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PERFORMANCE OF A HIGH T_c SUPERCONDUCTING ULTRA-LOW LOSS MICROWAVE STRIPLINE FILTER

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ABSTRACT

This article reports 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 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 of better than 16 dB, representing a significant improvement over a similar copper filter, and is comparable to low critical-temperature 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.

INTRODUCTION

Recent results of the intrinsic microwave properties of high-quality single crystals [1] and thin films [2] of the high critical-temperature (T_c) superconductors raise tremendous prospects for the applications of these materials in microwave devices. These results of the surface resistance imply significantly improved performance as compared with devices using conventional materials, such as copper. It is clear, however, that significant problems need to be 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 a 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 0.4-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 bandpass, a high out-of-band rejection ratio (at least 80~dB), and an extremely low insertion loss (~0.1 dB) to avoid in-band signal attenuation and added noise.

FILTER STRUCTURE

This article describes the fabrication and performance of an 8.5-GHz bandpass filter made of silver and coated with $Y_1Ba_2Cu_3O_{7-x}$ (YBCO). An interdigital tunable stripline resonator structure was selected over a microstrip filter as the optimal design due to its favorable performance characteristics [3], and its potential ability to meet the design criteria specified above. This structure is compact and, with the exception of waveguide filters, it has the highest unloaded resonator (Q) among the commonly used structure [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 each of the five fingers. This particular filter was designed with the aid of the low-pass prototype synthesis methods outlined in [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.

FABRICATION METHOD

Three different fabrication methods were considered: (1) making the entire filter out of bulk T_c superconductor; (2) coating a silver-plated copper filter with a thick YBCO film; and (3) coating a pure silver filter with a thick superconducting film. Despite 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.). Some of the edges tended to chip, and the drilling of so many holes weakened or even destroyed the structure. In the second approach a copper filter was machined and silver-plated with a 500-micron thick film. This filter was subsequently coated with a thick YBCO film. The resultant film looked dark gray and was not superconducting. This process was repeated with a number of test pieces without the desired success. A possible explanation of this may be that the silver buffer layer degraded at high temperatures and the copper substrate reduced the thick YBCO film. The same result was obtained even when the sintering temperature was reduced from 920 deg C to 900 deg C. Finally, the third method attempted was very successful. It involved machining the filter out of 99.9 percent pure silver, and subsequently coating the filter with a thick YBCO film, as in the previous method. The resulting films looked black and exhibited sharp superconducting transitions with T_c ~ $92 K. By using this last method, three different filters were fabricated and tested, making appropriate improvements each time.

The YBCO compound was prepared via a solid state reaction by using yttrium oxide, barium carbonate, and copper oxide. Stochiometric amounts of the constituent materials were mixed and ballmilled in methanol for 16 hr. The slurry was dried and vacuum calcined [6] at 800 deg C for 4 hr in an oxygen pressure of 2.7×10^2 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~deg~C for about 2~hr. The film was then sintered at 920 deg C for 4 hr in an oxygen partial pressure (PO_2) of 1.1×10^4 Pa and annealed at 450 deg C for 16 hr in 1 atmosphere of oxygen. Sintering in low PO_2 enhances [7] the sintering kinetics of YBCO. In addition, the melting point of silver is slightly higher in reduced PO_2. The resulting coating thickness was on the order of 50 microns.

MEASUREMENT RESULTS

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 by 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 allowed to warm up slowly. The insertion loss of the coaxial lines inside the CCR are substrated from the data presented. These lines were separately characterized as a function of temperature for the frequency band of interest.

For an equal-ripple Chebyshev filter, the insertion loss (L_s) at midband is given by the expression:

$$L_s\ (\text{dB}) = 8.686\ (C_n/WQ_u) \qquad (1)$$

where Q_u is the unloaded resonator Q, W is the fractional bandwidth, and C_n is a coefficient determined by the filter order and its band ripple [2].

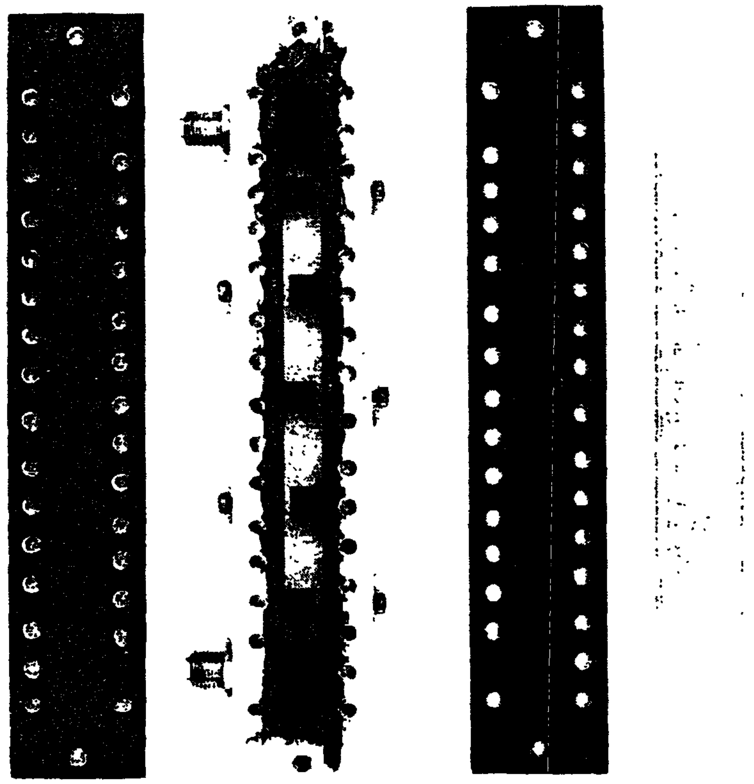

Fig. 1. The superconducting YBCO/Ag filter.

From Eq. (1), since Q_u \proportional to $1/R_s$, 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 on the order of 10^{-4} dB. From the results on the surface resistance of polycrystalline and single crystal YBCO materials [1], the authors expect insertion losses on 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 silver and YBCO filters as a function of temperature. All the data were taken at an input continuous wave (cw) power level of 38 micro W. Qualitatively, all 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 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, as compared with 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, namely that the differences in performance among 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 $L_m(T) = L_s(T) + L_0$, where L_0 is temperature-independent and arises from connector mismatch, tuning, etc. When this was realized, it was possible to achieve the best results with filter 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 [3] with NbTi (T_c = 9.8 K) filters substantiates the above 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 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 must be taken to reduce warping and dimensional changes in the structure due to the high temperatures 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 exact same way as the filter was also measured as a function of temperature down to 77 K by using a 14-GHz microwave cavity, with the sample disk as an end plate. 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 micron W to 40 pW. For the first cool down and very low input cw power levels (>1 nW) the filter loss approached very low values of about 0.05 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, which 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 an effect. A thermal gradient could, however, exist in the YBCO material at the ground-plane contacts. Although the silver surface was machined flat to within 0.001 in., irregularities caused by firing and uneven film thickness prevented perfect mechanical contact at the interface, and hence led to poor electrical and thermal performance. 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 radio frequency 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 silver body, leading to weaker contact force and hence higher losses.

Note several features of the device reported here that bear on comparisons with thin-film microstrip filters. As part of its design, the waveguide should possess the lowest losses achievable, in comparison with microstrip filter structures, which have higher losses. The five element configuration also provides a high out-of-band rejection (~80 dB), which is difficult to achieve with thin-film microstrip filters. Connectorization should, in principle, be easier here because of the metallic substrate. It was also noted that the very low insertion loss of the filter has forced careful evaluation of the procedures for measuring L_s, and indeed it is clear that even better performance will require more exact procedures. It should also be noted that at least in space communications, signal power levels are usually very low (~ nanowatts), which is the level at which this filter exhibits its lowest insertion loss (see Fig. 3).

The authors 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 of T_L = 20 K, the experiments yielded a noise temperature contribution of 4.6 K, which agrees well with that inferred from the measured insertion loss data.

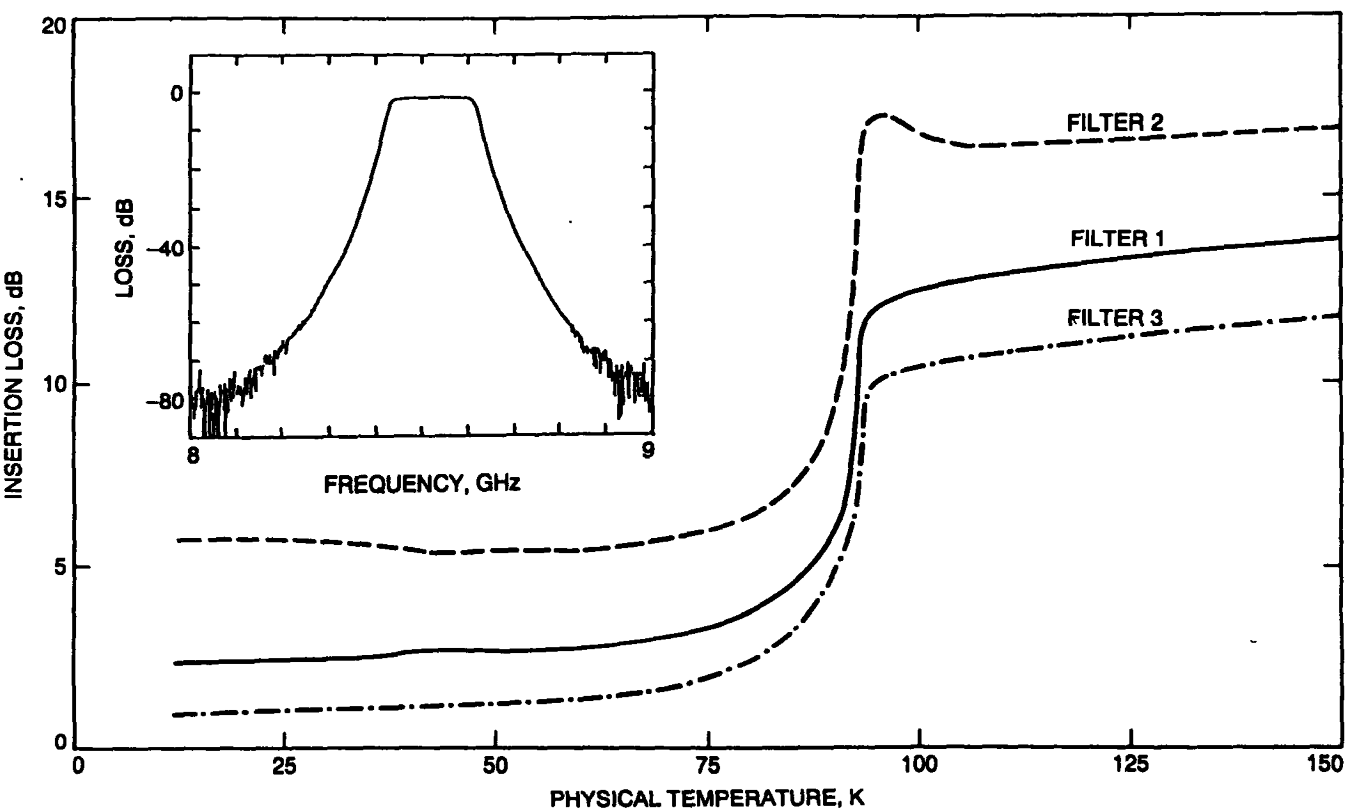

Fig. 2. Insertion loss (Ls) versus physical temperature (T) for three separate filters. The measurements were taken at an input power of 38 μW.

In conclusion, a stripline high T_c superconducting microwave bandpass filter wassuccessfully fabricated and tested. The lowest insertion loss measured was 0.05 dB, with an input return loss of better than 16 dB across the passband. The filter provides significant improvements over a comparable copper 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_c 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 the very low-noise communication systems of deep space applications.

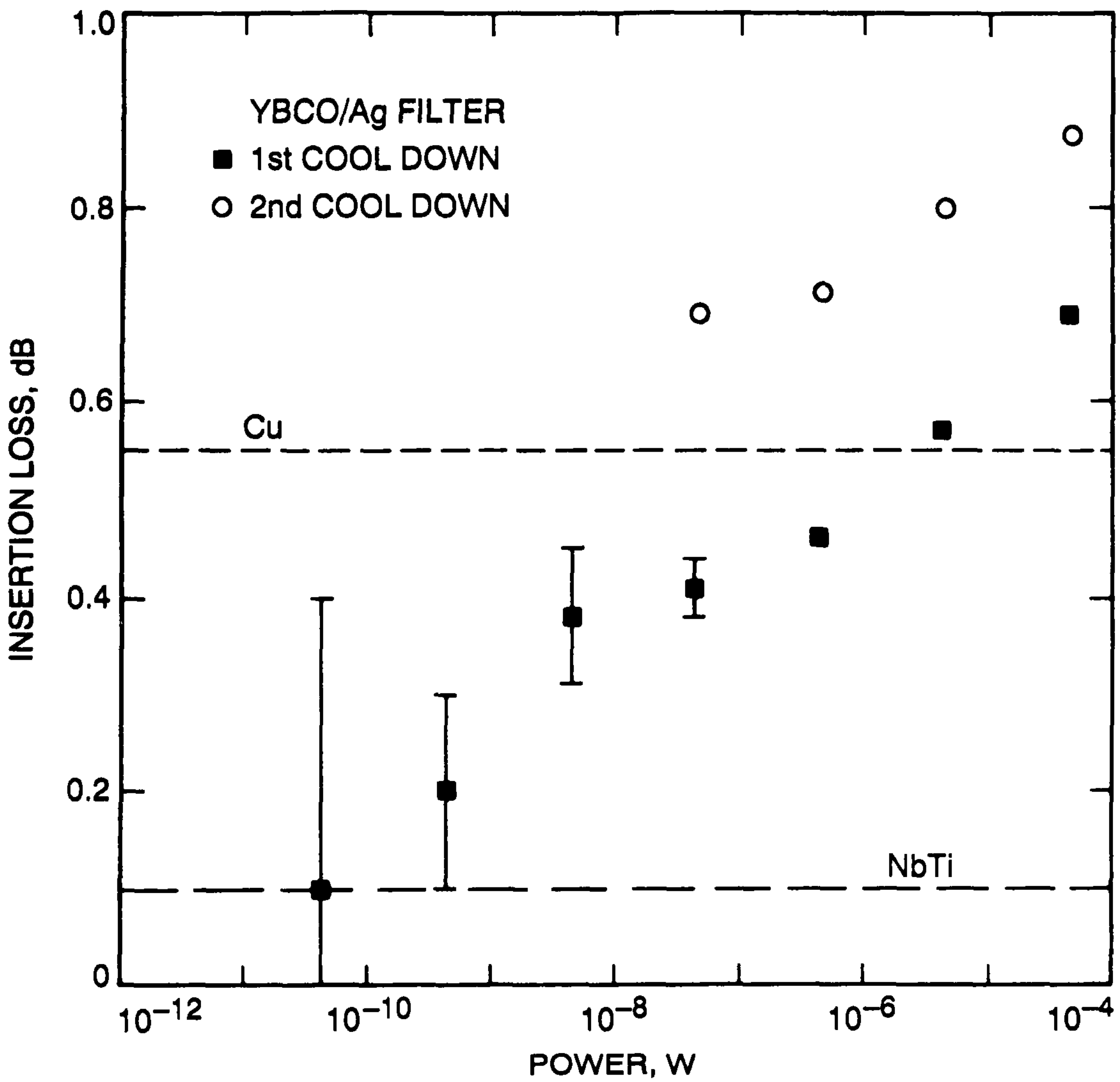

Fig. 3. Insertion loss measurement at various power levels at 12 K for the YBCO/Ag filter, and similar Cu and NbTi filters.

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