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The purpose of this work was to utilize the nonlinear current-voltage properties of induced grain boundaries in high temperature superconducting $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$ thin films to fabricate a planar microwave mixer. The experiment involved constructing a coplanar waveguide microwave circuit, the center conductor of which had a constriction patterned in it containing a single high angle grain boundary, thus forming a weak link junction. Analysis was provided by use of the resistively shunted junction model with excess current.

I. INTRODUCTION

Sufficient precedent exists, as a result of previous work in years past on low temperature superconducting mixers, which provides the motivation for conducting extensive research in microwave and millimeter wave mixers using high temperature superconductors. For example, theoretical calculations on lower bounds on noise temperature have been determined for superconducting-insulator-superconducting (SIS) mixers employing quasiparticle tunneling.¹ These theoretical limits have been approached experimentally, providing noise temperatures below those currently available in semiconductor devices.² At least one experimental result has demonstrated a positive conversion gain using low temperature superconducting tunnel junctions.³

Since the introduction of high temperature superconductors, several reports of mixing have appeared. Some of these measurements were performed using the transition resistance occurring above the temperature at which the dc resistance falls to zero.⁴ Other successful experiments in mixing have been reported using materials other than $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$ (YBCO).⁵ Microwave mixing using YBCO and employing weak link effects, have been reported. These devices contain weak links involving polycrystalline materials with multiple randomly oriented grain boundaries or involving step edge junctions.⁶⁻⁹ Some of these devices, indeed, have shown remarkable results in terms of conversion loss in mixing at microwave frequencies.¹⁰

The purpose here has been to construct truly planar superconducting YBCO mixers employing artificially induced grain boundaries with predictable angles, and to characterize these grain boundary mixers by employing suitable physical models.

II. EXPERIMENTAL DETAILS

The starting material was an epitaxial YBCO thin film, which was grown by laser ablation deposition on a bicrystalline SrTiO_3 substrate.¹¹ This substrate was composed of two crystals joined together with an interface that formed a 36.8° angle.

The coplanar waveguide circuit was patterned on this thin film, such that a $30 \mu\text{m}$ wide microbridge was formed,

which spanned the bicrystal boundary, and thereby induced a single grain boundary in the microbridge, as is evident in the mixer circuit depicted schematically in Fig. 1. The pattern was obtained by conventional wet etching.

This procedure resulted in circuits with constrictions that would contain a single grain boundary with an angle of 36.8° . Such circuits exhibit greatly reduced critical current densities and weak link properties.^{12,13}

The etched circuit was mounted on an acrylic block, and the coplanar waveguide was connected to 50Ω cables by means of SMA to microstrip launchers. The dc probes for applying bias current and measuring the voltage were composed of stainless steel spring loaded contacts, which mated with the surface of the center conductor in the circuit. This configuration is also shown in Fig. 1.

Output from the two microwave sources used for mixing could be independently adjusted in power and frequency. The signals were combined in a directional coupler, and then passed through a dc block and into the device. The output signal passed through the output launcher from the device and through a second dc block into a high gain spectrum

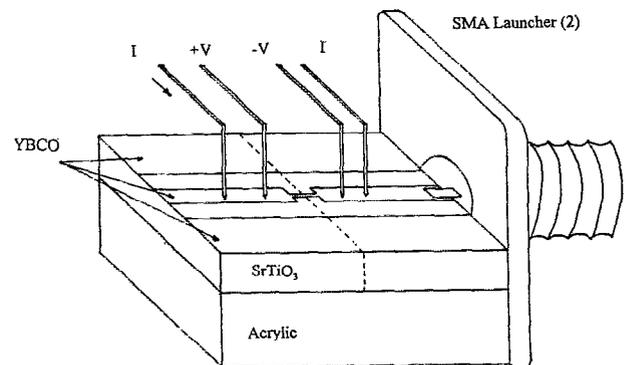


FIG. 1. Schematic drawing of coplanar waveguide YBCO mixer circuit showing the substrate bicrystal interface, the location of the microbridge constriction with respect to the bicrystal interface, the bias contacts, and the microwave SMA launchers.

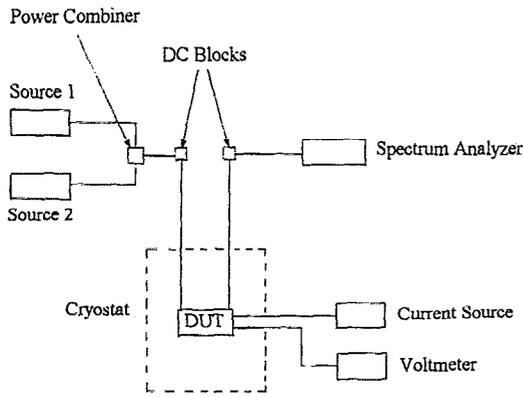


FIG. 2. Schematic diagram of the experimental microwave mixer test apparatus.

analyzer. The experimental apparatus is depicted in Fig. 2.

First, current versus voltage characteristic curves were obtained for the junction, in the absence of microwave energy, and recorded. When the junction was driven by the local oscillator, with microwave energy, current steps were produced in the current voltage characteristic curve. These steps appeared at voltages that were integral multiples of the flux quantum times the frequency. Both characteristic curves are overlaid in Fig. 3. The current steps, evident in Fig. 3, were the basis for adjustments of the current bias levels, and were the nonlinear contribution of the circuit, which was utilized for down-conversion mixing.

III. THEORETICAL MODELING

Modeling of the coplanar waveguide circuit involved the use of some approximations of the standard equations.¹⁴ Approximate values for the transmission line characteristic impedances were obtained using the value of $\epsilon_r = 9190$, obtained from published data¹⁵ and a value of $\tan \delta = 0.03$ obtained from literature.¹⁶ From the characteristic imped-

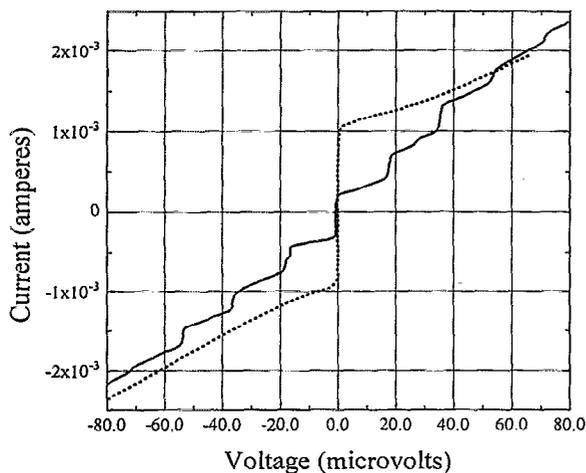


FIG. 3. Current voltage characteristic curves for YBCO grain boundary weak link junction. Dotted line is without rf signal. Solid line with rf energy at 8.7 GHz.

ances, together with the transmission line dimensions, and by using transmission line matrix methods, it was possible to calculate the input impedance of the transmission line at the signal frequency and the local oscillator frequency. The value obtained was found to be $Z_{IN,S} = 1.368 - j0.116$ and $Z_{IN,LO} = 1.396 + j0.044$. Using the input impedances and the transmission line matrices, together with the knowledge of the input signal power and input local oscillator power, it was possible to estimate the respective currents on the microbridge portion of the transmission line. This was found to be $I_S = -555.8 \times 10^{-6} - j562.4 \times 10^{-6}$ A and $I_{LO} = 483.8 \times 10^{-6} + j187.5 \times 10^{-6}$ A.

With an estimated value of the currents due to the two input microwave signals, and a knowledge of the bias current, a calculation for the output current level was obtained using the following two equations:

$$I = I_c \sin \phi \quad (1)$$

and

$$-\frac{\hbar}{q} \frac{d\phi}{dt} = R_N(I_B + I_{LO} \cos \omega_{LO}t + I_S \cos \omega_S t - I_0 - I_c \sin \phi). \quad (2)$$

Equations (1) and (2) are recognized as the Josephson relations used in the resistively shunted junction model for the shunted Josephson junction, with excess current, I_0 ,¹⁷ I_B is the dc bias current, I_0 is the superconducting excess shunt current, R_N is the normal mode resistance obtained from the characteristic curves, and q is the superconducting pair charge. These equations were solved numerically using the technique of Runge-Kutta in double precision and then subject to a discrete Fourier transform to extract the harmonic content. These calculations yielded the result for the magnitude of $I_{i.f.}$, the current of the intermediate frequency at the junction, which was $I_{i.f.} = 4.25 \times 10^{-6}$ A = 3.00×10^{-6} A (rms). The calculated value of $I_{i.f.}$ was then used again in the matrix representation of the transmission line using impedances determined at the intermediate frequency. The result was an output power of -82 dB m.

IV. RESULTS AND DISCUSSION

When the circuit was dc current biased near any one of the current steps, and when both the microwave local oscillator and the microwave signal were applied, an intermediate frequency was observed at the difference frequency. In the experiments, the local oscillator was at 8.7 GHz and the signal frequency was at 7.7 GHz, therefore the difference frequency was measured at 1.0 GHz. The input signals are shown as an inset in Fig. 4 and output intermediate frequency is shown in Fig. 4.

It was determined that the conversion loss of the mixer was dependent upon the input power and the bias current. Approximate relative values of conversion gain are shown in Fig. 5. It was evident during the experiment that mixing was absent for bias values between steps, whereas the i.f. signal was maximum when the bias current was located within the

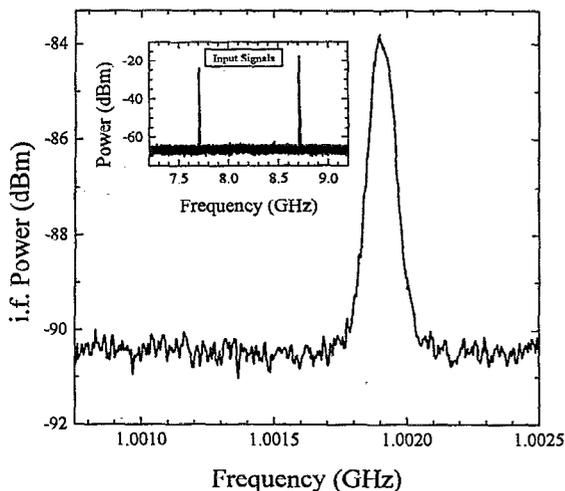


FIG. 4. Output intermediate frequency, i.f., signals at temperature 45 K, with dc current bias of 0.78 mA. Input microwave signals are shown in the inset.

range of values of the current steps. The smallest conversion loss appeared at current values corresponding to the $n = \pm 1$ steps.

The bias current levels were theoretically and experimentally observed to provide mixing when biased at the steps. The measured conversion loss agrees with the theoretical calculation to within 3 dB.

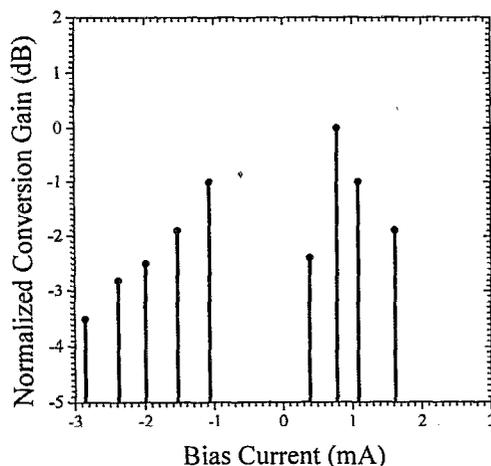


FIG. 5. Approximate experimental values of conversion gain for YBCO grain boundary mixer at $T=45$ K vs bias current. Values are relative to the minimum conversion loss at 0.78 mA bias current.

V. CONCLUSION

The coplanar waveguide geometry allowed the fabrication of a high frequency transmission line in one plane. This eliminated the need for copper grounding blocks, and allowed the circuit to be fabricated using standard wet etch technology. Thus, there is potential use in monolithic microwave integrated circuits.

The use of engineered grain boundary junctions provided the opportunity to characterize the intrinsic operation of the weak link junctions used as mixers. It allowed the reproducible fabrication and testing of weak link junctions with similar results, since the grain boundary angles could be assured during their construction. However, by using SrTiO_3 substrates, the resulting embedding impedances limited the amount of i.f. power efficiently coupled to the output.

Using the resistively shunted junction model with excess current, it was possible to mathematically model the operation of superconducting grain boundary mixers using the coplanar waveguide configuration. The calculations are in excellent agreement with the measured results, and should provide insight in further developments.

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