Propagation Characteristics of Monolithic YBaCuO Coplanar Strip Transmission Lines Fabricated by Laser-Writing Patterning Technique

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***Abstract*—We report our studies on the propagation characteristics of $YBa_2Cu_3O_7$-on-$LaAlO_3$ superconducting coplanar strip transmission lines and resonators fabricated with a novel laser-writing patterning technique. The measurements were performed in the 0.1 to 15 GHz frequency range at temperatures between 300 and 24 K. We show that at temperatures below the superconducting critical temperature, the S_{21} parameter of our transmission lines was close to 0 dB at all the frequencies, while the Q-factor of the resonator structure was as high as 5000 at 6 GHz and 24 K. The transmission line propagation velocity was about 10^8 cm/s. Our results indicate that the laser-writing patterning technique can be effectively used to fabricate high-quality superconducting microwave elements and circuits.**

I. Introduction

Recently, high-temperature superconducting (HTS) transmission lines have generated considerable interest due to their substantial performance enhancement offered to microwave circuits and systems [1]. HTS lines operate conveniently at liquid nitrogen temperature; however, contrary to metallic superconductors, their microwave properties are very sensitive to their fabrication process. Especially critical are the photolithographic and wet etching processes, since they often lead to patterns with fuzzy edges with a degraded (e.g., oxygen deficient) chemical composition. As a result, conventionally patterned HTS transmission lines usually experience degraded superconducting properties [2], such as, e.g., an increased surface impedance and abnormal magnetic penetration depth. Patterning techniques that do not employ resist masks and/or wet etching have then the potential for superior performance in microwave applications.

In this letter, we demonstrate that a novel laser-writing patterning technique can be used to effectively fabricate high-quality superconductive $YBa_2Cu_3O_x$ (YBCO) passive microwave elements. We report our measurements of the propagation characteristics for the laser-written YBCO-on-$LaAlO_3$ superconducting coplanar strip (CPS) transmission lines and CPS resonators at the frequencies 0.1 to 15 GHz and show that at temperatures below the film superconducting critical temperature, T_c, the laser-written structures exhibit excellent microwave properties with low transmission losses and high resonator quality factors.

Manurcript received December 6, 1993. This material is based in part upon work supported by the Air Force Office for Scientific Research under grant no. F49620-92-0075 (Rochester) and by the Texas Higher Education Coordinating Board Advanced Technology Program under Grant No. THECB ATP 003613-008 (Southern Methodist University). W. Xiong also acknowledges financial support from the Laboratory for Laser Energetics' Frank Horton Graduate Fellowship Program

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IEE Log Number 9401064.

II. Experimental Technique

The laser-writing patterning technique [3], [4] is based on the application of a focused Ar-ion laser beam to locally heat up an epitaxial YBCO film in a controlled, oxygen or oxygen-free, ambient atmosphere. The heating allows oxygen to diffuse in or out of the YBCO crystalline structure and form in the same film oxygen-rich (superconducting) $YBa_2Cu_3O_7$ regions close to oxygen-depleted (virtually insulating at low temperatures) $YBa_2Cu_3O_6$ regions. The technique is fully reversible, noninvasive, does not require a patterning mask, and results in completely planar structures that are free of surface contamination or edge degradation.

The transmission optical micrograph of the laser-written CPS structure patterned in a 200-nm-thick YBCO film is shown in Fig. 1. In the photograph, the dark regions correspond to the fully-oxygenated, superconducting $YBa_2Cu_3O_7$, while the light-gray areas indicate the deoxygenated $YBa_2Cu_3O_6$. The T_c of the CPS lines was 89.5 K and their critical current density exceeded 2 MA/cm^2 at 77 K. On the other hand, the sheet resistance of the oxygen-poor regions was above 10 MΩ/square at temperatures below 100 K. A 10-μm-wide insulating gap in the CPS (see Fig. 1) was laser-written in nitrogen atmosphere and established a capacitive coupling of the resonator structure. As shown in Fig. 1, our laser-written patterns were highly uniform and exhibited very sharp superconducting-semiconducting YBCO interfaces.

The YBCO CPS circuits were thermosonically wire bonded with gold wires into a substrate holder with gold-on-alumina CPS-coax transitions at each end. The gold wire bonds produced low resistance contacts to the $YBa_2Cu_3O_7$ circuit. The substrate holder was cooled in a temperature-controlled closed cycle refrigerator. The refrigerator was plumbed with 0.085 semi-rigid coaxial cables to transmit the microwave signals to and from the device. An HP8510 network analyzer was used to measure the S-parameters of the YBCO CPS circuits. The

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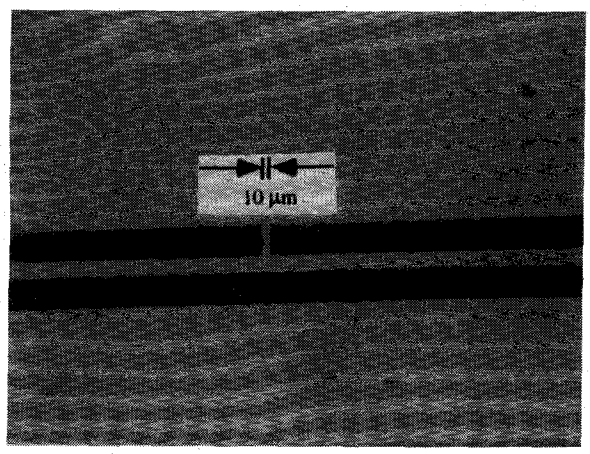

Fig. 1. Photograph of laser written coplanar strip transmission line circuit. The dark regions indicate the oxygenated superconducting strips. The superconducting lines are 60 μm wide, while the separation between the lines is 20 μm.

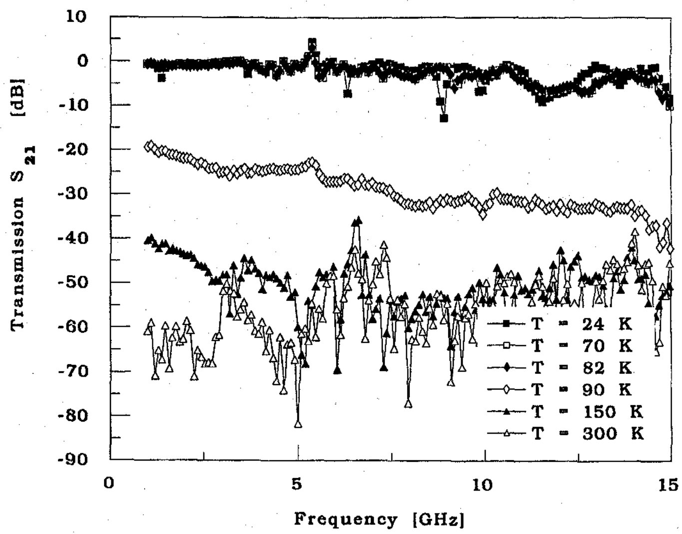

Fig. 2 Plot of S_{21} versus frequency from room temperature to 24 K. Note the rapid increase in transmitted power at the superconducting transition, where low-loss propagation of the microwave signal along the coplanar strip transmission line appears.

network analyzer was calibrated with a reference plane of the YBCO substrate edge.

III. Results

The CPS transmission lines were nominally designed to have a characteristic impedance, $Z_0 = 50\Omega$, using EESOF's LINECALC [5]. The measured Z_0 was 57 Ω, near the design value. The phase velocity was measured to be approximately 10^8 m/s, yielding an effective dielectric constant of ~8 for our CPS. Fig. 2 shows the transmission coefficient S_{21} versus frequency from 1 to 15 GHz measured as a function of temperature. The 1-cm-long CPS employed a strip width of 60 μm and separation of 280 μm. The data has been corrected to account for the drift in the calibration with temperature. At room temperature, the CPS circuit consists of fully oxygenated, nevertheless quite lossy $YBa_2Cu_3O_7$ lines and conducting $YBa_2Cu_3O_6$ regions. Thus, the line attenuation visible in Fig. 2 (open triangles) is very severe. As the sample is cooled, the conductivity of the $YBa_2Cu_3O_7$ strips increases linearly, while the resistivity of the $YBa_2Cu_3O_6$ phase increases almost exponentially,[1], thereby reducing both the series and shunt losses. At 90 K, just above T_c, the CPS propagates the microwave signal since $YBa_2Cu_3O_6$ has become almost insulating. However, the loss is still quite high due to a relatively low (as compared to metals) conductivity of $YBa_2Cu_3O_7$ in the normal state. Below T_c (T < 89 K), the $YBa_2Cu_3O_7$ strips become superconducting and their conductor loss becomes very small.

Interestingly, only small changes in the transmission line propagation characteristics result upon further cooling down to 24 K. The measured S_{21} is near 0 dB for all temperatures well below T_c, indicating a high Q structure, and the relatively long bond wires are believed to contribute much to the frequency dependence of S_{21} shown. Our preliminary measurements on an open-ended resonator circuit (see Fig. 1) have indicated unloaded Q-factors of approximately 5000 at 6.05 GHz and 24 K, while at 100 K (above T_c), the measured unloaded Q-factor was approximately unity. The measured value is very likely to be radiation limited, since we did not encapsulate our test structure. The ferroelectric behavior observed in bulk semiconducting YBCO [6], [7] was not detected by our measurements. In fact, the presence of the $YBa_2Cu_3O_6$ phase was found to reduce the effective dielectric constant of the transmission line structure suggesting the dielectric constant of the semiconducting YBCO is less than the dielectric constant of $LaAlO_3$ (ϵ_r =24). In [7], the bulk material dielectric constant was shown to decrease with decreasing temperature and increasing frequency, so it is possible the dielectric constant of the thin-film $YBa_2Cu_3O_6$ is indeed high at room temperature and low frequency. However, this regime is outside the range of any practical interest for HTS microwave applications.

[1] More accurately, oxygen-poor $YBa_2Cu_3O_6$ regions exhibit at low temperatures thermally activated transport, well described by a three-dimensional, variable-length hopping process [4].

IV. Conclusions

In conclusion, this work has demonstrated that superconducting YBCO CPS circuits fabricated by selective, laser-heating-induced oxidization and deoxidization of a YBCO thin film possess at temperatures below T_c very good microwave properties. The CPS transmission line exhibited very low losses and high (~10^8 cm/s) propagation velocity, while the quality factor of a CPS open-ended resonator was about 5000 at 6.05 GHz. The above findings show that our laser-writing technique shows promise for patterning high-quality HTS transmission lines for a variety of microwave applications without the risk of surface degradation associated with traditional photolithography and etching techniques. In addition, the laser-written transmission line circuits are perfectly planar.

REFERENCES

[1] M. Nisenoff, J. C. Ritter, G. Price, and S. A. Wolf, "The High Temperature Superconductivity Space Experiment: HTSSE I - Components and HTSSE II - Subsystems and Advanced Devices," *IEEE Trans. Appl. Supercond.*, vol. 3, pp. 2885–2890, 1993.

[2] P. H. Balentine, A. M. Kadin, and D. S. Mallory, *IEEE Trans. Magn.*, vol. 27, pp. 997–1000, 1991.

[3] R. Sobolewski, W. Xiong, and W. Kula, "Patterning of thin-film high-T_c circuits by the laser-writing method," *IEEE Trans. Appl. Supercond.*, vol. 3, pp. 2986–2989, 1993 (and references therein).

[4] R. Sobolewski, W. Xiong, W. Kula, and J. R. Gavaler, "Laser patterning of Y-Ba-Cu-O thin-film devices and circuits," *Appl. Phys. Lett.*, vol. 64, pp. 643–645, 1974.

[5] LINECALC is a product of EESOF Inc., 5601 Lindero Canyon Rd., Westlake Village, CA, 91362 USA.

[6] L. R. Testardi, W. G. Moulton, H. Mathias, H. K. Ng, and C. M. Rey, "Large static dielectric constant in the high-temperature phase of polycrystalline $YBa_2Cu_3O_x$," *Phys. Rev. B*, vol. 37, pp. 2324–2325, 1988.

[7] C. M. Rey, H. Mathias, L. R. Testardi, and S. Skirius, "High dielectric and nonlinear electric response in nonmetallic $YBa_2Cu_3O_{6+d}$," *Phys. Rev. B*, vol. 45, pp. 10639–10646, 1992.