Micron sized constrictions fabricated using the femtosecond laser technique on YBCO thin films.

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In this paper, I report on the fabrication of micron-sized constrictions in YBCO thin films using the femtosecond laser technique. The constrictions are S-shaped superconducting weak links fabricated on YBCO thin films. The constrictions show a measurable superconducting current flowing through them. Current – Voltage (I-V) characteristics were used to determine the critical current I_C of the constrictions at 77 K. The width of the constrictions was determined at the narrowest point using SEM (Scanning electron microscope). Three micron-sized constrictions were fabricated with a width of 2.88 µm, 1.72 µm, 1.69 µm and a length of 5 µm. Based on the width and length of these constrictions in relation to the coherence length (ξ) of the YBCO these constrictions should conduct supercurrent by Abrikosov vortices. The SEM images show that the femtosecond laser heats the samples beyond the geometric boundary, damaging some of the superconductive phase of the YBCO constrictions. As a result, the constrictions conduct current by one-dimensional depairing.

Keywords: Abrikosov vortices; Atomic Force Microscope (AFM); Critical currents; Flux pinning; Lasers; Scanning electron microscopy (SEM); YBCO thin film.

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I. INTRODUCTION

Superconducting micron size bridges are very useful for applications such as bolometers [1-6], fault current limiters [7] and microwave mixing [8] etc. In fact, YBCO based bolometers can reach a theoretically predicted phonon noise-limited noise equivalent power (NEP) of 3pW/Hz0.5 [9]. In this manuscript, we show the fabrication of micron sized constrictions realized in YBCO HTS films using the femtosecond laser technique. Initially it was assumed that the advantage of using the femtosecond laser in this experiment over the other microsecond (μs) lasers will stem from the fact that the low pulse duration femtoseconds (fs) of the femtosecond laser would prevent thermal degradation on the YBCO surface introduced by the other (μs) lasers. This if achieved could produce S-s'-S type constrictions rather than the S-N-S type where the material in the center is made normal. However, the low pulse duration of the femtosecond laser needs to be taken into consideration with other factors such as the translation stage feed rate and pulse frequency (pulse repetition rate) of the laser. Although the femtosecond laser has a pulse duration of 130 fs, the feed rate is in the order of 333 $\mu m s^{-1}$ and the pulse repletion rate is 1 kHz (1000 μs). Thus, in practice, the sample is still exposed to the laser for a much longer period than femtoseconds and thermal degradation still occurs. The constrictions made were cut in the shape of the letter "S" because it is easier to regulate both the length and the width of the constriction [10] using this technique. The length can be decreased by decreasing the overlapping of the laser ablation spots and the width by bringing the ablation spots closer together. In conventional laser etched constrictions the width can be regulated but the length is restricted to the laser ablation spot size.

Superconducting bridges can show A.C like behavior similar to Josephson junctions depending on their dimension and hence can be classified according to their dimensions. Josephson junctions can be used as a reference voltage standard for measurements as in [11-14], Following Likharev et al [15], in the limit of a short and one dimensional bridge $\left(w, \frac{l}{\xi(77K)} < 3.49\right)$ [15] where w is the width of the bridge, l is the length of the bridge and (ξ) is the coherence length of the YBCO thin film, the bridge behaves like a Josephson junction as can be seen in Fig. 1. When the bridge length is increased at the same T (temperature) and width such that $\left(w, \frac{l}{\xi(77K)} > 3.49\right)$ [15] one-dimensional depairing effects characterizes the current flowing through the bridge. Finally when increasing the bridge width to values $\left(l, \frac{w}{\xi(77K)}) > 4.44\right)$ [15] keeping the length the same, the maximum critical current density is not given by depairing effects but by Abrikosov vortices, this is valid in the homogenous limit, that is in the case where the YBCO crystals remain undamaged, the same throughout at the constriction. According to [16] the coherence length (ξ) of YBCO nanostructures is 2 nm in the limit of zero temperatures.

$$\xi = \frac{\hbar V_f}{\pi E_g} \tag{1}$$

where, $\hbar$ is Plancks constant, V_f is the Fermi velocity and E_g is the energy band gap of the YBCO thin film. Using this equation and values from [17], we calculate a coherence length (ξ) of about 7 nm at 4.2 K for our case.

We used the value of 7 nm for the coherence length of YBCO as an approximation at a temperature of 77 K. The width of the constrictions we fabricated range from 1.6 to 3 µm and the length is approximately 5 µm. These bridges fabricated by the femtosecond laser fall into the group where the maximum current density is produced by Abrikosov vortices according to Fig. 1.

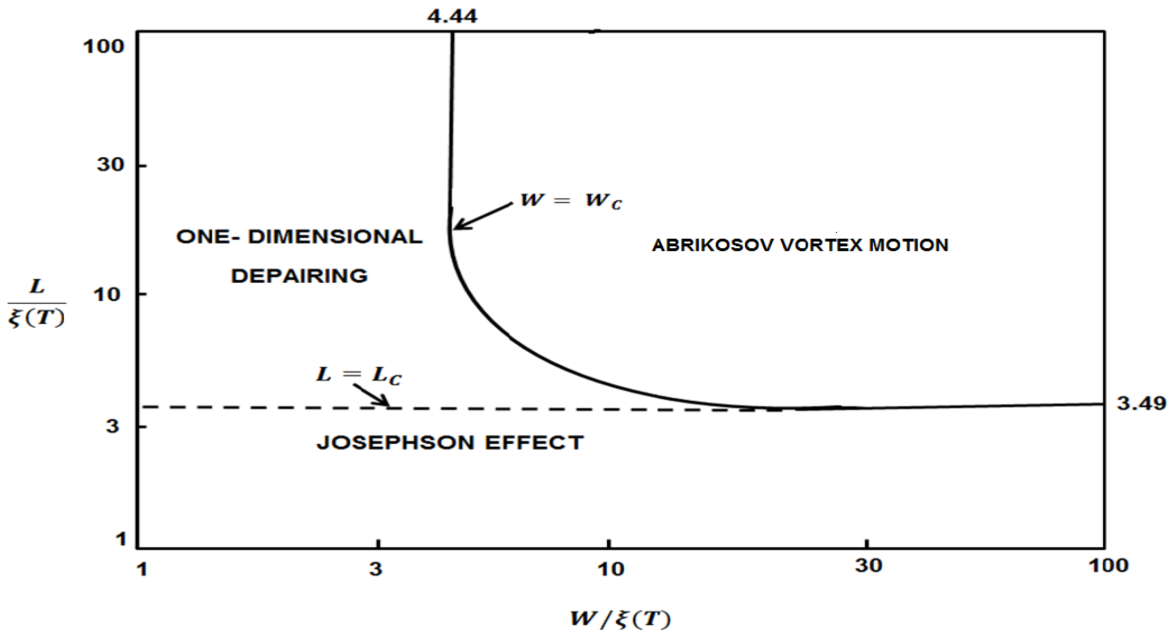

Figure 1. Variety of possible sizes of dirty weak links and causes of the flow of supercurrent through them [15]

For the Abrikosov vortices to develop the constrictions fabricated must be free of any inhomogeneity, then synchronization of the Abrikosov vortices to the external microwave radiation will occur by phase locking and Shapiro-like steps [18] would be observed in the samples proving an A.C Josephson-like behavior. The formula for the multiple steps can be seen in [19].

II. EXPERIMENTAL DETAILS

A. Thin films

We used commercially available YBCO thin films from ceraco ceramic coating company GmBH to fabricate the micron constrictions. The thin films were made on two substrates LAO and MgO similar to the substrate used in [20]. All thin films had the following dimensions; 9 × 9 mm YBCO film, single sided 200 nm with a grain orientation of (001), on 10 x 10 x 0.5 mm substrate, with one side polished**.** The YBCO thin film has a critical temperature T_c of 87 K.

B. Femtosecond laser

The femtosecond laser used has a wavelength of 795 nm, the power ranges from 0 to 1000mW and the pulse repetition rate or frequency ranges from 1 to 2kHz. When used to cut the thin film the laser was set to an optimized power of 2 mW, the pulse repetition rate at 1 kHz and the laser feed rate was set to 333 μms^{-1}. In order to fabricate bridges that are of a micron size, the laser ablation spot was passed through the process of beam collimation and beam shaping to reduce its size. The smallest laser ablation spot size achieved was approximately 10.5 µm. This ablation size can potentially fabricate a micron constriction or smaller.

The constrictions fabricated with the laser are referred to as S-shaped constrictions because they are designed in the shape of the letter "S". In order to cut the S-shaped constriction on the thin film a program was written in G-code. This is a programming language used to control the movement of the translation stage while cutting with the laser. The program consists of a section to etch the ablation strip lines and a second section to fabricate the S-shaped constriction. The ablation strip lines are used to separate one constriction from another electronically. They are formed by moving the laser vertically up and down 5 mm along the length of the YBCO thin film as seen in Fig. 2. Subsequently to fabricate the constriction the laser is moved vertically down the length of the sample, horizontally into the sample at a predetermined position and then moved out again. The laser is then moved down along the length of the sample, across the width of 1 mm to the other side. Then up to a predetermined position, horizontally into the sample, back out and then back to the top along the length to begin another strip line. The S-shape of the constriction fabricated can be seen in Fig. 2.

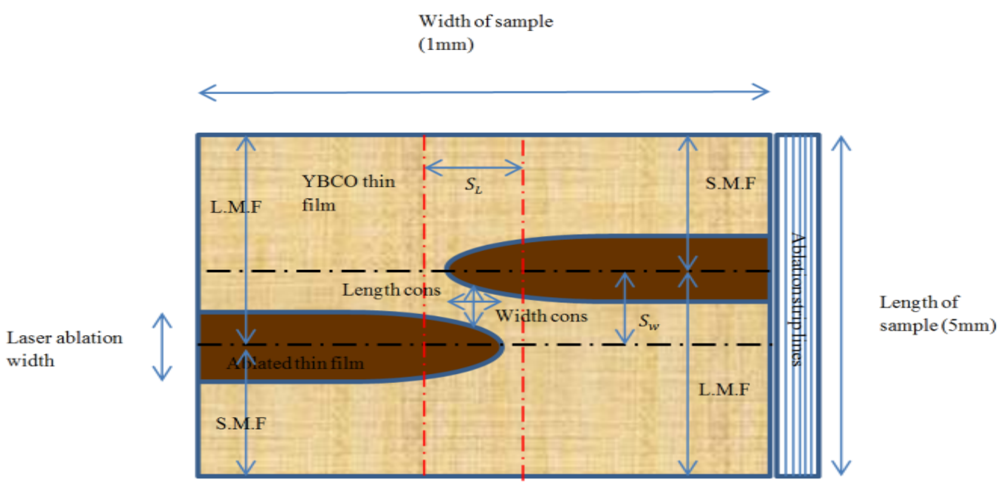

Figure 2. Design of the S-shaped constriction, Laser movement, Short movement factor (S.M.F), Long movement factor (L.M.F), Length Factor (L.F), the ablation strip lines, Length cons (constriction) and Width cons (constriction) [10].

The constrictions are cut in the shape of the letter "S" because it is easier to regulate both the length and the width of the bridge [10]. The length can be regulated by increasing or reducing the overlapping of the laser ablation spots (laser ablation width) and the width by bringing the ablation spots closer or further apart along the length of the sample. This process forms a constriction with a specified width. The width of the constriction is given by the formula in equation 2;

$$width\ of\ constriction = S_w - laser\ ablation\ width \qquad (2)[10]$$

where S_W is the separation distance set between the laser ablation spots along the length of the sample in order to determine the width of the bridge. The laser ablation spot size can be determined with an AFM after cutting. Three constrictions where fabricated, 2.88, 1.72, and 1.69 µm wide. Table 1 summarizes all the laser parameters related to the fabrication of these constrictions.

Table 1. Laser cutting parameters for each constriction

Constriction Name	Constriction Width	S_W Laser Separation distance	Laser Ablation Spot Size	Constriction Length	Measured (I_C) Critical Current	Lens Used for Cutting	Substrate
Micron-A	2.88 µm	24 µm	20.9 µm	5 µm	4.81 mA	45 mm focal length Spherical Convex lens	LAO
Micron-B	1.72 µm	18.3 µm	17 µm	5 µm	1.77 mA	45 mm focal length Spherical Convex lens	LAO
Micron-C	1.69 µm	11.8 µm	10.5 µm	5 µm	15.2 mA	Objective lens Numerical Aperture NA 0.25 X10	MgO

C. Current – Voltage Characteristics (IVC's) of the constrictions

The method used to determine the Current – Voltage (I-V) characteristics and the critical current of each sample is summarized in the block diagram shown in Fig. 3. The software used to plot the I-V curves is called "squid" from national instruments.

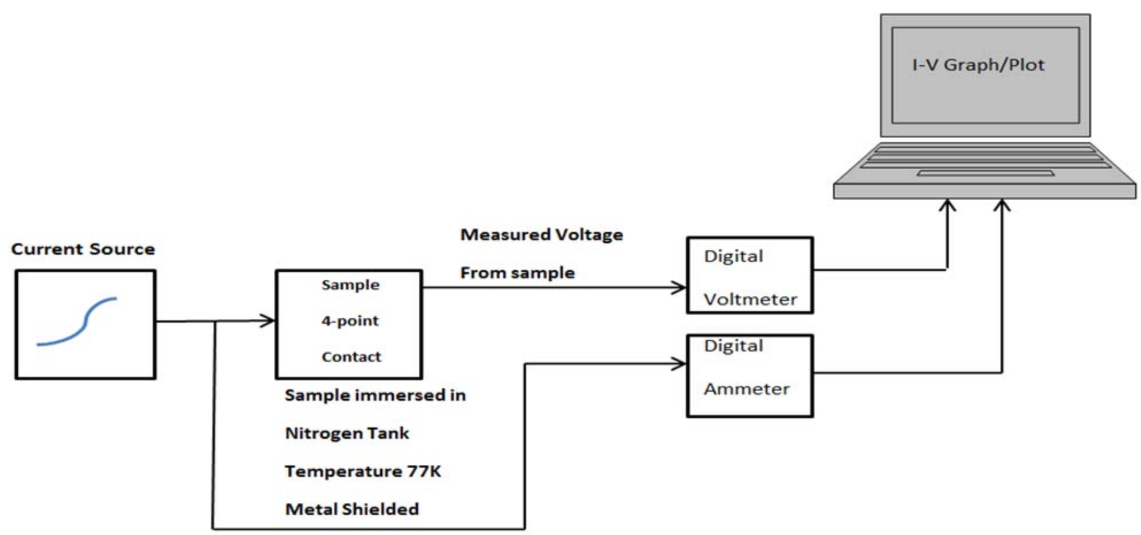

Figure 3. Set up for I-V measurements on the micron bridge samples.

4-point gold contacts were placed on the sample and then the sample was wire bonded to a PCB holder. The PCB holder together with the sample was mounted onto a probe. The probe was then immersed into a liquid nitrogen tank in order to take the sample to a cryogenic temperature of 77 K. D.C current source was used to pass current through the sample via two of the point contacts and the voltage produced was measured across the other two-point contacts using the D.C voltmeter. The D.C ammeter, which gets a reference signal from the current source and the D.C voltmeter, are connected to a computer, which with the aid of the "squid" software interface plots the I-V characteristics.

III. RESULTS

Micron constrictions with different widths were fabricated using the femtosecond laser [21-22]. The parameters of fabrication are summarized in table 1. Their widths were measured using the SEM at the narrowest points. Micron-A shown in the SEM image in Fig. 4a is 2.88 μm wide. Fig. 5a shows its I-V characteristic curve with a critical current I_C of 4.81 mA. The critical current was measured by taking a value of current at a voltage offset of 20 μV at the inflection point of the curve corresponding to the transition state from the superconducting to the normal state as shown in [23].

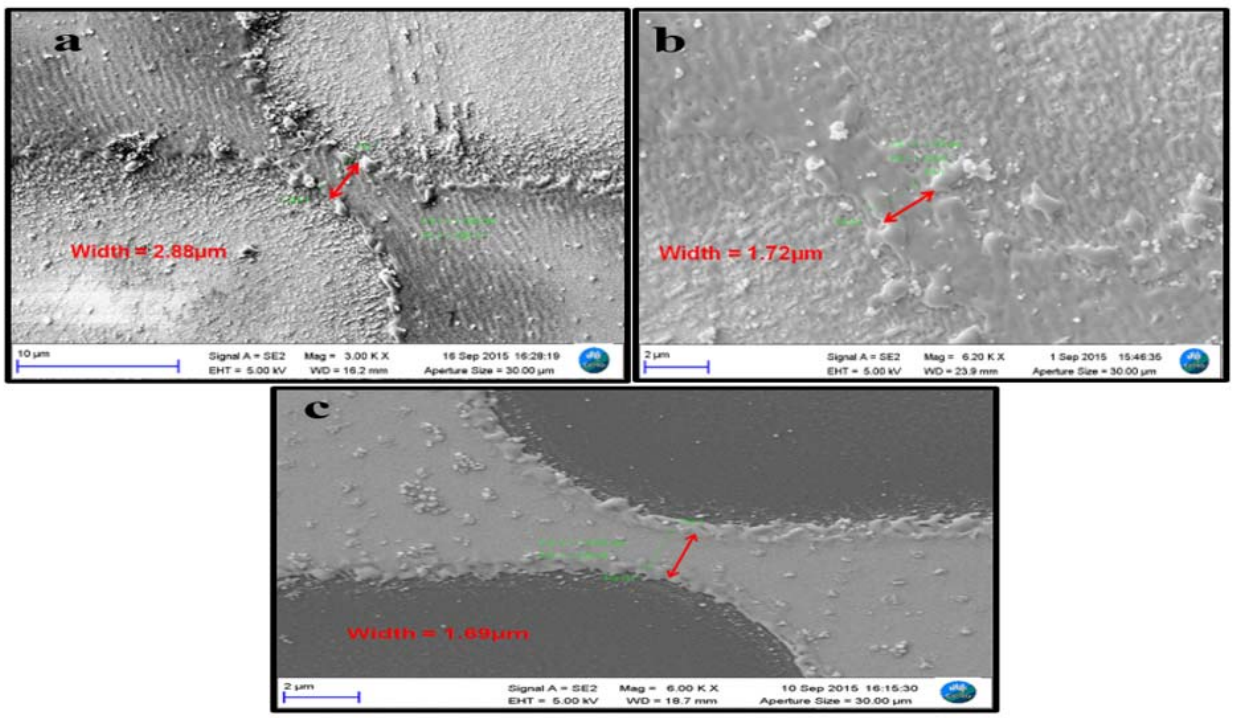

Figure 4 SEM images of constrictions Micron-A, Micron-B and Micron-C.

The SEM image of Micron-A in Fig. 4a shows there is local heating from the femtosecond laser, which produces some re-deposited particles on the geometric edge of the constriction. The actual superconductive phase of the sample is smaller than the geometric size [24]. The superconductive phase conducts the measured critical current. This current does not conduct by the coherent motion of Abrikosov vortices due to the inhomogeneities produced on the surface of the thin film as can be seen in the SEM image. The reduced width of the superconductive phase places the weak links into the category of bridges according to Likharev et al that conduct by one dimensional depairing technique, these do not show the AC Josephson-like effect. If the current was produced by Abrikosov vortices, then an A.C Josephson-like effect (Shapiro steps) could have been observed on this sample. Therefore, the constriction does not respond to microwave radiation.

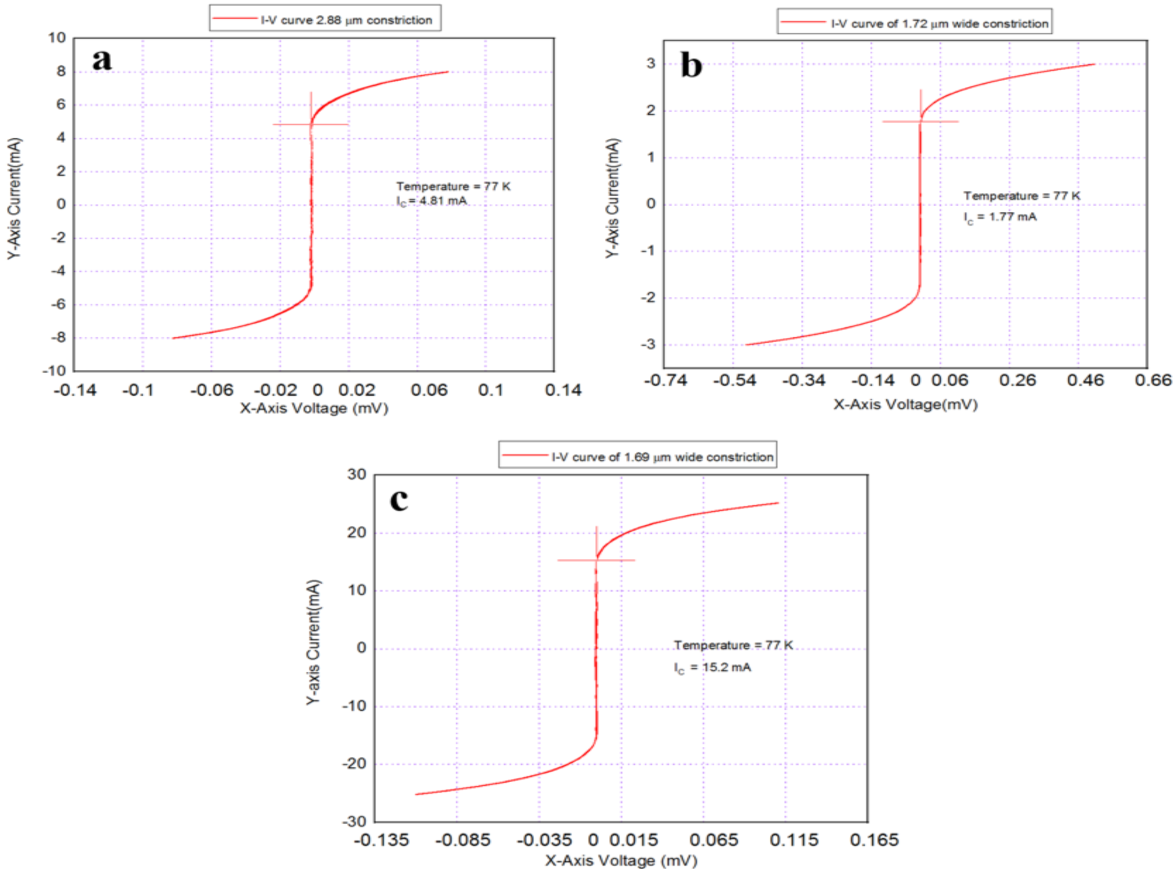

Figure 5. I-V Characteristics of constrictions Micron-A, Micron-B and Micron-C at a temperature of 77 K.

The width of constriction Micron-B was determined to be 1.72 µm wide using an SEM as can be seen in Fig. 4b. Its critical current in Fig. 5b is 1.77 mA. The voltage offset used for the measurement of the critical current is approximately 20 µV. Similarly, for this constriction the modified crystalline structure of the YBCO is not homogenous as seen in Fig. 4b. Therefore, Abrikosov vortices do not develop and the A.C Josephson-like effect cannot be seen.

The width of constriction Micron-C is 1.69 µm as can be seen in the SEM image of the sample in Fig. 4c. The I-V curve in Fig. 5c shows that the sample has a critical current of 15.2 mA. The critical current of Micron-C is almost one order of magnitude larger than that of Micron-B, while their geometric sizes of 1.69 µm and 1.72 µm respectively are similar. The reason for this can be explained as follows; for Micron-C the SEM image in figure 4c, shows that the YBCO thin film surface is uniform after fabrication. The crystalline nature is untouched beyond the geometric boundary. This is because an objective plano convex lens as can be seen in table 1 was used in focusing the laser beam in the fabrication of this sample. The objective lens has a numerical aperture of NA 0.25 and a X 10 magnification. Therefore, it has a very high focusing power that enables the laser beam spot to be reduced to a very small laser ablation spot of 10.5 µm as can be seen in table 1. This laser ablation spot cuts right on the edges of the constriction without passing beyond the geometric boundary into the superconductive phase of the YBCO. The measured critical current is therefore large because most of the superconductive phase still conducts the current. This is confirmed by the comparison with Micron-B device, which has roughly the same dimensions. Micron-B was fabricated using a spherical convex lens of focal length 45 mm to focus the laser beam before cutting. This lens produces a poorly shaped laser ablation spot which damages the edges of the YBCO channel, as confirmed by the SEM image of the device. As a consequence, the critical current of Micron-B sample is a factor of ten smaller than that of Micron-C.

The critical current density j_c of Micron-A and B is calculated to be of order 10^4 A/cm^2 while that of Micron-C is calculated to be of order 10^5 A/cm^2 at 77 K. These values are too high compared to the critical current density $j_c \approx 10^2$ A/cm^2 of tunneling Josephson junctions at the same temperature in [25] which show the Josephson effect, hence the bridges in this paper do not respond to microwave radiation.

The microwave radiation source used in our experiments with a frequency of 20 GHz will produce μA size step voltages as calculated from equations in [18-19]. These μA step voltages would not be visible in a mA current sweep. A terahertz frequency source will be required to view Shapiro steps in this case because of the large current sweep of 15.2 mA.

IV. CONCLUSION

I developed a femtosecond laser-based technique for the fabrication of micron-sized constrictions on YBCO thin films. This is demonstrated by the fabrication of three micron sized superconductive constrictions of width 2.88, 1.72, and 1.69 μm. When a spherical convex lens is used of relative focal length the laser goes beyond the geometric phase of the sample and encroaches into the superconductive phase. With the use of the objective lens of numerical aperture NA 0.25 in the optical setup the superconductive phase of the sample is untouched. The size of the superconductive phase of the material that remains unchanged determines the magnitude of the critical current produced by the sample. According to the condition$\left(l, (\frac{w}{\xi(77K)}) > 4.44\right)$, which is met in these constrictions, the current flowing should be due to the coherent motion of Abrikosov vortices. Due to inhomogeneities created by the laser, Abrikosov vortices do not form, the A.C Josephson-like effect is not observed and current flows by one dimensional depairing technique.

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