IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, VOL. 14, NO. 1, MARCH 2004 107

Miniaturized 3 GHz Cross-Coupled Planar Microwave Filters

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***Abstract*—Cross-coupled planar microwave filters were fabricated using $\mathrm{YB_2Cu_3O_{7-\delta}}$ superconducting thin films deposited on both sides of a $\mathrm{LaAlO_3}$ single crystal substrate by pulsed laser deposition. The hairpin resonator geometry allows one to miniaturize the 3-GHz filters by compacting the entire filter onto a substrate with dimensions 0.5 cm × 1 cm. By adjusting the relative spacing among the resonators to establish adequate couplings, filters with very sharp rejection skirt and extremely small insertion loss in passband were obtained.**

***Index Terms*—Compact miniaturized hairpin resonators, high-temperature superconducting (HTS) thin films, planar microwave filters.**

I. INTRODUCTION

THE TIGHT performance requirement in the fast growing wireless and mobile communication industry has created a wide open opportunity for implementing high-temperature superconducting (HTS) technology. Consequently, there have been many commercialized HTS technology-related wireless base stations up in operation in the United States, Europe, and Japan [1]. In general, the base-station subsystem composed of HTS devices has been shown to have low noise with significant size reduction, and other attractive characteristics, which promises to bring even more dramatic performance improvements in mobile communications [1]–[3]. Indeed, as current research demonstrates, the viability of using HTS in practical microwave passive devices is growing [4]–[15]. Most of these devices, however, used parallel-coupled planar resonators to form filters due to its ease in fabrication and low cost. One of the major drawbacks of conventional parallel-coupled planar filters is its bulky dimensions, preventing it from immediate adoption to modern mobile communication industry. The problem becomes more awkward considering the availability of a large single crystal substrate, as well as some difficulties encountered in obtaining homogeneous HTS films over a large area. As a result, there are growing demands in obtaining planar filter structures with a reduced size [4]–[6]. To this end, we try to design a 3-GHz cross-coupled planar microwave filters featuring four compact miniaturized hairpin resonators in a 2 × 2 configuration on a total area of about 0.5 cm × 1 cm.

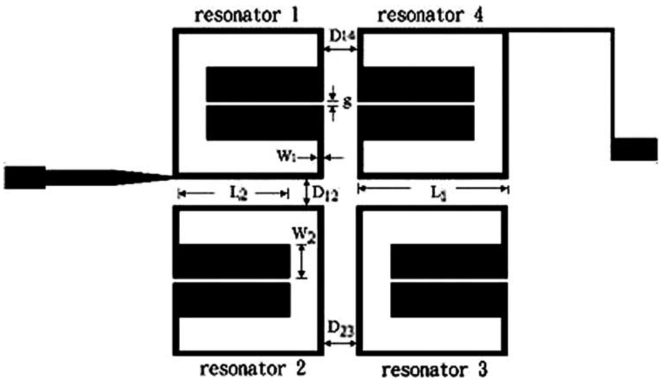

Fig. 1. Layout of the cross-coupled planar microwave filter used in this paper. Geometric parameters for each resonator: $W_1 = 0.1$ mm, $W_2 = 0.5$ mm, $L_1 = 2.1$ mm, $L_2 = 1.485$ mm, g $= 0.1$ mm, $D_{12} = 0.55$ mm, $D_{23} = 0.64$ mm, $D_{14} = 0.6$ mm.

The hairpin resonator effectively reduces the size to about one-sixth of the ordinary half-wavelength resonator by a fold-in geometry. An overall size reduction of about 80% was achieved. The coupling between each pair of resonators can be further controlled to become primarily electric or magnetic depending on the relative orientation of the open gap of the resonator. For instance, the maximum electric coupling is obtained with the two open gaps being faced to each other, while it will be primarily magnetic when the open gaps are on opposite sides [16]–[21]. In the current configuration, the magnitude of the coupling coefficients between two neighboring resonators is determined by the separation and the relative offset between the resonators. In the present study, by adjusting the neighboring spacing between each pair of the resonators to establish proper couplings, a compact miniaturized quasi-elliptic function filter is designed as depicted schematically in Fig. 1. The 2 × 2 configuration is adopted to produce two transmission zeros to increase the rejection in the stopband. Two additional zeros are created by controlling the input and output tapping positions at symmetric configuration (0° feed structure [19]) about the center of the resonators.

The two transmission zeros in this symmetric feed structure occur at the frequencies where the corresponding distance from the feed point to both edges approaches a quarter-wavelength. Note that, no transmission zero is expected to appear with anti-symmetric (non-0°) feed structure [19]. Practically, these transmission zeros can help the rejection of interference signal and,

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Manuscript received January 5, 2004. This paper was recommended by Associate Editor J. Mazierska. This work was supported in part by the National Science Council of Taiwan, Taiwan, R.O.C., under Grant NSC91-2112-M-009-048 and Grant NSC91-2112-M-009-049.

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Digital Object Identifier 10.1109/TASC.2004.824324

hence, increase the selectivity and out-of-band rejection of the filter [19]. It is anticipated that, by taking into account the above features of the quasi-elliptic function filter, a miniaturized filter with properties of low insertion loss together with sharp skirt selectivity in the passband, can be realized by using superconducting resonators. In this paper, fabrication and characterizations of such cross-coupled planar microwave filters will be described. The results demonstrate the great application potential of using HTS films to make compact miniaturized size in practical frequency bands.

II. EXPERIMENTAL

High quality double-sided $\mathrm{YBa_2Cu_3O_{7-\delta}}$ (YBCO) thin film deposited on both sides of a 1 cm × 1 cm $\mathrm{LaAlO_3}$ (LAO) substrate were prepared by pulsed laser deposition. The deposition system consists of a vacuum chamber equipped with a pulsed KrF excimer laser. The YBCO films were deposited in oxygen atmosphere at a growth rate of about 0.5 nm/s from a stoichiometric YBCO target. The optimal conditions for the samples are obtained at a substrate temperature of 790 $^\circ\mathrm{C}$ and 0.28 mbar oxygen pressures [22]. The as-deposited films were all c axis oriented, with a typical thickness of 300 nm. The LAO substrate has a room temperature relative dielectric constant of $\varepsilon_\mathrm{r} \cong 25$ and a loss tangent of $\tan\delta = 6 \times 10^{-5}$. The naturally formed twins of the LAO substrates, though may result in some inhomogeneities in the films, appeared to have little effect on the microwave properties of the YBCO films.

The main difficulty for double-side deposition is the direct contact between the substrate and the heater plate that usually induces some visible defect on the heater-facing surface. By inserting a thin Si-wafer between the substrate and the heater seemed to have solved the problem. This not only protects the backside of the polished substrates from contamination during deposition of the first film, but also works well for the second side deposition. In order to keep the minimum degradation of the first side and to optimize the highest performance of the second side, both films are deposited at the same substrate temperature and oxygenation environment.

The as-deposited YBCO thin films were analyzed by X-ray diffraction, atomic force microscopy (AFM) and resistivity measurements. The microwave properties are measured by microstrip resonator technique. On the one side of the films the designed pattern was transferred by photolithography and wet etch methods. The other side of superconducting YBCO naturally serves as the ground plane. The sample was put into a gold-coated aluminum housing with SMA connectors. The package was placed in a vacuum tube and immersed in liquid nitrogen. The S-parameters are measured by a HP8510C microwave vector network analyzer at the liquid nitrogen temperature.

III. RESULTS AND DISCUSSION

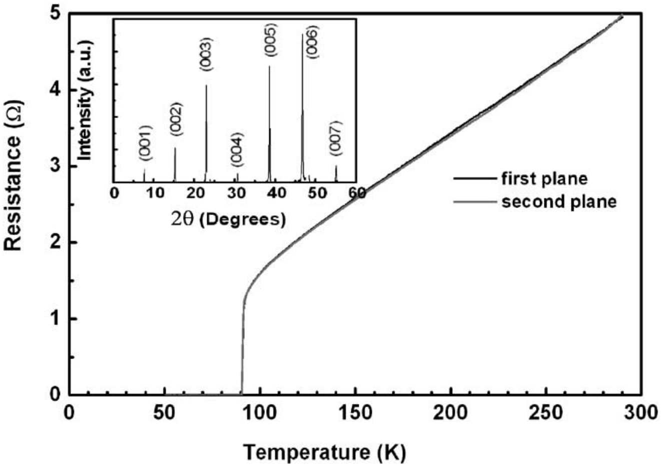

Fig. 2. Temperature dependence of resistance for YBCO thin film grown on $\mathrm{LaAlO_3}$. Notice the sharp transition temperature higher than 90 K. The inset shows the c axis oriented characteristics of the YBCO films as revealed by X-ray diffraction.

As shown in the inset of Fig. 2, the YBCO films display only (00ℓ) peaks as revealed by X-ray diffraction patterns, indicating that the films are indeed purely c axis oriented. The critical temperature and superconducting transport properties of YBCO film measured by standard four-probe technique are displayed in Fig. 2. The resistive transition curve shows that, under the optimized conditions, YBCO grown on LAO exhibits the typical metallic behavior at high temperatures with a sharp transition to the superconducting state at a temperature near 90 K.

Fig. 3(a) and 3(b) depict the images of the surface morphologies of the YBCO films deposited the first and second side of the substrate, respectively. It is evident that the microstructure of the films displays a three-dimensional (3-D) island-like morphology. The average grain size of the film is about 350 nm. The scanned area of the AFM image was $2 \times 2\ \mu\mathrm{m}^2$ and the vertical scale was 25 nm, respectively. It is evident that the grain morphology of the first side is markedly different from that of the second side. The appearance of agglomerated grains is believed to result from the high-temperature annealing effect during the deposition of the second side. Nonetheless, it appears that the annealing does not alter the nature of the film significantly, except for inducing grain coalescence.

A four-pole cross-coupled filter was designed using compact miniaturized hairpin resonators with 3 GHz center frequency and 4% bandwidth. The filter depicted in Fig. 1 is designed to perform using a YBCO film grown on a LAO substrate with a thickness of 0.5 mm. Fig. 4 shows the simulated coupling coefficients K_{ij} with respect to the distance between resonators i and j. These cross couplings give the input signal two paths between the input and output ports with the signal magnitude and phase being altered differently. The above results indicate that the sign of K_{12}, (and, hence, of K_{34}) and of K_{23} are positive, while the sign of K_{14} is negative and has a smaller magnitude than K_{12} and K_{23} [18]. Moreover, each coupling coefficient displays similar behavior with increasing spacing distance.

The simulation of S_{21} of the resonator gives an estimated unloaded Q of about 17 000. The performance of the designed structure was simulated by IE3D [23] software by assuming the superconductor as a perfect conductor and $\varepsilon_\mathrm{r} = 25.24$ for the LAO substrate with the structural parameters depicted in the caption of Fig. 1. The result is shown as the dashed curve in Fig. 5. The input and output feed points are of symmetric

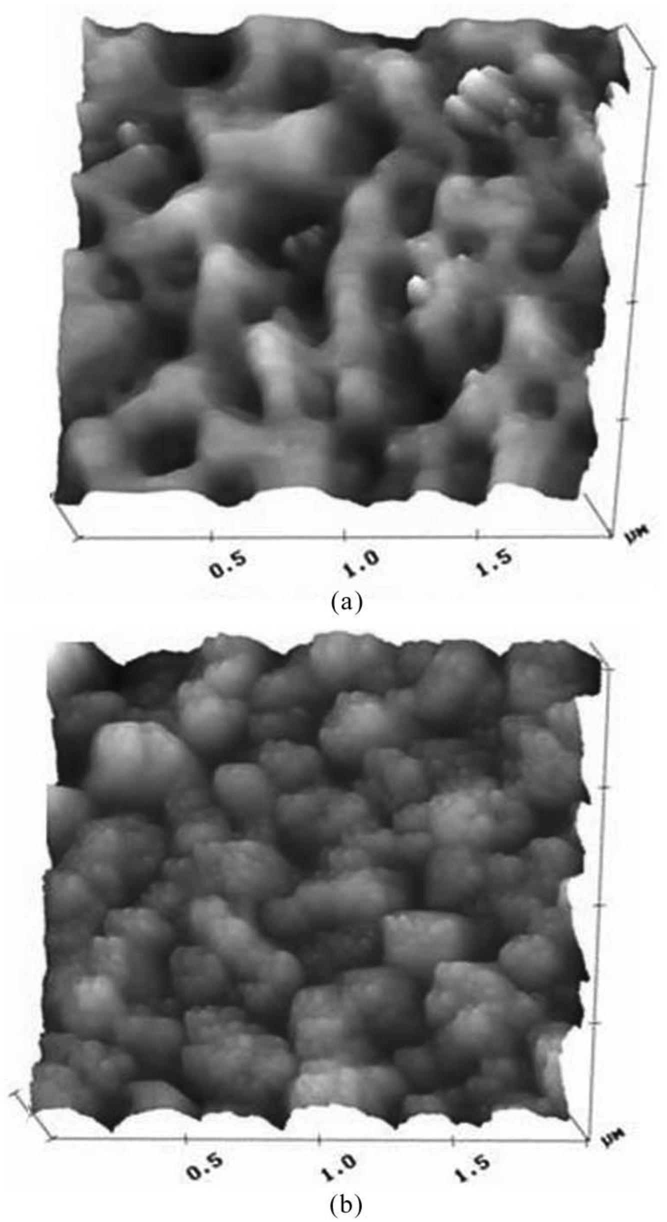

Fig. 3. (a) AFM images of the surface morphologies of the YBCO films deposited the first and (b) second side of the substrate, respectively. The scanned area of the AFM image was 2 × 2 $\mu\mathrm{m}^2$ and the vertical scale was 25 nm, respectively.

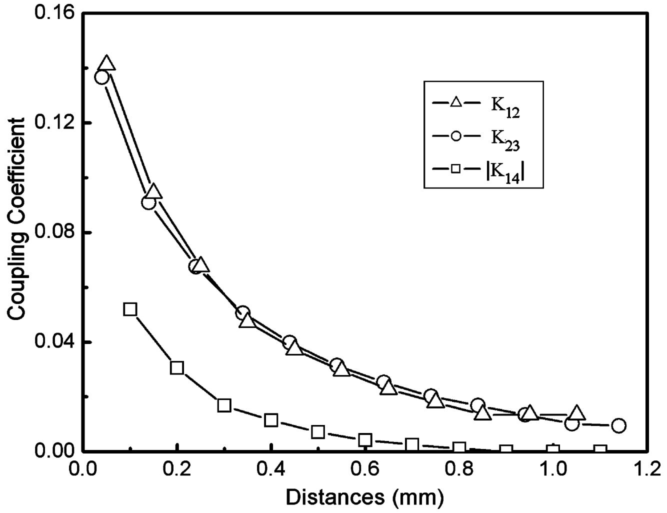

Fig. 4. Simulated coupling coefficients K_{ij} with respect to the distance between resonators i and j.

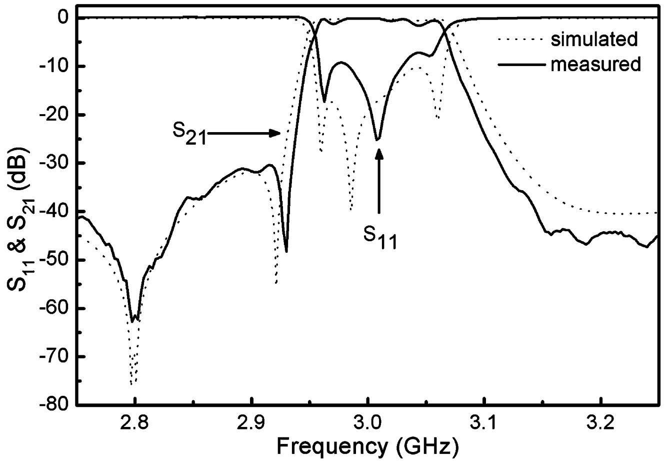

Fig. 5. Simulated (dashed curves) and measured (solid curves) transmission (S_{21}) and reflection (S_{11}) responses. The results show that the designing performance can be reproduced by using HTS films as the conductors.

configuration and locate oppositely about the center of the resonators. As discussed previously, this configuration is expected to add a pair of transmission zeros in both the lower and upper stopbands. However, we observed only two transmission zero points in the lower stopband. It is interesting to note that, similar design with a 180° feed structure [19] has resulted in only a pair of near-band-edge transmission zeros in both sides of the stopband due to cross coupling effect. However, by moving the output feed line into a symmetric configuration, an additional pair of transmission zeros in both sides of the stopband were observed [19]. Since the appearance of the transmission zeros is intimately dependent on the interferences between the signals traveling along the two paths in the present design, the coherence of the phases between the clockwise and counterclockwise signals and their exact magnitudes might ultimately determine the device's performance. The fact that both the coupling induced zero and the symmetry-related zero in the higher frequency region were missing in our case suggests that the magnitude mismatch may be the more predominant factor responsible for the disappearance of the upper-band zeros. It is generally conceived that structures designed using wider transmission lines are having smaller conductive loss and better performance merits. Due to the much thinner, as compared with [18] and [19], transmission lines used in this study, the signal magnitude may be significantly affected from the respective conductor loss of each traveling route. This, in turn, gives rise to incomplete cancellation and other unexpected effects that prevent the occurrence of the expected transmission zeros.

The real device performance for this structure measured at the liquid nitrogen temperature reproduces the simulated results extremely well. As shown by the solid curve in Fig. 5, both transmission (S_{21}) and reflection (S_{11}) results are very close to the simulated responses. The center frequency, insertion loss and fractional bandwidth are 3.01 GHz, 0.1 dB, and 3.7%, respectively. The central frequency has a small shift of about 1 MHz and the fractional bandwidth was 7.5% less than the simulation. The very low passband insertion loss is by far comparable to the best performance for devices of this kind. For microwave applications, two of the most important parameters are the surface resistance R_s and the critical current density J_c. The typical of R_s and J_c values at 77 K for YBCO HTS thin films are about $0.02\ \mathrm{m\Omega}\ (\mathrm{Cu} :\approx 4.5\ \mathrm{m\Omega}$ [2]) and $10^6\ \mathrm{A/cm^2}$, respectively. It is anticipated that further improvement on these parameters might be crucial for the realization of HTS implementations. In any case, the current results clearly demonstrate that using YBCO for a 3 GHz filter not only effectively reduces the filter size but also yields at least one order of magnitude improvement in passband insertion loss as compared with its normal conductor counterpart ($\mathrm{IL} \approx 2-3\ \mathrm{dB}$ [18]–[21]). Further works are currently underway to harvest the great application potential of the double-side HTS films for some higher order (eight-poles) filters to improve the performance with, perhaps, some tunable features.

IV. CONCLUSION

We have designed, fabricated, and demonstrated a miniaturized cross-coupled planar microwave filter using double-side YBCO HTS thin films. The devices, designed to operate at 3 GHz, not only have more than 80% of size reduction compared with conventional parallel-coupled planar filters, but also display an insertion loss of 0.1 dB for the S_{21} responses.

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