77 K for YBCO) will show an equivalent surface resistance that, although higher than the true R_s of the material itself, is the usable loss parameter for the film. The R_s value quoted here, therefore, is a conservative estimate of the quality of our films. It agrees well with literature reports [6].

The $\tan\delta$ of $LaAlO_3$ was measured using a YBCO microstrip resonator with a fundamental resonance at 650 MHz. The resonator was designed so that the conductor loss contribution to the unloaded Q was low. Besides resonating at a low frequency, the line was relatively wide (0.05 cm) and its distance to the ground plane relatively large (0.087 cm). The characteristic impedance was approximately 30 Ω. The measured unloaded Q of the resonator at the fundamental harmonic and 77 K was 25000, corresponding to $\tan\delta = 4\times10^{-5}$. This value is conservative since the effect of conductor loss was neglected. It is in agreement with literature reports [7] of similar measurements. It was assumed that the dielectric loss factor was constant through the X band. This has not been confirmed experimentally.

Since accurate design of the filter center frequency and the bandwidth require that ϵ_r be determined to high precision, the real part of the permittivity, ϵ_r, was not determined from the same experiment as $\tan\delta$. The reason was that the 650 MHz resonator used was a meander microstrip line with an electrical length significantly different from that of a straight line of the same physical length. Radial bends, a certain amount of parasitic coupling between arms, and the effect of the end terminations all contributed to this difference. Modeling and corrections for these effects would have detracted from the precision required for filter design. Rather, the value of $\epsilon_r = 24.5$ published in some early work [8] was used to design two- and four-pole filters for the initial stages of our HTS work. From deviations of the measured center frequencies from design for several filters, a value for ϵ_r of 23.4 at 77 K was found, which yielded results close to design for the six-pole filters discussed below. This value of ϵ_r is in agreement with that in [9], obtained from microstrip resonator measurements. In [9], however, the technique used to measure the $\tan\delta$ of $LaAlO_3$ was rather indirect and yielded a conservative value (5×10^{-4} at 77 K). As explained above, a more direct measurement using a high-Q resonator with low conduction losses yields a $\tan\delta$ value one order of magnitude lower.

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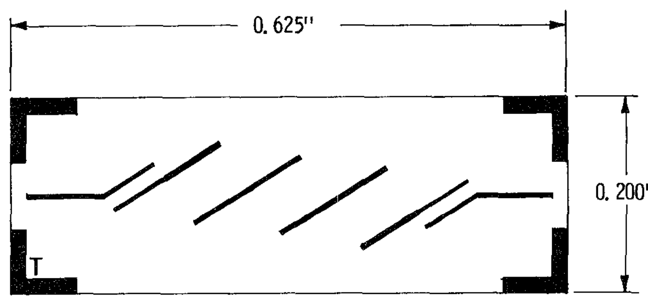

Fig. 4. Geometry of the four-pole parallel-coupled resonator microstrip filter. The dimensions of the substrate are given as an indication of the scale of the drawing.

IV. HTS Four-Pole Filter Design and Fabrication

Four-pole, quarter-wave, parallel-coupled line microstrip filters were built with both normal and superconductor ground planes. The filter geometry is shown in Fig. 4. This filter has five coupled sections. Because it was not yet possible for us to deposit *in situ* epitaxial films on both sides of a substrate, the filter housing was designed to accommodate a separate ground plane substrate. Even

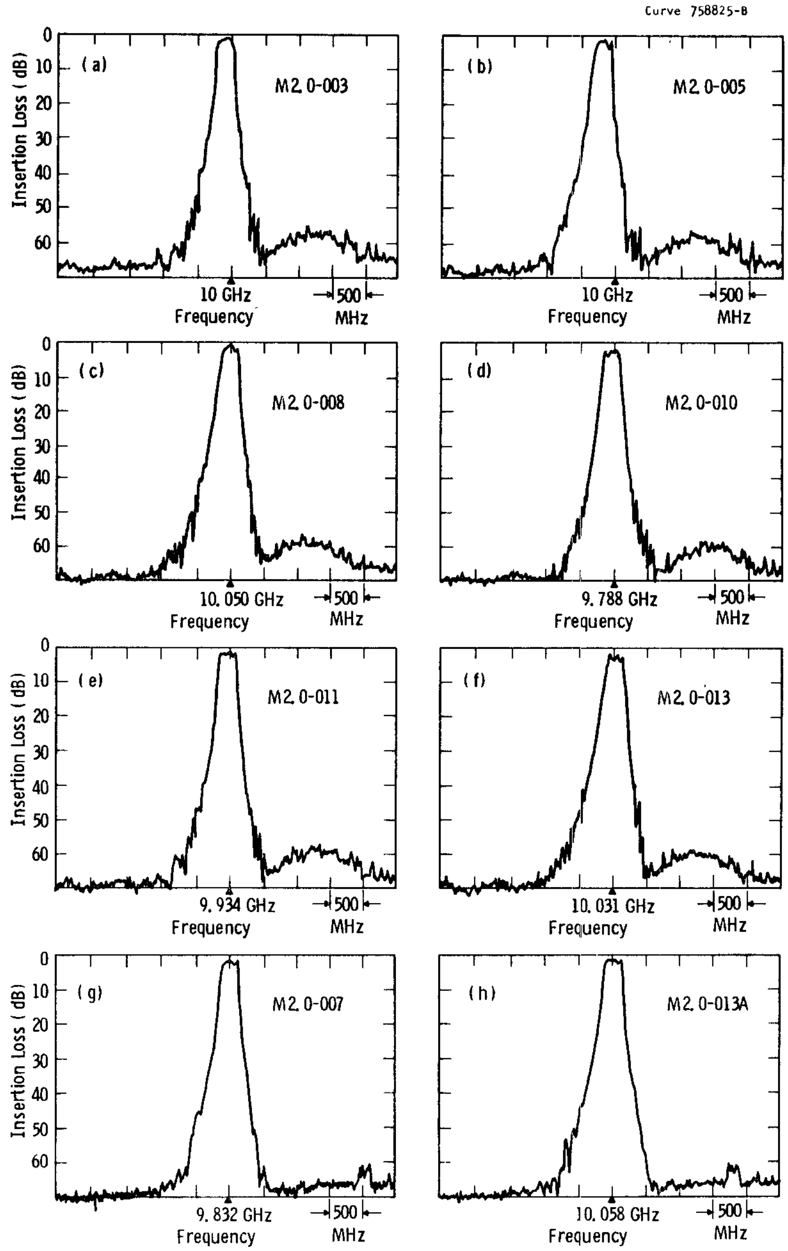

Fig. 5. Passbands at 77 K (liquid nitrogen) for eight four-pole high-temperature superconducting filters, showing a high degree of reproducibility in shape and out-of-band rejection. Fig. 5(f) is for a superconducting ground plane. All the other filters had a normal conductor as a ground plane.

though this approach tends to result in detrimental air gaps between the substrate with the patterned superconductor and the ground plane, the fabrication scheme chosen allowed us to explore the full potential of HTS materials in high-performance microwave filters.

A microstrip configuration was chosen over stripline in order to limit the number of substrates per filter to 2 when including a HTS ground plane. Microstrip has the further advantage that a housing designed to be a cutoff waveguide has larger dimensions than if stripline were used, allowing the use of rectangular substrates without the narrowed-down sections at the input and output ports shown in Fig. 1. This is especially important in HTS film work, since $LaAlO_3$ substrates have a high dielectric constant ($\epsilon_r \simeq 24$). As mentioned previously, a housing with cutoff waveguide dimensions is necessary for obtaining low input–output electromagnetic coupling and, hence, a large out-of-band rejection.

Of primary importance to the success of these devices is the package. Although there are obvious differences between housing microstrip and stripline circuits, key techniques first demonstrated in the LTS stripline case discussed above were adapted and perfected for use with the microstrip HTS filters. Discussions of packaging considerations and microwave measurements on these four-pole filters have been presented elsewhere [10], [11]. Fig. 5 shows the passbands of eight of these filters, taken at 77 K, showing the degree of repeatability we obtained. Fig. 5(f) corresponds to a filter with a superconducting ground plane. The rest are for filters with normally conducting

TABLE I
HIGH-TEMPERATURE SUPERCONDUCTING FILTER PAIR AT X-BAND: DESIGN CHARACTERISTICS

Chebychev response
Microstrip
Coupled quarter-wave sections: 7
Poles: 6

$\epsilon_r = 23.4$
$\tan\delta = 4\times10^{-5}$
$h = 0.0432$ cm (microstrip-to-ground-plane distance)
$h_c = 0.635$ cm (cover height)

	Low-Frequency Filter	High-Frequency Filter
Center frequency (GHz)	9.705	9.925
Ripple bandwidth (%)	1.55	1.51
Passband ripple (dB)	0.10	0.10
Lower ripple band edge (GHz)	9.63	9.85
Higher ripple band edge (GHz)	9.78	10.00
26 dB rejection at (GHz)	9.595, 9.815	9.815, 10.035

ground planes. The center frequency and the bandwidth were higher than the design values for all of these filters, 9.5 GHz and 190 MHz, respectively [11]. As can be seen in Fig. 5, there was also considerable variation in center frequency among the filters. This was attributed to air gaps between the ground plane and the bottom of the substrate with the patterned filter. On the other hand, the passbands look very clean, with a high out-of-band rejection and a reasonably flat top. Other details of the electrical characteristics of these filters were discussed in [11]. The insertion loss for the filter with HTS ground plane (Fig. 5(f)) was not better than the others in the figure because the losses were limited by the mismatch losses at both ports [12].

V. HTS SIX-POLE FILTER PAIR AT X BAND

A six-pole Chebychev filter pair with a design goal similar to that for the LTS filter pair was fabricated in HTS. These filters were made using essentially the same techniques developed for the four-pole ones. A major difference, however, was the ground plane, which was a normal conductor (gold) directly deposited on the back of the $LaAlO_3$ substrate supporting the patterned HTS film. The filters were designed to have adjacent passbands. The design parameters are listed in Table I. As discussed previously, a relative dielectric constant of 23.4 was used for the $LaAlO_3$ substrate in the design of these filters. The filter geometry was essentially the same as that shown in Fig. 4 but with seven coupled sections instead of five. Likewise, the housings were somewhat larger than those for the four-pole filters but otherwise identical to them [10], [11]. Fig. 6 shows the passbands for the filter pair. Notice that in this case the experimental results were much closer to the design goals than for the four-pole filters. The center frequencies for both filters were about 30 MHz lower than the designed value. The crossovers were measured at −28 dB, only 2 dB lower than the design goal of −26 dB. Fig. 7 shows the higher frequency filter passband superimposed to the design objective, indicating the bandwidth and skirt selectivity requirements,

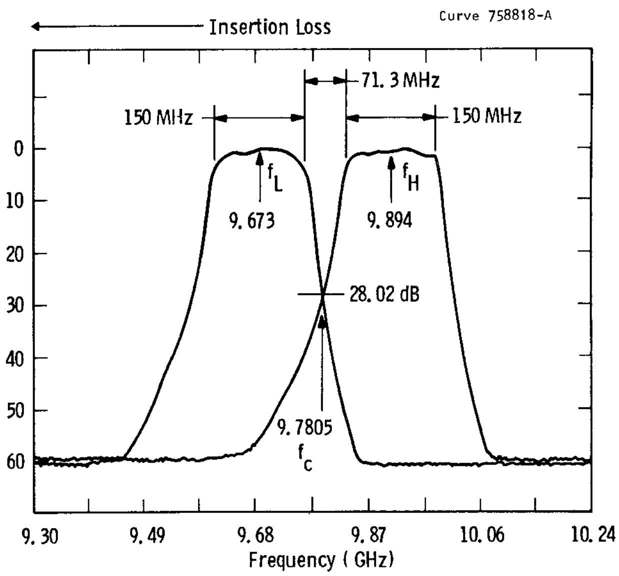

Fig. 6. Superimposed passbands at 77 K for the six-pole high-temperature superconducting filter pair.

shifted downward in frequency by 31.5 MHz in order for it to lie on the measured response. As can be seen, the upper skirt meets the design very closely, but the fit of the lower skirt is not as close. The lower frequency filter (Fig. 6) had a more rounded passband than was desired. Overall agreement with design was very good for both filters, however.

Fig. 7 also shows the return losses for both ports of the higher frequency filter. These are higher than those obtained for the four-pole filters [11], which is attributed both to the use of a ground plane directly deposited on the back of the HTS substrate and to improved assembly techniques from the experience gained with the four-pole filters.

VI. CONCLUSIONS

Low-loss, narrow-band microstrip filters can become a reality using superconductors. Their potential has been demonstrated and the techniques developed so far show that results reasonably close to design goals can be obtained repeatedly. Several issues must still be addressed before system evaluations and production can become possible. In particular, double-sided deposition of *in situ* epitaxial films is being developed in order to eliminate air gaps and complicated packaging. This improved configuration will be tested soon. Techniques requiring post-deposition annealing are already being used successfully for this purpose [13].

An important consideration for superconducting filters is obtaining a good impedance match at the input and output ports. The reason is that conductor losses are now small enough to be of the same order as matching losses. This problem has been discussed at greater length in [12]. This is a critical issue and great care must be devoted to all aspects of the fabrication of superconducting filters to

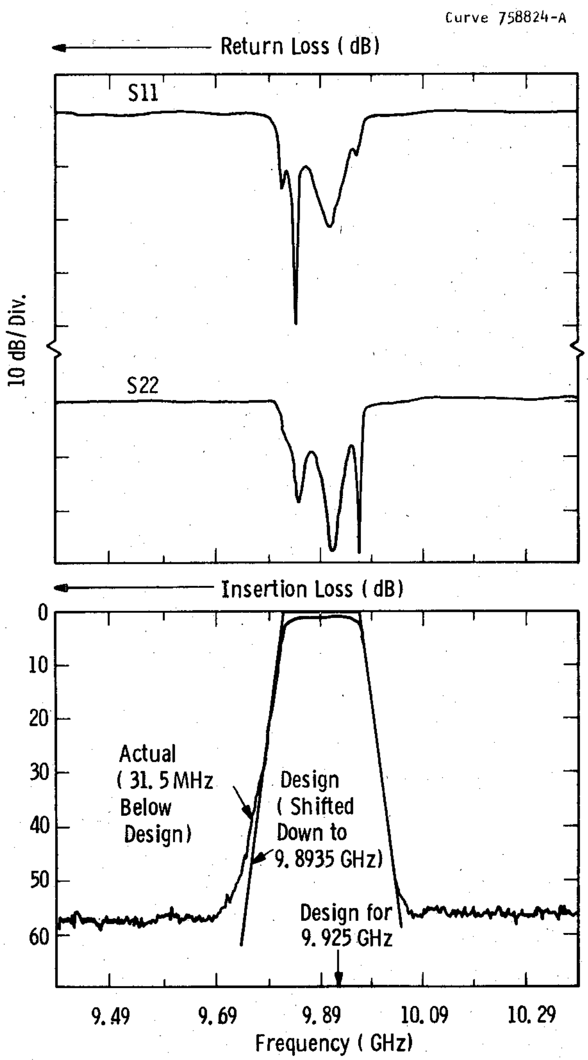

Fig. 7. Return and insertion loss response at 77 K for one of the high-temperature superconducting six-pole microstrip filters. A normal-metal ground plane was used for this filter. Superimposed to the passband is the design objective shifted down by 31.5 MHz to lie on the measured response.

achieve the return losses required ($\simeq$ 20 dB) in order to produce as-designed filters with 1% bandwidth or less.

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References

[1] R. P. Owens, J. E. Aitken, and T. C. Edwards, "Quasi-static characteristics of microstrip on an anisotropic sapphire substrate," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-24, pp. 499–505, Aug. 1976.

[2] J. Talvacchio, M. G. Forrester, J. R. Gavaler, and T. T. Braggins, in *Science and Technology of Thin Film Superconductors II*, R. McConnell and S. A. Wolf, Eds. New York: Plenum, 1990, pp. 57–66.

[3] J. R. Gavaler and J. Talvacchio, *Physica B*, vols. 165 and 166, pp. 1513–1514, 1990.

[4] J. W. Ekin, A. J. Panson, and B. A. Blankenship, "Method for making low-resistivity contacts to high T_c superconductors," *Appl. Phys. Lett.*, vol. 52, no. 4, pp. 331–333, 1988.

[5] R. C. Taber, "A parallel plate resonator technique for microwave loss measurements on superconductors," *Rev. Sci. Instrum.*, vol. 61, no. 8, pp. 2200–2206, 1990.

[6] H. Piel and G. Mueller, "The microwave surface impedance of high-T_c superconductors," *IEEE Trans. Magn.*, vol. 27, pp. 854–862, Mar. 1991.

[7] M. Kuhn, M. Klinger, A. Baranyak, and J. H. Hinken, "HTSC inverted and conventional geometry microstrip resonator for UHF frequencies," *IEEE Trans. Magn.*, vol. 27, pp. 2809–2812, Mar. 1991.

[8] W. G. Lyons, "Low-loss substrates for high-temperature superconductors," MIT Lincoln Laboratory Quarterly Technical Report, Oct. 1989.

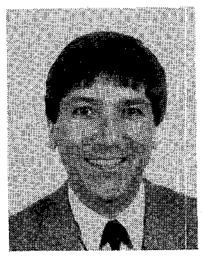
[9] R. R. Bonetti and A. E. Williams, "Preliminary design steps for thin-film superconducting filters, in *1990 MMT-S Int. Microwave Symp. Dig.*, pp. 273–275.

[10] M. A. Janocko *et al.*, "Packaging considerations for high T_c microwave devices," to be published.

[11] S. H. Talisa *et al.*, "Microwave superconducting filters," *IEEE Trans. Magn.*, vol. 27, pp. 2544–2547, Mar. 1991.

[12] S. H. Talisa, M. A. Janocko, J. Talvacchio, and C. Moskowitz, "Present and projected performance of high-temperature superconducting filters," in *1991 MTT-S Int. Microwave Symp. Dig.*, pp. 1325–1328.

[13] W. G. Lyons *et al.*, "High-T_c superconductive microwave filters," *IEEE Trans. Magn.*, vol. 27, pp. 2537–2539, Mar. 1991.



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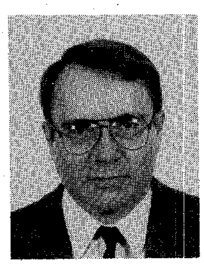

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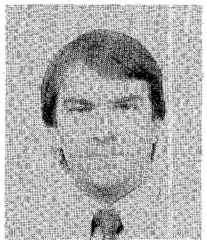

John Talvacchio received the B.S. degree in physics from Case Western Reserve University, Cleveland, OH, in 1977 and the Ph.D. degree in applied physics from Stanford University, Stanford, CA, in 1982. His dissertation was a study of the current-carrying limits of superconductors.

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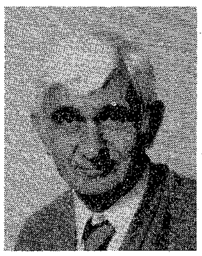

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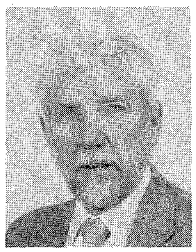
In 1983 Mr. McAvoy was awarded the Westinghouse Engineering Achievement Award and in 1990 a Westinghouse Signature Award of Excellence. He is a member of the committee MTT-18, Microwave Superconductor Applications, and is chairman of MTT-2, Microwave Acoustics. He has served on the technical program committees for the International Microwave Symposium and the Ultrasonics Symposium and is on the Editorial Board of the IEEE MICROWAVE AND GUIDED WAVE LETTERS. He was the recipient of an IEEE Centennial Medal.



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D. H. Watt, photograph and biography not available at the time of publication.