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YBCO HIGH-TEMPERATURE SUPERCONDUCTING
FILTERS ON M-PLANE SAPPHIRE SUBSTRATES

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ABSTRACT

Since the discovery of High Temperature Superconductors (HTS) in 1986, microwave circuits have been demonstrated using HTS films on various substrates. These HTS-based circuits have proven to operate with less power loss than their metallic film counterparts at 77 K. This translates into smaller and lighter microwave circuits for space communication systems such as multiplexer filter banks. High quality HTS films have conventionally been deposited on lanthanum aluminate ($LaAlO_3$) substrates. However, $LaAlO_3$ has a relative dielectric constant (ϵ_r) of 24. With a $\epsilon_r \sim 9.4$-11.6, sapphire (Al_2O_3) would be a preferable substrate for the fabrication of HTS-based components since the lower dielectric constant would permit wider microstrip lines to be used in filter design, since the lower dielectric constant would permit wider microstrip lines to be used for a given characteristic impedance (Z_0), thus lowering the insertion losses and increasing the power handling capabilities of the devices. We report on the fabrication and characterization of $YBa_2Cu_3O_{7-\delta}$ (YBCO) on M-plane sapphire bandpass filters at 4.0 GHz. For a YBCO "hairpin" filter, a minimum insertion loss of 0.5 dB was measured at 77 K as compared with 1.4 dB for its gold counterpart. In an "edge-coupled" configuration, the insertion loss went down from 0.9 dB for the gold film to 0.8 dB for the YBCO film at the same temperature.

INTRODUCTION

Multiplexer filter banks used for channel separation in communication satellites require components that are as small and lightweight as possible. The filters used in multiplexers have

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been successfully made using waveguide or coaxial techniques, yet are large and heavy. Microstrip filters using conventional conductors, which potentially can be used in filter banks, are small, but are often too lossy for multiplexer applications, while conventional superconductors are less lossy, but have to be cooled with liquid helium to 4-5 K. There would be many advantages in developing circuits that could operate at 77 K, since these could be cooled at less cost with liquid nitrogen (boiling point of 77 K). The discovery of High Temperature Superconducting (HTS) materials has brought a solution to these problems. Microstrip filters using HTS films are just as small and lightweight, but can display even less power loss than their waveguide or coaxial counterparts[1-3]. Considering that filter banks are composed of many filters, the gains achieved by using a lower-loss filter are often multiplied.

HTS thin films used in microstrip filters have been deposited on substrates such as Lanthanum Aluminate (LaAlO$_3$), Magnesium Oxide (MgO), Neodymium Gallate (NdGaO$_3$), and sapphire (Al$_2$O$_3$). In general, the best performance of HTS-based microwave components has been obtained from films deposited on LaAlO$_3$. This material, however, has a relatively high dielectric constant, $\epsilon_r \sim 24$[4]. Sapphire (Al$_2$O$_3$) has a much lower dielectric constant of 9.4-11.6, depending on crystal orientations, and would be a better choice for a substrate. The lower dielectric constant would permit wider microstrip lines to be used for a given characteristic impedance (Z$_0$), thus lowering the insertion losses and increasing the power handling capabilities of the devices. Although power handling capabilities of microstrip filters using high ϵ_r substrates (such as LaAlO$_3$) have been improved by using low Z$_0$ resonance elements, the input power is limited by current crowding at junction between the feed line and first resonator[5]. In addition, sapphire has a comparable loss tangent ($tan\delta \sim 4 \times 10^{-8}$) to that of LaAlO$_3$ ($tan\delta \sim 0.76 \times 10^{-5}$) at 77 K and 10 GHz[5]. This combination of a lower dielectric constant and a low loss tangent results in an overall lower power loss[5].

One slight drawback to the use of sapphire as a substrate, however, is the fact that YBCO film cannot be deposited successfully directly on the substrate due to the reactivity of the two materials. At the temperature required for deposition, sapphire reacts with barium oxide (BaO) to form barium aluminate (BaAl$_2$O$_4$). Therefore a buffer layer such as SrTiO$_3$ or MgO, which are both unreactive with the two materials, must be deposited on sapphire before the YBCO film can be deposited. Unfortunately, this creates some loss due to the resultant lattice mismatch. This loss, however, should be minimal enough that the gains from using an HTS film should more than compensate for the loss due to crystal lattice mismatch[6].

HTS films have been successfully deposited on both (1$\bar{1}$00)- and (1$\bar{1}$02)- oriented sapphire (M- and R-plane, respectively). The optic axis in M-plane sapphire is aligned parallel to the substrate surface, whereas in R-plane sapphire it is oriented 32.4 degrees from the substrate surface. Circuit design is complicated by the dielectric anisotropy of the substrate, and becomes most challenging for substrate orientations for which the optic axis is neither perpendicular or parallel to the substrate plane (such as R-plane sapphire). Recent work[7] has shown that the unloaded Q values of linear, one-half wavelength resonators patterned on M-plane sapphire are considerably higher than on R-plane (2100 versus 600). Since the low Q values on the R-plane sapphire could not be attributed to conductor or dielectric losses, the only possibility is that the radiation losses in R-plane sapphire were higher than on M-plane sapphire. The difference in Q values was attributed to radiation losses associated with the fact that the optic axis in R-plane sapphire is neither parallel nor perpendicular to the optic axis, while the optic axis for M-plane sapphire is in the plane of the substrate. Thus, M-plane sapphire is a better candidate for microwave circuits.

In the following sections, we will present design and test results of microwave 3-pole bandpass filters. Four filters were made using two basic designs. Each design was fabricated on M-Plane sapphire substrates using gold or YBCO films. (The YBCO films were obtained from a commercial vendor.) All four were tested at 77 K, and display low-loss performance.
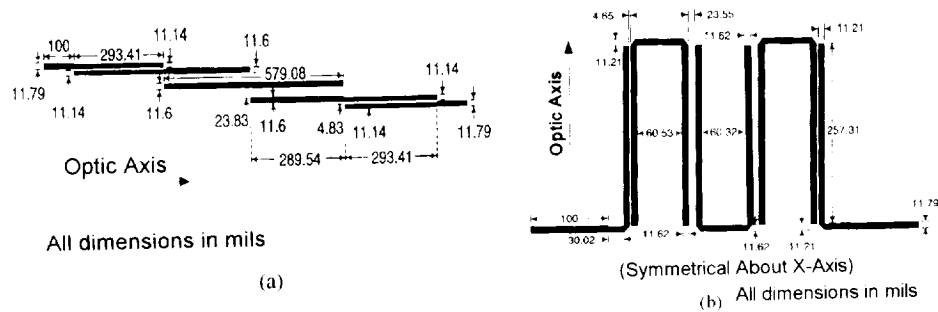
Figure 1. Dimensions of the YBCO/Al₂O₃ edge-coupled (a) and hairpin (b) filters

FILTER DESIGN, FABRICATION, AND TESTING

Two types of bandpass filters were designed using Eagleware© software. The filters were designed to resonate at 4.0 GHz on M-plane sapphire with a dielectric constant of 9.4. One was a hairpin shape and the other was an edge-coupled design (figure 1). Both were two-port, three-pole Chebyshev configurations with 50-ohm lines and 4 percent bandwidths. Four filters were fabricated in a clean room from photo-reduced masks using standard photo-lithography and chemical etching techniques: two using gold film and ground planes (both 2.5 microns thick), and two using single-sided YBCO film and gold ground planes. The gold filters were fabricated on 17-mil thick sapphire substrates. Since the YBCO films were deposited on 12 mil thick substrates, the linewidths and gaps were scaled to yield identical center frequencies and bandwidths. The sapphire used for the YBCO filter had a buffer layer of MgO and had a 3000Å thick YBCO film deposited by magnetron sputtering[8]. A 4000Å thick patch of gold 80 microns narrower than the width of the feedline was deposited on the edges of the YBCO feedlines to improve coupling from the coaxial pin to the filter. None of the YBCO filters were post-annealed, since YBCO on M-plane sapphire films have previously responded unfavorably to this process, becoming substantially more susceptible to thermally-induced microcracks[7]. The edge-coupled filters were fabricated with feedlines parallel to the optic axis, and the hairpin filters were made with feedlines orthogonal to the optic axis, so that the coupling between resonant elements would be perpendicular to the optic axis, and hence the dielectric constant seen by the field lines in the coupling direction would be 9.4.

The filters were tested using a Hewlett-Packard 8510C Automated Network Analyzer (ANA). Both were mounted on brass test fixtures with coaxial pin launchers. The test fixture was mounted inside the vacuum can of a closed-cycle helium gas refrigerator and fed a signal by an HP8517B S-parameter test set. The temperature was controlled using a Lake Shore DRC 91C temperature controller. Both the temperature and ANA were controlled by an HP-BASIC program to record data. The ANA cables and connectors to the launchers on the test fixture were calibrated at room temperature (298 K) using a short-open-load-through calibration technique. An HP 9000-216 computer recorded measurements under vacuum (below 1 millitorr) and in the 20 K to 100 K temperature range. Data at 77 K was particularly used for insertion loss and unloaded Q analysis. Two s-parameters were recorded as a function of frequency, S_{11} (reflection), and S_{21} (transmission). The insertion losses at the maximum of the transmission parameters and at the midband points were recorded. The unloaded Q was calculated using the following equation:

$$Q = \frac{8.686 C'_v \omega_1}{w(\Delta L_t)_0}$$

(1)

Table 1. Insertion losses and unloaded Q values

|	Insertion Loss (dB)	Unloaded Q
Gold Hairpin Filter	1.4	421
YBCO Hairpin Filter	0.5	-
Gold Edge-coupled Filter	0.9	368
YBCO Edge-coupled Filter	0.8	-

where ω_1' is the low pass prototype cutoff frequency (normally $=1$), w is the percent bandwidth, $(\Delta L_A)_0$ is the minimum insertion loss in dB (assuming a symmetrical and flat passband), and C_n is the constant dependent on the Chebyschev ripple and filter order[9]. The constant 8.686 is a conversion from nepers to dB.

RESULTS

The insertion losses at 77 K for edge-coupled and hairpin filters are shown in Table 1. The insertion loss of the hairpin filter changed more drastically when the material was switched to YBCO than did the loss of the edge-coupled filters. At 77 K, the insertion loss of the gold hairpin filter was 1.4 dB. When the YBCO hairpin filter was tested at 77 K, the insertion loss went down to 0.5 dB. The YBCO edge-coupled filter performed very well at lower temperatures. We observed an insertion loss of less than 0.3 dB at 35 K. However, the loss went up to 0.8 dB at 77 K, which was not significantly different from the gold edge coupled filter with a loss of 0.9 dB (also at 77 K).

The unloaded Q values of the gold filters were around 400 (table 1). The unloaded Q values were not calculated for the YBCO filters. These filters had very asymmetrical transmission parameters, unlike the gold versions (figures 2 and 3). All four filters had center frequencies around 4 GHz, but for the HTS filters, the point of minimum insertion loss was shifted a bit higher than the center frequency, making calculation of the unloaded Q using equation (1) difficult. The assymetrical shape and poor performance of the filters were attributed to radiation losses associated with the substrate's anisotropy.
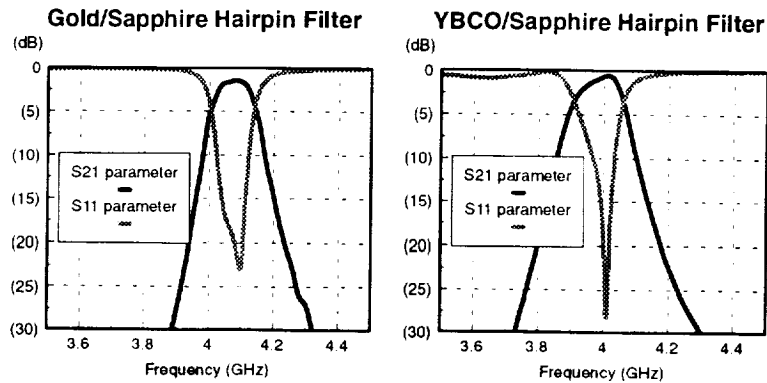
Figure 2. Reflection and transmission parameters of the gold and YBCO hairpin filters.

Gold/Sapphire Edge-Coupled Filter **YBCO/Sapphire Edge-Coupled Filter**
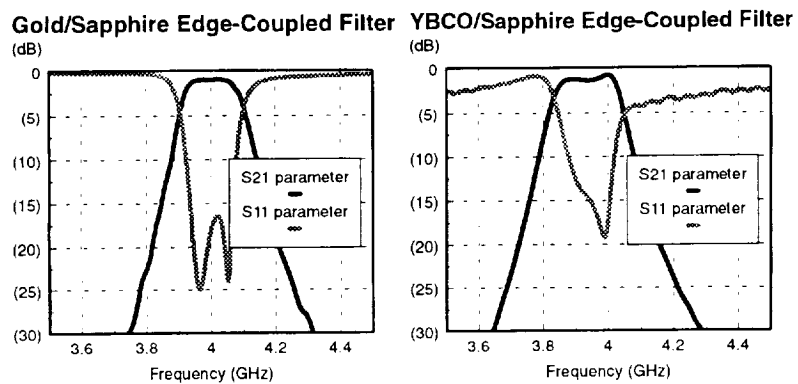
Figure 3. Reflection and transmission parameters of gold and YBCO edge-coupled filters

CONCLUSIONS

HTS YBCO filters have been fabricated on sapphire substrates because of its lower dielectric constant and loss tangent. We attribute the poor performance of the filters to radiation losses resulting from the dielectric anisotropy of the substrates. Despite our efforts to minimize the effects of dielectric anisotropy by aligning the resonator elements parallel to the optic axis, the performance for the YBCO filters is only slightly better than their gold counterparts. Because of this, only a small improvement was obtained by using low-loss YBCO films as the conductors. Since the Q value of a single, one-half wavelength long resonator was measured to be 21000^7, we conclude that most of the microwave energy in the three-pole filters was lost in coupling between elements.

ACKNOWLEDGEMENT

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