Performance of a high $T_c$ superconducting ultralow-loss microwave stripline filter

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We report the successful fabrication of a five-pole interdigital stripline filter made of the 93 K superconductor $Y_1Ba_2Cu_3O_y$ coated on a silver substrate, with a center frequency of 8.5 GHz and an extremely high rejection ratio of 80 dB. The lowest insertion loss measured was 0.1 dB at 12 K, with a return loss better than 16 dB, representing significant improvements over a similar Cu filter, and comparable to low $T_c$ filters. The insertion loss appears to be limited by extrinsic factors such as tuning mismatch and joint losses, and not by the superconducting material losses.

Recent results on the intrinsic microwave properties of high-quality single crystals$^1$ and thin films$^2$ of the high $T_c$ superconductors raise tremendous prospects for the applications of these materials in microwave devices. These results on the surface resistance imply significantly improved performance in devices, compared to devices using conventional materials such as copper. It is clear, however, that significant challenges need to be met and solved in order to translate the results on small scale samples into realistic structures necessary for actual devices.

A bandpass filter is of great utility in systems limited in performance by radio frequency interference (RFI) at the input. This is particularly important in space communications, where the front-end amplifier is a delicate high electron mobility transistor (HEMT) or maser amplifier with very low noise temperature. The effect of incident RFI is primarily determined by the level and frequency of the RFI. Both in-band and out-of-band RFI can result in significant gain compression, noise temperature increase, and in the case of the maser, spurious output signals. For example, a 0.1 dB increase in insertion loss can result in a 0.1 K increase in noise temperature, which can be serious in low-noise systems. Therefore a usable (out-of-band) RFI filter should have stringent specifications: a narrow passband, a high out-of-band rejection ratio (at least 80 dB), and an extremely low insertion loss ($\sim 0.1$ dB) to avoid in-band signal attenuation and added noise.

In this letter we describe the fabrication and performance of an 8.5 GHz bandpass filter made of Ag and coated with $Y_1Ba_2Cu_3O_y$ (YBCO). An interdigital tunable stripline resonator structure was selected over a microstrip filter as the optimal design due to its favorable performance characteristics,$^7$ and its potential ability to meet the design criteria specified above. This structure is compact and, with the exception of wave guide filters, it has the highest unloaded resonator $Q$ amongst the commonly used structures.$^4$ The filter, shown in Fig. 1, consists of five transverse electromagnetic (TEM) mode stripline resonators. Each resonator is approximately one quarter-wavelength long at the midband frequency and is short circuited at one end and open circuited at the other. These resonators are placed between two ground plates which are attached to the filter body by as many screws as possible in order to reduce losses at the joints. Bandpass tuning is accomplished by varying the capacitance of the resonators with the five adjustable screws opposite to each of the five fingers. The particular filter was designed with the aid of the low-pass prototype synthesis methods outlined in Ref. 4. It is a 0.05 dB equal ripple bandpass filter with an equal ripple bandwidth of 0.15 GHz centered at 8.5 GHz.

Three different fabrication methods were considered: (1) making the entire filter out of bulk high $T_c$ superconductor, (2) coating a silver-plated copper filter with a thick YBCO film, and (3) coating a pure Ag filter with a thick superconducting film. Despite our experience with bulk high $T_c$ structures,$^5$ the first method, after some initial trials, was abandoned due to the complexity of the structure (many sharp edges, screw holes, threads, etc.). In the second approach a copper filter was machined and silver plated with a 500-μm-thick film. This filter was subsequently coated with a thick YBCO film. The resultant film looked dark gray and was not superconducting. A possible explanation of this may be that the Ag buffer layer de-

![Superconducting YBCO/Ag filter.](image)
graded at high temperatures and the Cu substrate reduced the YBCO thick film. Finally, the third method attempted was very successful. It involved the machining of the filter out of 99.9% pure silver and the subsequent coating of the filter with a thick YBCO film. The resulting films looked black and exhibited sharp superconducting transitions with $T_c \sim 92$ K. Using this last method three different filters were fabricated, each time making appropriate improvements, and were tested.

The Y$_1$Ba$_2$Cu$_3$O$_{7-x}$ compound was prepared via a solid-state reaction using yttrium oxide, barium carbonate, and copper oxide. Stoichiometric amounts of the constituent materials were mixed and ball milled in methanol for 16 h. The slurry was dried and vacuum calcined at 800 °C for 4 h in an oxygen pressure of $2.7 \times 10^2$ Pa. Thick films were fabricated by mixing the YBCO powder with an organic solvent and a dispersant was added to improve the rheological properties. The suspension was applied to the silver filter substrate and dried at 80 °C for about 2 h. The film was then sintered at 920 °C for 4 h in an oxygen partial pressure of $1.1 \times 10^2$ Pa and annealed at 450 °C for 16 h in 1 atm of oxygen. Sintering in low PO$_2$ enhances the sintering kinetics of YBCO. In addition, the melting point of silver is slightly higher in reduced PO$_2$. The resulting coating thickness was of the order of 50 μm.

An 8510B Hewlett-Packard Network Analyzer with an S-parameter test set was used to precisely tune the filter and perform both the return and insertion loss measurements. The filter was originally tuned at room temperature to better than 20 dB of return loss across the frequency band of interest and subsequently cooled down to 12 K using a closed cycle refrigerator (CCR). Its temperature was monitored by two separate sensors attached to its body and the temperature dependent data were taken as the filter was to warm up slowly. The insertion loss of the coaxial lines inside the CCR is subtracted from the data presented. These lines were separately characterized as a function of temperature for the frequency band of interest.

For an equal-ripple Tchebyscheff filter, the insertion loss $L_s$ at midband is given by the expression

$$L_s (\text{dB}) = 8.686 \left( \frac{C_s}{W Q_u} \right),$$

(1)

where $Q_u$ is the unloaded resonator $Q$, $W$ is the fractional bandwidth, and $C_s$ is a coefficient determined by the filter order and its bandwidth.

From Eq. (1), since $Q_u \propto 1/R_s$, it is readily seen that the insertion loss of a filter is proportional to the surface resistance of the material it is made of. For conventional superconductors like Pb ($T_c = 7.2$ K) and NbTi ($T_c = 9.8$ K) at 4.2 K and at X-band frequencies, the surface resistance is known to be as much as three orders of magnitude lower than that of copper. The expected insertion loss for an ideal filter like the one considered here is therefore of the order of $10^{-4}$ dB. From our own results on the surface resistance of polycrystalline and single-crystal Y$_1$Ba$_2$Cu$_3$O$_{7-x}$ materials, we expect insertion losses of the order of 0.25 dB for the polycrystalline and no more than $10^{-3}$ dB for an “ideal” single-crystal filter.

Figure 2 shows the temperature dependence of the insertion loss of the three different Ag/YBCO filters as a function of temperature. All of the data were taken at an input cw power level of 38 μW. Qualitatively all of the curves look similar. A sharp transition at 93 K is observed as the film becomes superconducting. The insertion loss then tails off at about 70 K at which point it starts decreasing linearly down to 12 K. The lowest value reached is 0.69 dB, and if extrapolated down to 4.2 K, the insertion loss would be 0.61 dB compared to 0.55 dB for a similar copper filter. At lower values of input power the filter exhibits losses lower than that of copper, as discussed later.

The data of Fig. 2 for the three filters that were constructed reveal an important feature, viz., that the differences in performance between the three trials were not due to material properties (i.e. $R_s$), but rather due to nonoptimization of the final devices. This is evident if one superposes the three curves by subtracting constant (temperature-independent) offsets, whence the three curves become identical. Thus in practice, the insertion loss is represented by $L_i (T) = L_i (T) + L_0$, where $L_0$ is temperature independent and arises from connector mismatch, tuning, etc. When this was realized, we were able to achieve our best results with filter No. 3 by improving the ground plane contacts, and by carefully assembling and tuning the filter at room temperature to the lowest insertion loss achievable.

Earlier work with NbTi ($T_c = 9.8$ K) filters substantiates the above the conclusions for the high $T_c$ filter. In the NbTi filter, it was discovered that poor ground plane contacts can contribute as much as 0.5 dB to the insertion loss at cryogenic temperatures, and could be minimized by using knife edges at the joints. The ultimate residual loss achieved with the NbTi filter was 0.10 dB, and it was concluded that this represented the loss due to the connectors.

Thermal cycling strongly affects the $L_s$ data. For filter No. 3, $L_s$ was found to increase after the first thermal cycle and following the filter assembly. After the first thermal cycle, $L_s$ increased by 0.7 dB at room temperature, and the subsequent cool-down data showed an increase by the same amount. Following the final cryogenic measurement, it was found that room-temperature disassembly and reassembly of the filter increased its loss by 3.0 dB. Thus, for
future designs care will have to be taken to reduce warping and dimensional changes in the structure due to the high temperature involved in the fabrication process. In addition engineering design changes will have to be incorporated to eliminate the contact losses at the ground planes.

The surface resistance of samples prepared in the exactly same way as the filter was also measured as a function of temperature down to 77 K, using a 14 GHz microwave cavity, with the sample disk as an endplate. The $R_s$ data showed the same qualitative temperature dependence that was observed for the insertion loss measurements.

As mentioned earlier, the insertion loss $L_s$ was found to exhibit a strong input power dependence even at very low input powers. Figure 3 shows $L_s$ as a function of input power which was varied from 38 $\mu$W to 40 $\mu$W. For the first cool down and very low input cw power levels ($<1$ nW) the filter loss approached very low values of about 0.1 dB. As indicated in Fig. 3, the maximum error at the low power levels and for very low values of $L_s$ is about 0.3 dB, and represents a very conservative upper bound on the measurement.

Such strong dependence on the input power is somewhat puzzling, since the incident magnetic fields on the superconducting film are too weak to account for such effect. A thermal gradient could, however, exist in the YBCO material at the ground plane contacts. It is likely that power levels above 38 nW could be sufficient to locally heat the YBCO material at the shorted base of the resonators a few kelvin above the rest of the material. It should be recalled that the rf current densities are highest at the shorted base of the resonators. This is consistent also with the observed thermal cycling degradation, since the stainless-steel screws would have a slightly different coefficient of expansion than the Ag body, leading to weaker contact force and hence higher losses.

We note several features of the device reported here, which bear on comparisons with thin-film microstrip filters. The waveguide nature of the design by itself should possess the lowest losses achievable, in comparison to microstrip filter structures. The five element configuration also provides a high out-of-band rejection ($\sim$ 80 dB), which is difficult to achieve with thin-film microstrip filters. Connectorization should in principle be easier here because of the metallic substrate. We also note that the very low insertion loss of the filter has forced us to carefully evaluate the procedures for measuring $L_s$, and indeed it is clear that even better performance will require more exact measurement procedures. It should also be noted that at least in space communications, signal power levels are usually very low ($\sim$ nW) which is the level at which our filter exhibits its lowest insertion loss (see Fig. 3).

We have also tested the filter in an actual system configuration designed to measure system noise temperature with a HEMT front-end amplifier. Details of the measurement will be presented elsewhere. At a physical system temperature of $T_m = 20$ K, and with the amplifier noise temperature $T_e = 20$ K, the experiments yielded a noise temperature contribution of 4.6 K, which is in excellent agreement with that inferred from the measured insertion loss data.

In conclusion, we have successfully fabricated and tested a stripline high $T_s$ superconducting microwave bandpass filter. The lowest insertion loss measured was 0.1 dB with an input return loss of better than 16 dB across the passband. The filter provides significant improvements over a comparable Cu filter, and is at present limited not by the superconducting material, but rather by design limitations possibly originating at the time of fabrication. Even at present the filter is comparable to low $T_s$ superconducting devices (with a distinct advantage over the latter, in that operation is possible at elevated temperatures which are cost effective), and meets design criteria for very low noise communication systems, such as in space applications. Design improvements can significantly improve further the performance.

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