Metrological Study of YBCO Josephson Junction Arrays Integrated in a Fabry-Perot Resonator

A. Sosso, D. Andreone, V. Lacquaniti, A. M. Klushin, M. He, and N. Klein

***Abstract*—The application of High Temperature Superconductor Josephson junctions to voltage metrology is promising for many reasons, beyond the evident advantage of simplified cryogenics and reduced costs of the apparatus. Owing to their intrinsic non-hysteretic behavior, arrays of shunted bicrystal YBCO junctions are particularly interesting for the realization of an ac voltage standard with quantum accuracy. Moreover, shunted bicrystal YBCO junctions arrays are advantageous because of the reduced area of the junctions, the wide range of characteristic voltages, and large critical currents. However, some specific problems arise, like possible effects related to the higher operating temperature. Furthermore, fabrication technology sets tight constraints on the design of structures for the distribution of microwave currents along the array junctions. We investigated the step properties under millimeter wave irradiation at frequencies about 75 GHz of HTS junction and arrays prepared on bicrystal substrates having grain boundaries. High sensitivity techniques were adopted to evaluate the step flatness at nV level and assess the accuracy of the step voltage. A new method that makes use of an open resonator, was implemented to irradiate the array, providing synchronization of a large number of junctions.**

***Index Terms*—High temperature superconductors, measurements, metrology, superconductivity, voltage standards.**

I. Introduction

A MAJOR drawback of superconductivity, also for selected applications, such as quantum voltage standard, is the necessity of liquid helium working temperatures. As a matter of fact all primary voltage standard both dc and programmable, are based on niobium [1], [2], or possibly Nb nitride devices [3]. This prevents the extension to secondary standards for the production world. The limitation can be overcome by using non-metallic high temperature superconductors (HTS). HTS junctions are useful for the generation of small dc and ac voltages, but the intrinsic difficulty in realizing large HTS circuits, with several thousands or even hundreds of thousands junctions, imposes a limit to the maximum voltage output. Yet, if the driving frequency is significantly increased, an output level suitable for metrology-grade measurements can be reached, with possible applications to calibration of secondary standards, like Zener diodes and voltage dividers.

Voltage standards practically used at present in national calibration laboratories and companies make use of conventional superconductors like Nb [1]–[3]. This requires a low operating temperature of 4.2 K and, in general, liquid helium for cooling. The use of junction technology based on non-metallic high temperature superconductors (HTS) will allow this limitation to be overcome. The HTS junction technology presently available for voltage metrology has been developed at Forschungszentrum Jülich GmbH. It enables fabrication of microwave driven series arrays for reference voltages of 10 mV [4], [5]. The drive frequency is 32 GHz. Due to the relatively low frequency, the microwave coupling circuit is large which prevents the use of a considerably larger number of junctions. As a result, the DC output voltage is low. To further improve the performance of HTS arrays, it is therefore of great importance to raise the maximum drive frequency to about 70 GHz.

Quantum based standards could be employed in practically all laboratories using Zener references and digital voltmeters with a Zener reference, which require permanent and expensive re-calibration. Increasing the output voltage with the use of a higher drive frequency would be an important step towards long-term developments of a Josephson voltage standard based on HTS junctions with a very simple crycooling apparatus. Indeed, operation of LTS voltage standards with 4 K cryocoolers was demonstrated, but at present such cryocoolers are expensive, space and power-consuming devices, hence their use is limited to research laboratories or national standard institutes. Owing to the dramatic reduction in power consumption of compressors and the compact size (a single stage is sufficient) of a 60–70 K cryocooler, HTS is very promising for spreading the use of quantum voltage standards to industrial environments and integration within instrumentation.

The aim of this paper is the investigation of Josephson junctions using a Fabry-Perot resonator in the frequency band from 70 GHz to 80 GHz which is a new method of irradiation of junctions with electromagnetic fields. An effective coupling of Josephson junctions with electromagnetic oscillations in an open resonator could be also used for investigating electromagnetic sources up to terahertz frequency band. The arrays of parallel connected junctions will form the base of such sources.

Current voltage characteristics of shunted grain boundary junctions (GBJ) were studied in the frame of the resistively shunted junction (RSJ) model, considering the influence of the inductance L of the shunt on the properties of junctions. It was found that RSJL model describes adequately dc and ac characteristics of shunted grain boundary junctions (GBJ).

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In particular, amplitudes of Shapiro steps can be very well described by investigation of the arrays with this model.

II. BICRYSTAL JUNCTION TECHNOLOGY

We have investigated Josephson junctions made on commercially fabricated symmetrical bicrystal yttria-stabilized zirconia (YSZ) substrates ([001] tilt) with misorientation angle 24°. According to the manufacturer, the accuracy of the misorientation angle was $\sim 1^\circ$. Epitaxial $\mathrm{YB_2Cu_3O_7}$ (YBCO) films were formed by reactive high-oxygen-pressure metal co-evaporation, using a rotating substrate holder. The substrate temperature was $665^\circ\mathrm{C}$ and the deposition rate about 0.4 nm/s. To prevent interface reactions, 10 nm thick $\mathrm{Y_2O_3}$ buffer layers were deposited prior to depositing the YBCO films [6]. The details of the intermittent film deposition scheme have been published previously [7]. YBCO films with thickness d equal to 0.2 $\mu\mathrm{m}$ were fabricated. The contactless inductive method was used for measuring the transition temperature T_c and the critical current density of superconducting films. T_c was 87 K to 89 K. The critical current density j_c of these films was typically larger than $2\times10^6\ \mathrm{A/cm^2}$ at 77 K. *In situ* evaporated, thin gold films were used as a shunt layer. After cooling to room temperature in 200 mbar of dry oxygen, the chamber was evacuated again and a 50 nm thick gold cap layer was deposited. This process guarantees typical interface contact resistivities of the order of $10^{-8}\Omega\mathrm{cm}^2$, which are essential for effective shunting of grain boundary junctions. Each 10×10 mm YBCO film or an Au-YBCO bilayer was patterned using a standard positive photo resist. The pattern transfer was achieved using Ar+ ion milling at 250 eV with a beam current density of $\sim 2.5\ \mathrm{A/m^2}$. Patterned microbridges with a width of 4 $\mu\mathrm{m}$ cross the grain boundary thus forming Josephson junctions. On each substrate two independent series arrays of 400 junctions with a lateral size of 4 mm were fabricated. Special thin film current leads allowed independent dc-bias currents and voltage measurements on separate sub-arrays.

III. FABRY-PÉROT RESONATOR DESIGN

The Fabry-Perot resonator was arranged in a hemispherical configuration in which plane and spherical mirrors were used [8], [9]. In such configuration a flat sample is used as a plane mirror and small diameter specimens are investigated. Low sensitivity of the quality factor of the resonator to the deviation from the parallelism between the mirrors is also important. Such resonators have been used extensively at millimeter and sub millimeter wavelength for investigation of electromagnetic properties of YBCO films [8], [11] and in electron spin resonance spectrometers for the study of spectra of metallic and dielectric (solid and liquid) samples [13], [14].

A sample with an array forming a plane mirror of a hemispherical resonator is shown in Fig. 1. The radius of the spherical mirror $r = 25\ \mathrm{mm}$ and the distance between the mirrors of about $d = 24\ \mathrm{mm}$ determinate the optimum frequency from 73 GHz to 75 GHz. In this case the radii of the beam waist ω_0, which is obtained at the plain mirror for fundamental $\mathrm{TEM_{00q}}$ mode was equal to 2.5 mm. At the distance ω_0 normal to the center axis of the resonator the electric field falls to $1/e$ of its value on the axis.

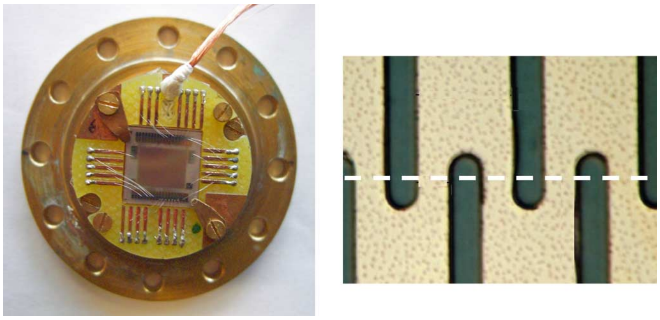

Fig. 1. Plane mirror of the Fabry-Perot resonator with mounted bicrystal substrate. Enlarged portion demonstrates meander type array. Dashed line shows the grain boundary.

The design of the Fabry-Perot resonator allows us to use a standard liquid nitrogen dewar for the irradiation of arrays in the millimeter wave frequency band from 70 GHz to 80 GHz.

IV. PRECISION MEASUREMENTS OF THE ARRAY VOLTAGE

We have tested a prototype device consisting of several sub-arrays to verify their compatibility for a measuring scheme where programmable quantized levels can be extracted.

Since our study is aimed at metrological applications it is essential to determine with high accuracy and sensitivity the electrical properties of the array. The amplitude and flatness of voltage steps are crucial parameters for voltage standard applications, as they define the ultimate accuracy in dc voltage applications (HTS quantum standard to replace Zener references in primary calibration services), and are essential for evaluating the performances in switched-bias applications for ac generation.

A. *Voltage Step Amplitude of a Single Josephson Junctions*

To explore the influence of the shunt on the step amplitude we performed simulations of the IV-curves of shunted Josephson junctions. The RSJ model was used for describing zero-capacitance shunted junctions [14]. In this model the total current I is the sum of three terms: Josephson superconducting current $I_\mathrm{c} \sin\varphi$, where φ is the difference in the phase of the superconducting wave function across the junction; the current through the junction normal resistance R_N and the current I_s through the shunt represented as connected in series resistance R_s and inductance L_c. The system of differential equations describing this circuit was solved with a Josephson circuit simulator JSIM [15] for different dimensionless inductances $\beta_\mathrm{L} = L_\mathrm{s}/L_\mathrm{c}$, where $L_\mathrm{c} = \Phi_0/2\pi I_\mathrm{c}$ is a characteristic inductance of Josephson junction and Φ_0 is a magnetic flux quantum.

In Fig. 2 the IV characteristic of the shunted bicrystal junction with the critical current $I_\mathrm{c} = .2\ \mathrm{mA}$ measured at the temperature $T = 71\ \mathrm{K}$ is shown. The resistance of this junction is $R = 0.11\ \Omega$ and the characteristic voltage $V_\mathrm{c} = 0.13\ \mathrm{mV}$ which corresponds to characteristic frequency $f_\mathrm{c} \equiv V_\mathrm{c}/\Phi_0 \cong 64\ \mathrm{GHz}$. This curve was fitted in the frame of RSJL model with normal junction resistance $R_\mathrm{N} = 0.42\ \Omega$, shunt resistance $R_\mathrm{s} = 0.15\ \Omega$

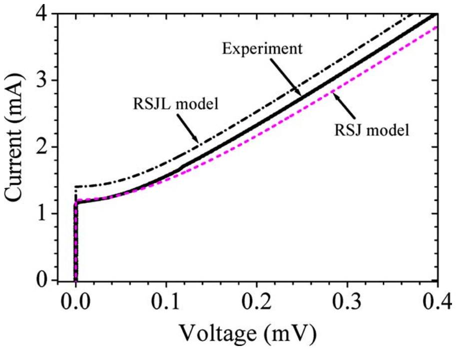

Fig. 2. Experimental IV curve for one shunted bicrystal Josephson junction at 71 K (solid line) as well as IV-curves simulated in the frame of RSJ model ($L_s = 0$, dashed line) and RSJL model ($L_s = 0.53$ pH, dashed-dotted line). IV curve simulated by RSJL model is shifted up for 0.2 mA along y-axis for clarity.

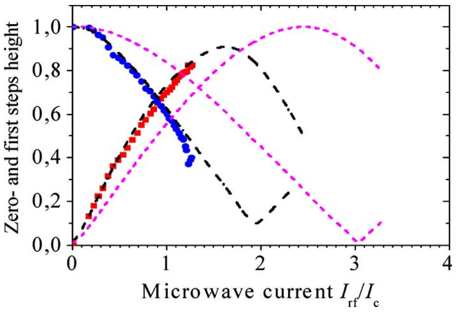

Fig. 3. Dependence of the amplitude of the zero (●) and the first (■) voltage steps on ac bias current. For comparison similar curves simulated in the frame of RSJ model ($L_s = 0$, dashed line) and RSJL model ($L_s = 0.53$ pH, dashed-dotted line) are shown.

and shunt inductance $L_s = 0.53$ pH or $\beta_L \cong 2$. The simulated curve is shifted up along y-axe for clarity as it is shown in Fig. 2. It demonstrates full coincidence of the measured and simulated data. For the comparison we have shown IV curve simulated in the frame of RSJ model with $L_s = 0$ pH. In this case the substation differences between the measured and simulated curves are evidently.

To reveal the influence of the shunt on the voltage step amplitude we have explored the behavior of the amplitude of the zero and the first step as a function of ac bias current. The experimental results as well as the results of computer simulations are presented in Fig. 3. The experimental data for the zero, I_0/I_c (closed circle) and the first, $\Delta I_1/I_c$ (closed square) steps are fitted very well in the frame of the RSJL model (dashed line) with the parameters used previously. At the same time remarkable differences between the measured dependences and the simulated ones in the frame of RSJ model (Fig. 3, dash-dotted line) are clearly visible. The maximal value of the step amplitude slightly decreased with β_L from $\Delta I_1/I_c = 1$ for $\beta_L = 0$ to $\Delta I_1/I_c = 0.9$ for $\beta_L = 2$. The decreasing of the step amplitude with β continues till $\Delta I_1/I_c = 0.65$ for $\beta_L = 6$.

B. *Voltage Step Amplitude of an Array of HTS Josephson Junctions*

Arrays containing 182 junctions were investigated. The typical current-voltage characteristics of an array containing 64

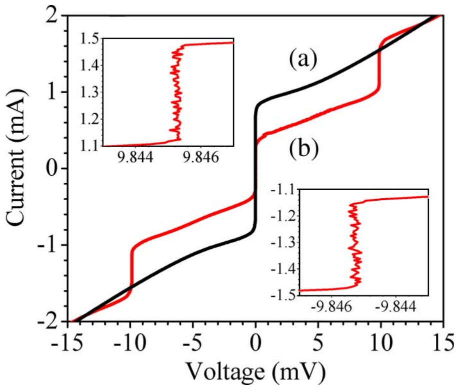

Fig. 4. Current-voltage characteristics for a series array of 64 junctions at 75 K (a) without and (b) with external mm wave irradiation. Enlarged portions demonstrate the steps' amplitudes and their steepness.

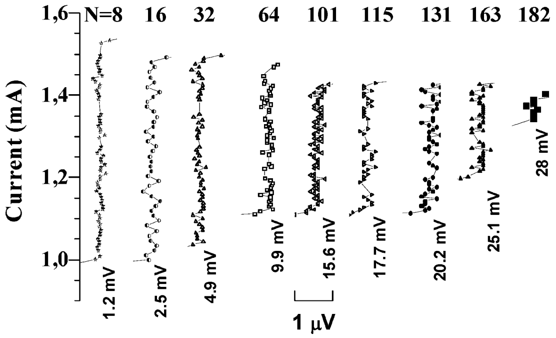

Fig. 5. High resolution profiles of the steps of the HTS array observed at 77 K with 74.4 GHz microwave frequency. Trace labels indicate the step voltage. In the upper row the number of series-connected junctions corresponding to each trace is reported.

HTS Josephson junctions are shown in Fig. 4. The IV-curve (Fig. (4a)) was measured without external irradiation and curve (Fig. (4b)) under mm wave irradiation with $f = 74.4$ GHz. The Josephson junctions in the array had an average critical current of $I_c = 0.7$ mA, the average resistance of the shunted junctions was 0.14 Ω. The resulting characteristic voltage $V_c \cong 0.1$ mV was at optimum for the observation of the first voltage step under millimeter wave irradiation. The inset in Fig. 2 shows an enlarged portion of the IV-curve (Fig. (4b)) demonstrating steep steps with a height $\Delta I_1 > 0.3$ mA at a voltage about 10 mV. This result documents that those arrays of HTS Josephson junctions exhibit promising properties to be utilized in quantum voltage metrology.

To determine the step profile, the array bias was spanned over a step, while measuring with a high sensitivity voltmeter the voltage difference between the array and a voltage reference with high stability. The results, summarized in Fig. 5, show that steps with amplitude larger than 200 μA are obtained at voltages up to 20 mV. These values are suitable for the application in voltage metrology. For an ac standard, since steps with adequate amplitude are observed with more that 150 series-connected junctions, the use of HTS arrays for waveform generation seems feasible up to 8 bit resolution.

The maximum number of junctions being synchronized was equal to 182. In this sub-array a step amplitude ΔI_1 equal to

0.08 mA at 28 mV was observed. Since the width of the junctions was 6 μm and the distance between the junctions 5 μm, 182 junctions were spaced over a distance of 2 mm. We suppose that the limitation is caused by the non-uniformity of the field determined by the width of the Gaussian beam in the fundamental mode of the FP resonator. This is no fundamental limitation, since the width of the Gaussian beam can be increased by increasing radius of curvature and diameter of the spherical mirror [9].

In dc voltage applications, owing to the limitation in the output voltage, the array must be used with an external divider to reach 10 V as an ordinary Zener references. However, the uncertainty due to the divider does not exceed the uncertainty of the best electronic voltage standards, limited by the noise of the Zener diodes [16]. Proper choice of the divider ratio allows choosing a trade off between array output voltage and step amplitude.

V. CONCLUSION

Operation of HTS junction arrays in metrological application was described. A technique for irradiation making use of a Fabry-Perot resonator was presented. The resonator allows us to shine the millimeter wave signal and generate voltage steps suitable for application in a voltage standard. The analysis the step profiles suggest that HTS arrays can be profitably used for both dc and ac voltage standard operating with liquid nitrogen or small cryocoolers.

The application of the quasioptical systems in general and a Fabry-Perot resonator in particular is very useful for synchronization of the arrays of Josephson junctions and possible application for voltage standards for many reasons. First, the developed cryoprobe with a Fabry-Perot resonator is compatible with standard liquid nitrogen or helium dewars. Second, the microwave design of the superconductor circuit is much simpler as compared with the typical niobium JJA. In our case, a substantial simplification of the technology of niobium arrays could be achievable. Third, it is important to note that our quasioptical coupling method can be extended to the higher frequencies.

Next steps will be further testing by direct comparison against an LTS Josephson array. We expect that this method can be used to irradiate the arrays up to about 150–180 GHz, allowing the generation for voltages up to 0.1 V at 77 K.

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