Presented at the CEC/ICMC Conference, Portland, Oregon, July 28-Aug 1, 1997.

"Advances in Cryogenic Engineering - Materials", vol. 44
ed. International Cryogenic Materials Conference, Plenum, 1998

# MINIATURIZED MULTILAYER FILTERS WITH $YBa_2Cu_3O_{7-\delta}$ ON $LaAlO_3$ AND MgO SUBSTRATES

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## ABSTRACT

The need for filter miniaturization without performance degradation has become a critical requirement for the payload of the next generation of communication satellites. Currently, these payloads contain hundreds of filters that are used for frequency multiplexing. Typically, these filters consist of dual mode cavities or dielectric filled resonators which generally are large and heavy. An ongoing effort between the Electron Device Technology Branch of the NASA LeRC and Space System/Loral has resulted in a demonstration of a proof-of-concept (POC) C-band $YBa_2Cu_3O_{7-\delta}$ (YBCO) on $LaAlO_3$ multilayer filter with a raw value for the minimum insertion loss of 0.18 dB at 77 K, 3.81 GHz, and ~3 W input power. Implementing this dual-mode, four pole filter with gold instead of YBCO resulted in a minimum insertion loss of 3.39 dB at room temperature and of 1.61 dB at 77 K at 3.86 GHz and 10 dBm input power. The volume of this filter is ~0.46 $cm^3$ which is less than 1 percent of the volume of its dielectric counterparts at C-band. The filter was also implemented using MgO substrates, which have a dielectric constant lower than their $LaAlO_3$ counterparts (9.7 versus 24, respectively). For a YBCO on MgO filter, a raw minimum insertion loss of 0.34 dB was measured at 6.09 GHz and 77 K, while its gold counterpart exhibited 1.86 dB and 1.11 dB at 5.98 GHz at room temperature and 77 K, respectively. The advantages and limitations of this novel filter configuration will be discussed.

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## INTRODUCTION

Microwave filters intended for satellite communications must exhibit very low losses, narrow passband, and steep skirts (i.e., out-of-band rejection) in order to comply with the stringent demands of the frequency spectrum utilization. Thus, high temperature superconducting (HTS)-based filters represent a viable alternative because of their already well demonstrated low microwave losses. Due to the simple fabrication processes necessary for etching circuits on HTS thin films (i.e., standard photolithography and chemical or dry etching techniques), HTS-based filters for multiplexing applications can be fabricated at a lower cost than their cavity counterparts. One type of filter that has been explored for these applications is the dual-mode patch filter.[1–3] Contrary to the microstripline-based filters (e.g., edge coupled filters) which in general exhibit high insertion losses and are not suitable for bandwidth of less than 5 percent,[1] dual-mode patch resonators could allow for the fabrication of narrow passband (less than 1 percent) filters which are smaller and lighter than the dual mode cavities and dielectric filled resonators currently used. In addition, their power handling capability is enhanced since the available surface area reduces the current density.[3]

In this paper, we report on the performance of a C-band, four pole, dual-mode multilayer filter implemented with $YBa_2Cu_3O_{7-\delta}$ (YBCO) and gold (Au) thin films on (100) single-crystal $LaAlO_3$ (LAO) and (100) MgO substrates. The volume of this filter is ~0.46 $cm^3$, which represents less than 1 percent of the volume of their dual mode cavities or dielectric filled resonators counterparts (~400 to 2000 $cm^3$). The fabrication, testing, and performance of this filter configuration will be discussed.

## EXPERIMENTAL

A schematic representation of the filter discussed in this work is shown in Figure 1. This filter consists of two dual mode stripline, planar patch resonators stacked together in a multilayered configuration and electromagnetically coupled through slot irises. Coupling between the dual orthogonal modes of each resonator is attained by introducing a perturbation (i.e., a notch) to the symmetry of the previously single mode resonator at a location that is offset 45° from the axes of coupling to and from the resonator. The microwave signal is fed to the bottom patch of the structure through feed lines directly coupled to the resonator. The theoretical considerations for this design have been discussed by Fiedziuszko, et al.[4] and Kwok, et al.[5] in previous works.

The YBCO thin films on LAO and MgO used in this study were obtained from two commercial vendors. The films on LAO were deposited by laser ablation on 508 μm thick substrates and were ~350 nm thick. Those on MgO were deposited by thermal coevaporation on 508 μm thick substrates and were 500 nm thick. Both types of films exhibited $T_c \geq 87$ K, where $T_c$ is the zero dc-resistance transition temperature as measured using standard four-point probe measurement techniques. The circuit patterns for each of the filter's layers were transferred to the YBCO films using standard photolithography techniques and chemical etching (etch-back) using diluted phosphoric acid ($H_2O$:$H_3PO_4$;100:1 concentration). The Au films were deposited "in-house" using electron beam evaporation. The e-beam deposition process consisted of growing a ~15 nm thick adhesion layer (either chromium or titanium), followed by a 2.5 μm thick Au film. Etching of the Au circuits was also achieved by standard photolithography techniques and chemical etching. Because of the vertical stacking nature of this filter, care was taken of etching "mirror-like" circuits in the contiguous faces of adjacent substrates, as shown in Figure 1. This not only allows for better contact between the layers, but also reduces the degrading effects of air gaps between the layers of the filters. As reported by others,[6] inclusion of the circuit pattern on

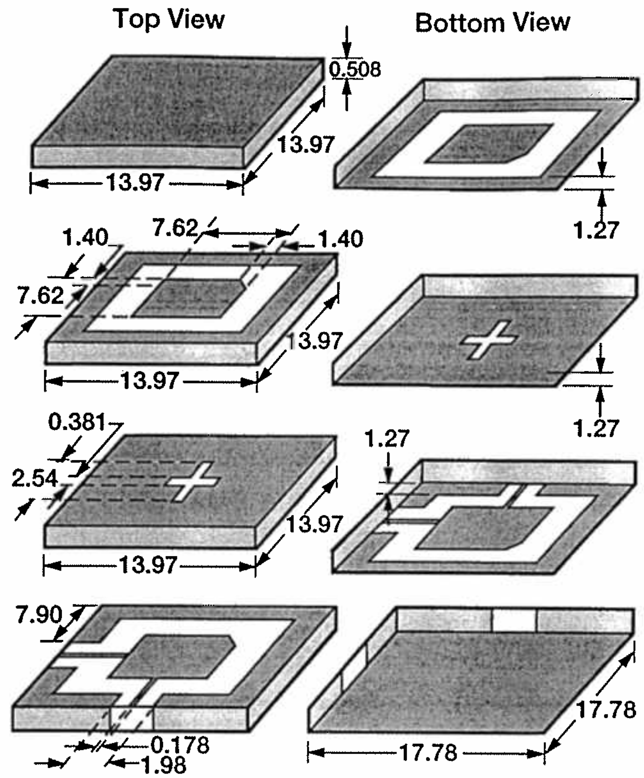


Figure 1.— Physical layout of a four-pole dual mode multilayer filter; dimensions are in mm.

the adjacent faces of contiguous substrates becomes more relevant when dealing with stacking (i.e., packaging) of hard substrates such as LAO and MgO. When vertically stacked, as in the stripline configuration, these substrates may introduce interface and grounding problems which result in considerable deterioration of the filter performance.[5,6]

Microwave testing of the YBCO filters was performed at 77 K, while for their Au counterparts data were taken at room temperature and 77 K. The filters were mounted in a test block designed to fit inside a custom-made aluminum vacuum chamber and on top of the cold finger of a helium gas closed-cycle refrigerator. Figure 2 shows a Au dual mode resonator (i.e., the first layer of the stacked configuration) mounted on the test fixture as well as a schematic representation of the mounting assembly of the full structure. Grounding of the structure was achieved by applying silver paint to the edges of the layers. The microwave signal was coupled to the feed lines of the filter through SMA coaxial connectors. The reflection ($S_{11}$) and transmission ($S_{21}$) scattering parameters were measured using an HP-8510 C Network Analyzer. All the calibrations were performed at room temperature using standard Short-Open-Load-Thru (SOLT) calibration techniques. The reference planes for the calibration were established at the connecting points between the SMA connectors and the coaxial semi-rigid cables going to the analyzer. Therefore, the insertion losses reported here represent the "raw" data without correcting for the losses introduced by the SMA launchers.

## RESULTS

Figure 3 shows $S_{11}$ and $S_{21}$ data for a Au on LAO filter at room temperature and at 77 K. This filter shows a minimum insertion loss of 3.43 dB at room temperature and 3.86 GHz, and of 1.61 dB at 77 K. Observe that the filter exhibits a bandwidth of ~3.6 percent at both tempera-

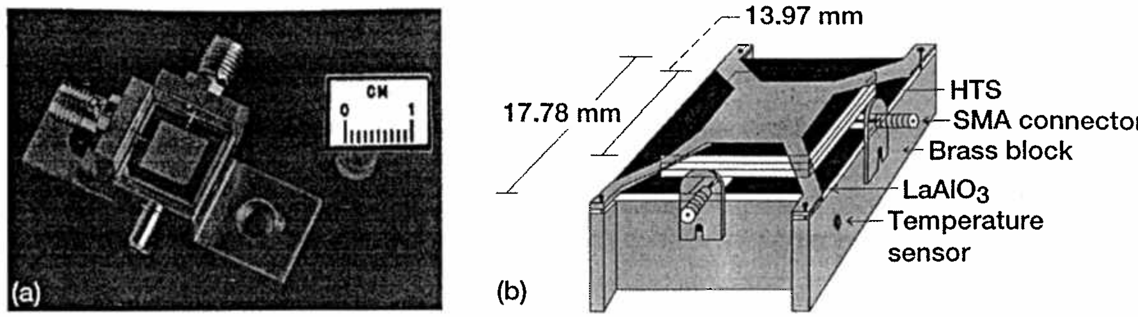


Figure 2.—(a) dual mode proof of concept (POC) gold resonator with corner-cut and (b) schematic representation of the testing assembly for the full multilayer filter.

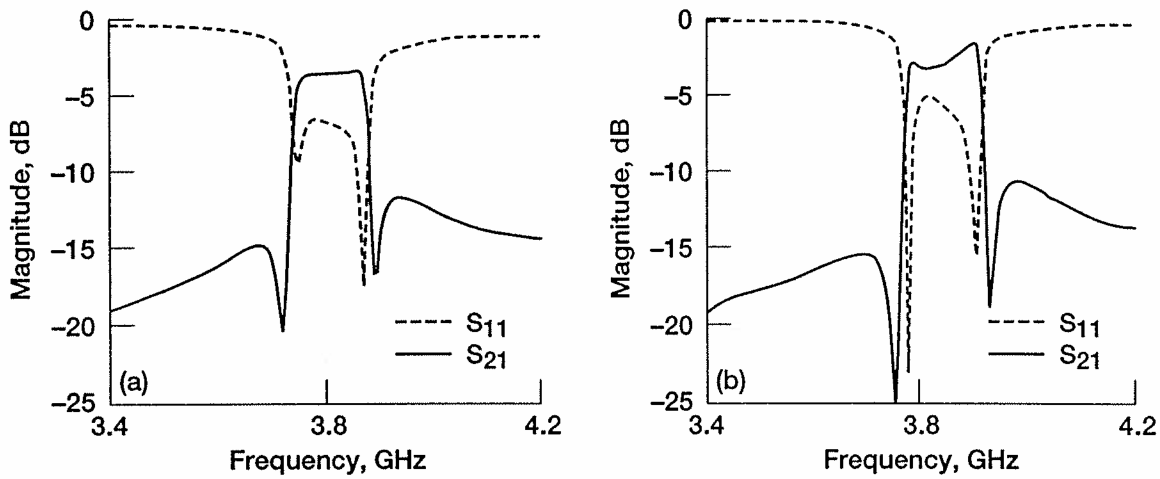


Figure 3.—Experimental data for a Au on LAO multilayer filter at room temperature (a), and 77K (b).

tures, although the flatness of the passband degraded slightly at low temperatures. This measured bandwidth is narrower than the design value of 4.6 percent partly because of the imperfect alignment of the mirrored narrow irises. A slightly larger iris should be used on one layer to compensate for this misalignment. The filter also shows well defined finite transmission zeros by the passband. From $S_{11}$ it can be observed that only 2 of the poles are appreciably seen, while the suppression of the others indicates that the filter couplings are not optimized. Figure 4 shows the data for the YBCO multilayer filter on LAO at 77 K. This filter exhibits a minimum insertion loss of 0.18 dB at 3.81 GHz, which represents an improvement of 3.25 dB and 1.43 dB with respect to its gold counterpart at room temperature and 77 K, respectively. Note that as for the gold version, only two poles of the filter are appreciably seen in the $S_{11}$ data. As compared to the Au version, it is more difficult to achieve electrical contact for the HTS multilayer due to inconsistancies in the quality of the YBCO films.

One of the most important parameters in filters designed for multiplexing applications is their power handling capability. This aspect is more critical for filters intended for multiplexers in the transmission end of the satellite transponder, where high power signals are handled. Therefore, we performed power handling tests in our filter using the HP-8510 C network analyzer, a customized test set (HP-8511 A frequency converter), and an S-band Hughes traveling wave tube amplifier (TWTA), model 1277H. A correlation between the power selected in the analyzer and the input power to the filter was performed by measuring the input power at the coaxial connector outside the vacuum chamber using an HP 436A power meter. We observed that the insertion loss of the filter remained close to 0.18 dB up to input powers below 3.72 W, at which the insertion loss increased drastically. Although larger cw power handling capabilities (~40 W)

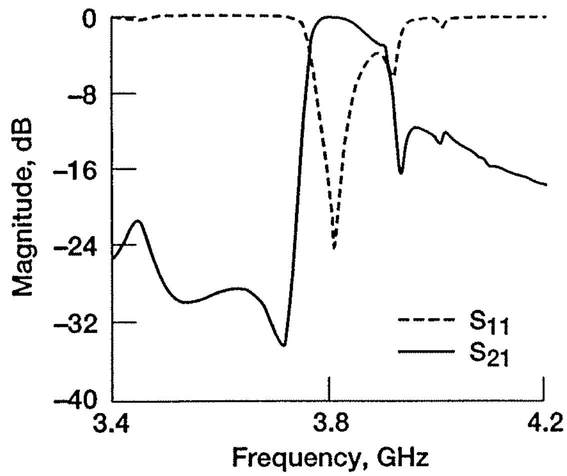


Figure 4.—Experimental data for a YBCO on LAO multilayer filter at 77K.

**Table 1.** Power handling capability of multilayer filter at 77 K and 3.8 GHz

| Input power, W | Insertion loss, dB |
|---|---|
| 0.016 | –.18 |
| 0.050 | –.18 |
| 0.100 | –.18 |
| 0.250 | –.18 |
| 0.631 | –.18 |
| 1.41 | –.18 |
| 3.16 | –.19 |
| 3.72 | –13.98 |

have been reported for larger (~12 $cm^3$) HTS-based dielectric resonator oscillators,[7] the power reported here is larger than the 0.3 W recently reported for YBCO coplanar transmission lines at 1.3 GHz and 70 K.[8] Our power data are summarized in Table 1. The equivalent power handling capability of a reference filter of four-poles, 1 percent bandwidth, is about 1.12 W with our configuration.[9]

There are some concerns among the researchers in this field regarding the use of the LAO substrates for HTS-based microwave components, not only because of the variations in dielectric constant but also because of the surface roughening after the HTS deposition process.[10] We have found that the dielectric constant of LAO (~24) may vary even up to 1.2 percent from substrate to substrate. These changes may degrade filter performance and reproducibility. Therefore, we have also fabricated the multilayer filter using MgO as a substrate, since it not only has a dielectric constant (~9.7) lower than LAO, but also is twin free. No adjustment of the dimensions of the filter were made other than minor adjustments on the coupling, in order to keep the filter volume as well as the test set up the same. Figure 5 shows $S_{21}$ and $S_{11}$ data for a Au on MgO filter at room temperature and at 77 K. Note that because of the smaller dielectric constant, the filter passband has shifted to frequencies near 6 GHz, a factor of $\sqrt{24/9.7} = 1.57$ higher than the LAO counterpart. This filter exhibits a relatively flat passband at both temperatures, ~4.2 percent bandwidth, and well defined finite transmission zeros. The filter has a minimum insertion loss of 1.86 dB and 1.11 dB at room temperature and 77 K, respectively. Note that these losses are smaller than those measured for its Au on LAO counterpart. This may be due to a lower quality of metallization for the LAO circuit, given the fact that the loss tangents (tan$\delta$) for both substrates are comparable ($\leq 10^{-5}$).[11] Figure 6 shows data for the YBCO on MgO filter at 77 K. This filter exhibits a minimum insertion loss of 0.34 dB at 6.09 GHz and 77 K. It also shows a bandwidth of ~3.7 percent. Although the passband is not completely flat, this minimum insertion loss is 0.8 dB better than that exhibited by its gold counterpart at the same temperature, and just slightly larger than that of the YBCO on LAO filter at 3.81 GHz. Therefore, YBCO films on MgO could enable fabrication of this type of filter, facilitating design because of the low dielectric constant and "twin free" nature of MgO, but at the expense of a minor increase in filter volume as compared to LAO for a given frequency of operation. As in the LAO version of the filter, the measurement of the MgO multilayer filters also indicates that for this configuration stringent control of the alignment and contact of corresponding circuits in the different multilayers are critical elements for optimal performance.

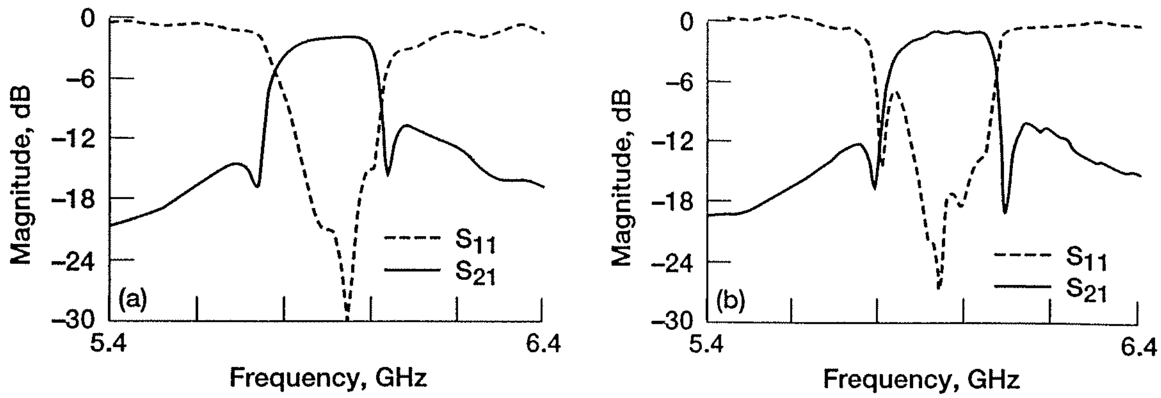


Figure 5.—Experimental data for a Au on MgO multilayer filter at room temperature (a), and 77K (b).

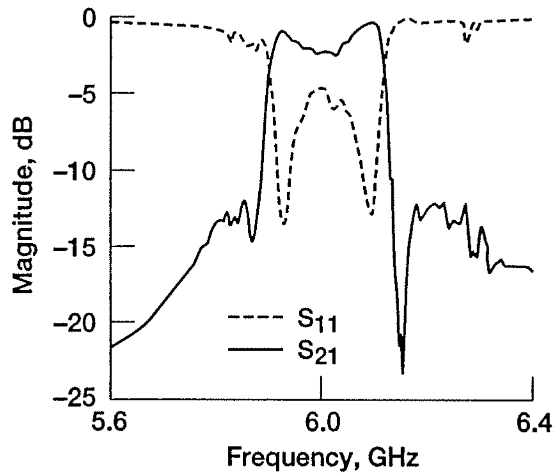


Figure 6.—Experimental data for a YBCO on MgO multilayer filter at 77K.

## CONCLUSIONS

We have measured the performance of miniaturized C-band, dual mode, YBCO on LAO and YBCO on MgO multilayer filters. The YBCO on LAO filter exhibited a ~3.6 percent bandwidth and a "raw" minimum insertion loss of ~0.18 dB at 3.81 GHz, 77 K, and up to 3.72 W. Its gold on LAO counterpart exhibited minimum insertion losses of 3.39 dB and 1.61 dB at room temperature and 77 K, respectively. Similarly, the YBCO on MgO filter exhibited a bandwidth of ~3.7 percent and minimum insertion loss of 0.34 dB at 77 K, and 6.09 GHz, versus 1.86 dB and 1.11 dB at 5.98 GHz for gold at room temperature and 77 K, respectively. For this filter geometry, close attention should be paid to the alignment and contact of corresponding circuits in the different multilayers to achieve optimal filter performance. However, we have demonstrated that this filter configuration could enable the realization of high performance miniaturized C-band filters at a lower cost and at less than 1 percent of the volume of currently used technology.

## ACKNOWLEDGMENTS

The authors are grateful to Mr. R. Romanofsky for his assistance with the power measurements and to Mr. N. Varaljay for the fabrication of the YBCO on MgO circuits.

## REFERENCES

1. J.A. Curtis and S.J. Fiedziuszko, Miniature dual mode microstrip filters, *IEEE MTT-S Dig.*: 443 (1991).
2. S.Y. Lee, K.Y. Kang, and D. Ahn, Fabrication of YBCO superconducting dual mode resonator for satellite communications, *IEEE Trans. Appl. Supercond.* 5: 2563 (1995).
3. A. Flores, C. Collado, C. Sans, J. O'Callaghan, R. Pous, and J. Fontcuberta, Full-wave modeling of HTS dual-mode patch filters and staggered coupled-line filters, *IEEE Trans. Appl. Supercond.* 7: 2351 (1997).
4. S.J. Fiedziuszko, J.A. Curtis, S.C. Holmes, and R.S. Kwok, Low loss multiplexers with planar dual mode HTS resonators, *IEEE Trans. Microwave Theory Tech.* 44: 1248 (1996).
5. R.S. Kwok, S.J. Fiedziuszko, F.A. Miranda, G.V. León, M.S. Demo, and D.Y. Bohman, Miniaturized HTS/dielectric multilayer filters for satellite communications, *IEEE Trans. Appl. Supercond.* 7: 3706 (1997).
6. G.L. Matthaei and G.L. Hey-Shipton, Novel staggered resonator array superconducting 2.3-GHz bandpass filter, *IEEE MTT-S Dig.*: 1269 (1993).
7. R.R. Mansour, B. Jolley, V. Dokas, S. Ye, and F. Thomson, Design of high power superconductive output multiplexers, *IEEE MTT-S Dig.*: 1485 (1996).
8. Z.Y. Shen, C.W. Wilkers, P. Pang, D.W. Face, C.F. Carter III, C.M. Harrington, Power handling capability improvement of high temperature superconducting microwave circuits, *IEEE Trans. Appl. Supercond.* 7: 2446 (1997).
9. R.R. Mansour, B. Jolley, S. Ye, F. Thomson and V. Dokas, Assessment of the Power Handling Capability of HTS-Filters, *IEEE MTT—S Workshop*, 1996.
10. G.L. Matthaei and G.L. Hey-Shipton, High temperature superconducting 8.45-GHz bandpass filter for the deep space network, *IEEE MTT-S Dig.*: 1273 (1993).
11. T. Konaka, M. Sato, H. Asano, and S. Kubo, Relative permittivity and dielectric loss tangent of substrates materials for high-$T_c$ superconducting film, *J. Supercond.* 4: 283 (1991).