NARROW–BAND YBCO SUPERCONDUCTING PARALLEL–COUPLED COPLANAR WAVEGUIDE BAND–PASS FILTERS AT 10 GHZ

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ABSTRACT

High–T_c superconducting coplanar waveguide (CPW) three–pole, four–pole, and five–pole band–pass filters fabricated from *in situ* sputter deposited $YBa_2Cu_3O_{7-x}$ thin–films on $LaAlO_3$ substrates with dimensions 10x25 mm² are presented. The design is based on the evaluation of CPW test chips integrating differing resonators and transmission line structures. The measured data were fed into a CAD program using general transmission line elements instead of CPW elements. Both YBCO and gold versions were constructed and mounted in gold–plated brass test fixtures. At liquid nitrogen temperature (77 K), the filters were characterized by center frequencies at 10 GHz and bandwidths smaller than 1.3 %. Total insertion loss and out–of–band rejection values of the complete packaged devices were better than 2.2 dB and 30 dB, respectively.

INTRODUCTION

The construction of planar microwave and millimeter-wave circuits is among the most promising applications foreseen for thin–film high–T_c superconductors (HTS) [1,2]. A prime motivation for the use of HTS is the reduction of component loss at high frequencies. Here, in comparison with normal metallic conductors, superconductors have a much lower surface resistance and a frequency–independent penetration depth that determines the field penetration rather than a frequency–dependent skin depth. In particular compact planar microwave HTS filters (with small bandwidths) are expected to have serious near–term applications in front end filter banks. E.g., some of the most stringent requirements are found in communications satellites where the required low–loss linear–phase narrowband filters are almost always waveguide designs which are well developed and with which planar HTS applications must compete. The current HTS technology is commonly based on the deposition of $YBa_2Cu_3O_{7-x}$ (YBCO) thin–films on lanthanum aluminate ($LaAlO_3$) substrates [3,4].

Coplanar waveguide (CPW) technology provides convenient thin–film structures, requiring the coating of only one side of the substrate and thereby simplifying the fabrication processing and assembly. Usually, the line width can be chosen without accounting for RF loss and total delay. This comes from the fact that the characteristic impedance is mainly determined by the gap–to–line width ratio. A disadvantage of CPW's is the higher RF loss due to current concentration at the edges; but the high HTS conductivity may compensate for that. Among the CPW shortcomings is also the lack of accurate models for CPW structures in the available CAD software. Thus, in spite of its attractive advantages, filter development on CPW has been very sporadically in comparison with microstrip line. Up to the present, various filter structures using HTS thin–films have been reported [5–9]. A widely used planar component is the parallel–coupled band–pass filter which basically uses a cascade of symmetric coupled quarter wavelength sections to form a series of maximally coupled half wavelength resonators [10]. Approximate design equations for microstrip line versions were developed by *Cohn* [11,12] and extended by *Katehi and Dunleavy* [13].

HTS FILMS

The YBCO thin–films were *in situ* sputter deposited on $LaAlO_3$ substrates with dimensions 10x25 mm². The films show routinely critical temperatures and critical current densities of about 90 K and 2 to $5 \cdot 10^6$ Acm^{-2} (at 77 K), respectively. RF frequency characterization has been done using 10x10 mm² testchips integrating various CPW resonators. From the experimental quality factors and resonance frequencies surface resistance and magnetic penetration depth of the high–T_c thin–films were deduced. The temperature dependence of the magnetic penetration depth was empirically scaled as

$$\frac{\lambda(T)}{\lambda(0)} = \frac{1}{\sqrt{\left(1-0.1(T/T_c)-0.9(T/T_c)^2\right)}}$$

with $\lambda(0)$ ranging from 105 to 224 nm. The surface resistance is more sensitive to the film quality than the magnetic penetration depth. At 6 GHz, we evaluated low values ranging from 70 to 300 $\mu\Omega$.

DESIGN PROCEDURE

The filters are composed of parallel–coupled short–circuited CPW resonators as is seen in Fig. 1 which gives a typical layout schematic. Herein, devices 3A, 5A and 1A are a threepole filter, a fivepole filter and a resonator, respectively. The pads will be needed for bond wires to connect the ground conductors. Among our first steps in prototyping the high–T_c filters were the design of band–pass filters with Chebyshev responses using the equations given by *Cristal*

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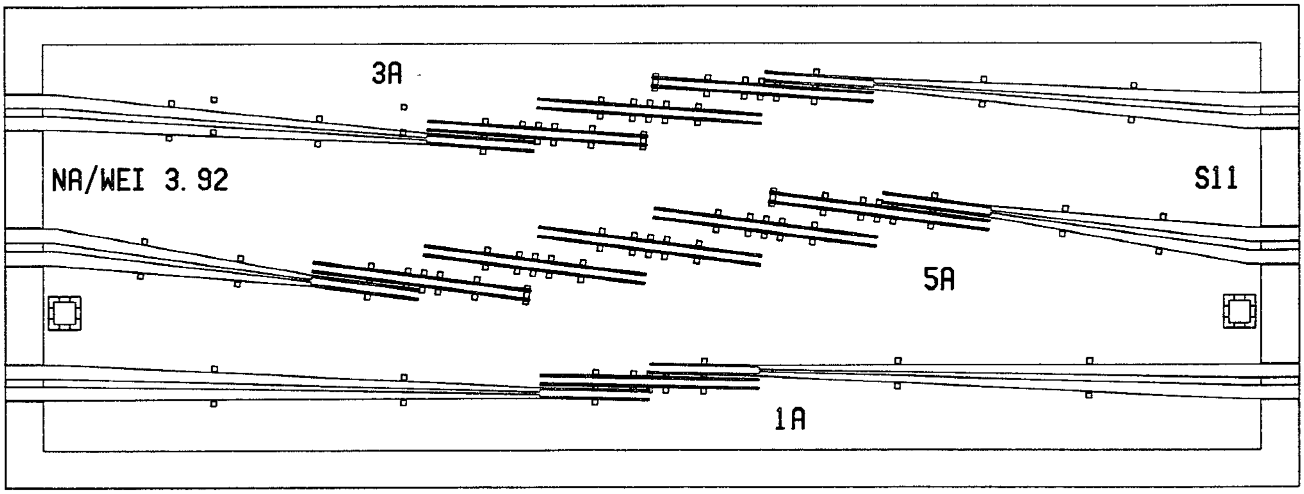

Fig. 1 Layout of multipole parallel–coupled CPW resonator filters

[14] and the construction of conventional gold film devices on Al_2O_3. This investigation provided both a first approximation for the final high–T_c circuit design and a benchmark for performance comparison. The design of high–T_c CPW filters on $LaAlO_3$ involves the problem that models for CPW discontinuities and losses were lacking in the available commercial CAD facilities. Thus, we evaluated the RF characteristics of the high–T_c circuits with a set of CPW test chips. These chips integrate differing CPW resonators and transmission line structures. The S parameters of these test structures were measured using a 26 GHz bandwidth wafer probe and a network analyzer. From the experimental results CPW effective permittivity and effective lengths were deduced. We also measured the functional dependence of the coupling coefficient on the separation between two parallel CPW transmission lines of a quarter wavelength; Fig. 2 gives the denotations. As an example, Fig. 3 shows the experimental frequency response (————) of an HTS test resonator at 77 K. To this curve, the simulated response (– – – –) which was obtained by the use of conventional commercial microwave CAD software was fitted. By doing so, the parameters of the resonators were fixed. Fig. 4 gives the magnitude of the coupling coefficient S_{21} of parallel CPW's of a quarter wavelength versus the separation a for various w/d–ratios. We also found that the short end inductivity increased with decreasing space as is seen in Fig. 5. Therefore, the resonator length has to be corrected in the design of multi–pole filters.

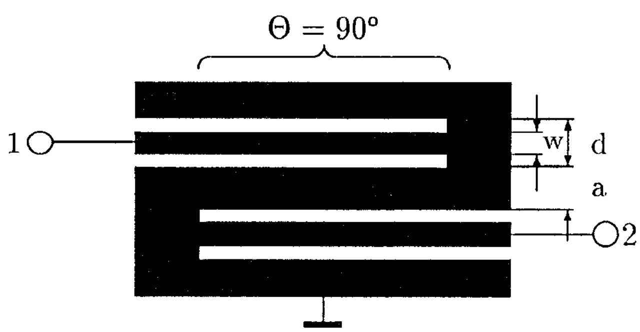

Fig. 2 Two parallel–coupled CPW transmission lines schematic

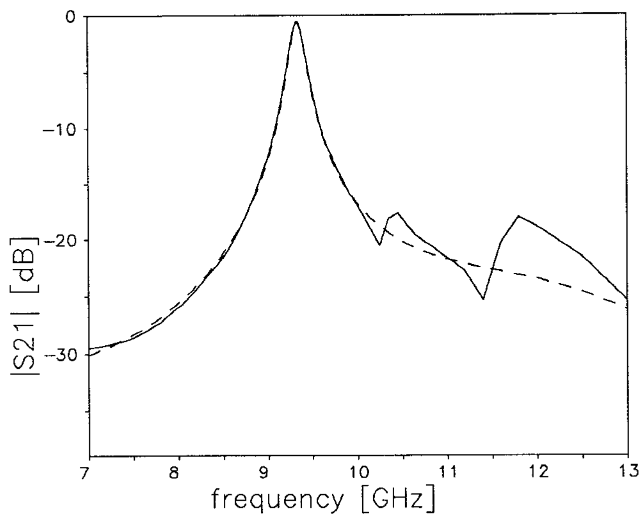

Fig. 3 Experimental (————) and simulated (– – – –) frequency response of a superconducting test resonator

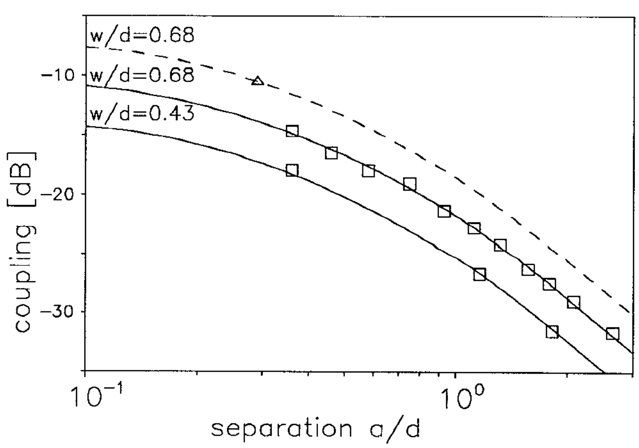

Fig. 4 Coupling coefficient of normal conducting resonators (□) and of superconducting resonators (Δ) (scaled for $LaAlO_3$) vs. separation a

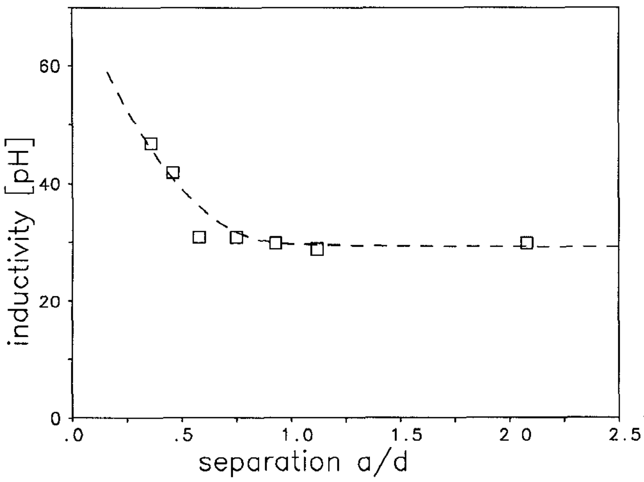

Fig. 5 End inductivity of the CPW short vs. separation for w/d = 0.68

The measured functional dependencies were scaled from $\epsilon = 9.8$ (Al_2O_3) to $\epsilon = 24$ ($LaAlO_3$) and fed into a common CAD program using general transmission line elements instead of CPW elements. The test structures were modeled using a weighted average best fit. Based on these approximations, narrow–band multi–pole YBCO high–T_c parallel–coupled CPW band–pass filters were designed using the CAD software.

FABRICATION

The YBCO thin–films had a thickness of approximately 220 nm and were patterned into the circuitry by wet etching and standard photolithography. The films were etched using diluted phosphoric acid, followed by a cleaning treatment in a plasma reactor. Gold pads with dimensions 80x80 μm^2 were evaporated in a second deposition step, patterned by lift–off and diffused in the plasma reactor. Onto these gold pads airbridges were bonded with 17.5 μm diameter gold wires in order to suppress the parasitic CPW even mode. Gold was also deposited onto all areas where metallic connections are made to, namely to the connector pins and to the test fixture walls. Additionally, on the ground area near the outer rim of the substrate silver paint was deposited to improve the electrical contact to the test fixture walls.

Incorporating three filters per substrate, both YBCO and gold versions were constructed and mounted in gold–plated brass test fixtures. The open test fixtures were dipped into liquid nitrogen. To avoid mechanical stress due to differing thermal expansions of the test fixture and substrate during cooling, both parts of the test fixture were elastically screwed together using flat springs. The contacts to the central transmission line were made with Wiltron K–connectors. The flexible sliding contacts provide good performance even without bonding or using an adhesive. The small width of the sliding contact also allows the use of slim tapers. The center and the ground of the connector are short–circuited via the YBCO structure, since the coupled resonators are also short–circuited. This allows to control the quality of contact between connector and superconductor during down–cooling. Although the electrical contacts were usually good, slightly improved results were obtained by the use of silver paint.

EXPERIMENTAL RESULTS

At liquid nitrogen temperature (77 K), the three–pole filter was characterized by a center frequency of 9.8 GHz and a bandwidth of 1.3 %. The total insertion loss of the complete packaged filter was 2.2 dB, which is about 17 dB lower than the insertion loss of an equally cooled normal–conducting version. The overall out–of–band rejection was better than 30 dB, and no passband ripple was observed. Fig. 6 shows the computed and the experimental frequency response of the device. Center frequency and bandwidth of the four–pole filter were 9.9 GHz and 0.9 %, respectively. The total insertion loss of the complete packaged device was 2 dB. Again, no passband ripple occurs. The sidelobe suppression was 48 dB. Fig. 7 gives the frequency response. The five–pole filter exhibits very similar results with an out–of–band rejection of even 50 dB but with a passband ripple of 4 dB as is seen in Fig. 8.

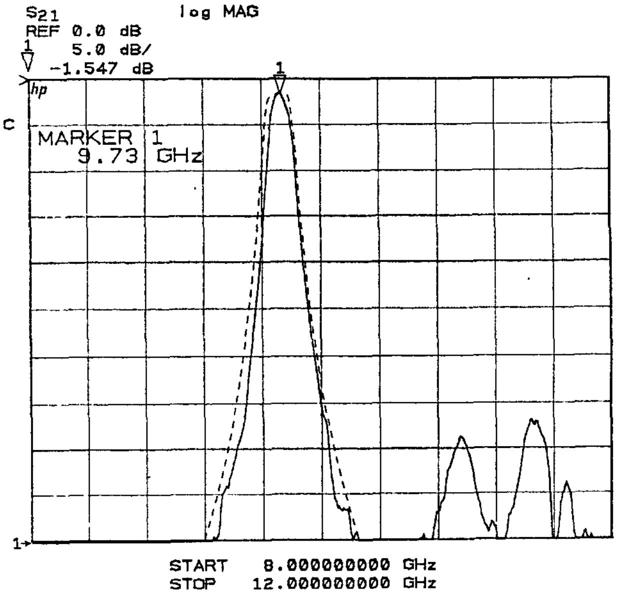

Fig. 6 Experimental (———) and computed (– – – –) frequency response of three–pole filter

Besides the CPW HTS filters we also fabricated microstrip line HTS filters with double–side deposition of YBCO thin–films. However, these filters did not exhibit an improved behavior. This is primarily due to the fact that there is some deteriation of the already grown film when it is heated to temperatures above 700 °C in order to grow the second film on the opposite side of the substrate.

CONCLUSION

Complete packaged YBCO superconducting CPW filters have been described. Design models have been worked out which involve approximate formulas and which were used with commercial microwave CAD software. The present work demonstrates the potential of the SMIC technology (SMIC: Superconducting Microwave Integrated Circuit). However, before system applications can become possible, many engineering issues must still be addressed.

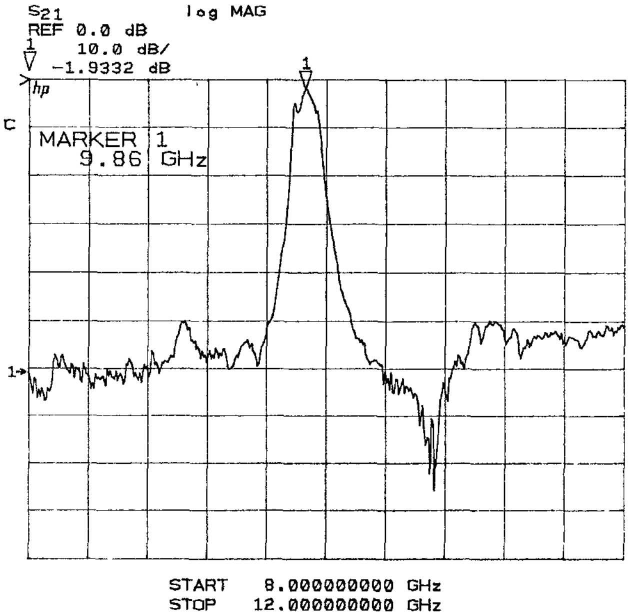

Fig. 7 Measured frequency response of four–pole filter

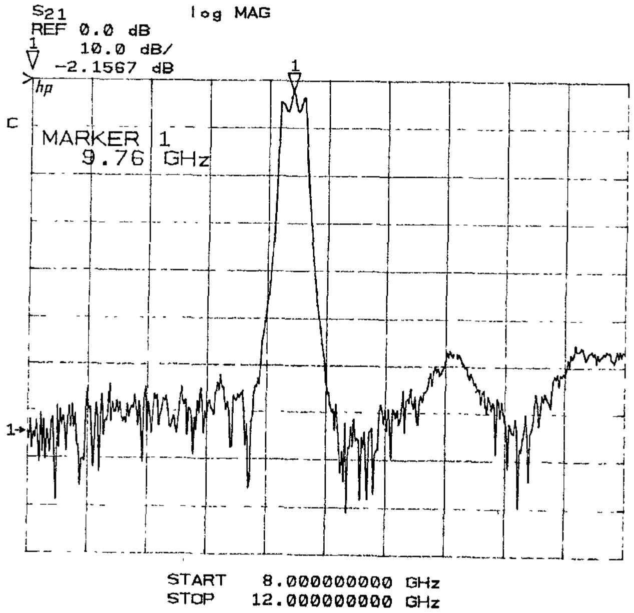

Fig. 8 Measured frequency response of five–pole filter

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