Full Synchronization of Arrays of High-T_c Josephson Junctions

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***Abstract* - We explored high-temperature superconductor Josephson junction arrays embedded in a hemispherical Fabry-Perot resonator. We compared the characteristics of three designs of arrays to achieve steps at higher voltage with a better coupling to the millimeter wave irradiation power. With an optimal design, we achieved a maximum Josephson volt age of about 0.1V for an array of 620 bicrystal junctions at a temperature of 79.2K and a frequency of 77.465 GHz. Also steps from 0.01 V up to 0.1 V were observed. Our results showed that such circuits are promising for applications in quantum voltage metrology. It is important to note that our quasioptical coupling method can be extended up to terahertz frequencies.**

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I. INTRODUCTION

One of the important applications of the Josephson effect in superconducting electronics is in quantum voltage standards. The principal importance of this application is due to the fact that no other physical effects are known today, which provide a similarly accurate representation of the volt. Series arrays of microwave-irradiated Josephson junctions (JJ) constitute the base of present voltage standards. Required are thousands of JJs in series, phase-locked to the applied microwave signal. All of the junctions in the array should have very similar parameters *i.e.*, critical current I_c and normal resistance R_n, while their current-voltage (IV) characteristics should conform to the resistively shunted junction (RSJ) model. Usually, niobium junctions operating at helium temperatures are applied in such systems [1, 2].

Recently, programmable voltage standards have attracted much attention because they can generate a set of precision voltages. This radically changes the comparison scheme and increases the accuracy and speed of calibration. A new type of the voltage standard for fast dc measurements has been recently demonstrated with Nb- and NbN-based resistively-shunted Josephson junctions having a nonhysteretic current-voltage characteristic at liquid helium temperature [3-5].

Such nonhysteretic junctions are naturally available in a high-temperature superconductor (HTS) technology. The main advantage of HTS is the higher operation temperature easier achievable by low-power cryocoolers. However, the spread of parameters of HTS junctions is presently very high compared to low-temperature superconductor (LTS) Josephson junctions. Different technological approaches have been used to fabricate planar $YBa_2Cu_3O_7$ (YBCO) junctions such as the grain-boundary junctions [6], the ramp-type junctions [7] and junctions produced by ion damage [8-10]. The last technique has been recently used for producing planar MgB_2 Josephson junctions and series arrays containing up to 20 JJs [11].

II. OUR EARLIER RESULTS OBTAINED WITH HTS ARRAYS

Our approach relies on bicrystal arrays with external shunt resistors [12]. Shunted bicrystal HTS Josephson junctions are promising candidates to be used in voltage standard applications. First, they conform to the resistively shunted junction (RSJ) model. Second, these junctions may have large critical currents and, upon irradiation, first current steps at temperatures up to 80 K. In arrays, this can provide stability against noise as well as a large output current. Third, their characteristic voltages, I_cR_n (where R_n is the shunted junction resistance), can easily be varied in a practically important range between 20 μV and 200 μV thus enabling voltage standard operating frequencies from 10 GHz to 100 GHz. Finally, a significant enhancement of junction packing density is possible by using a substrate with several parallel grain boundaries and electron-beam patterning of the YBCO circuit.

Shunted bicrystal junctions were fabricated by using Au-YBCO bilayers deposited *in situ* on symmetrical grain boundary yttrium-stabilized zirconium oxide (YSZ) substrates. With such an array, the spread of the junction normal state resistance R is kept at only a few percent, whereas the spread of the critical current I_c is still on the order of typically 30 %. Under these conditions, the individual voltage steps of all N junctions emerge within an overlapping current interval resulting in the occurrence of one single voltage step of a reasonable width (with respect to thermal noise) for the whole array at a voltage $V = N f/K_J$, where f is the irradiation frequency and $K_J \equiv h/2e$ the Josephson constant. When coupling the microwave energy via the coplanar waveguide (CPW, see below), the maximal number of synchronizing junctions N was equal to 256 [13].

Indeed, the important requirement for the formation of stable and wide Shapiro steps is to make a uniform microwave energy coupling over all the junctions. In low-temperature voltage standards, a straight-line series array of Josephson junctions is embedded along either a micro strip line [14], or the center conductor of a CPW [15], or in both conductors of the slot line [16]. The propagating electromagnetic wave effectively drives the arrays containing up to several thousands of junctions. In contrast, the series array of bicrystal junctions is laid out as a meander line. This prevents the uniform distribution of ac current along such an array. To overcome this drawback the meander array was placed parallel to the usual CPW. This provided parallel feeding of microwave power to all junctions [13]. Microstrip [17] and waveguide resonators were previously explored for irradiation of the JJ array at frequencies below 40 GHz [18].

Recently we suggested and successfully implemented an efficient method of irradiating arrays of high-T_c Josephson junctions by coupling them to the resonant modes of a millimeter wave Fabry-Perot (FP) resonator [19]. The Fabry-Perot resonator is an open resonator and can resonate at mm-wave and even sub-mm wave with a high quality factor [20]. When it works in quasi basic TEM mode, the electromagnetic field distribution near the plane mirror in a hemispherical FP resonator is similar to the plane wave. It can thus irradiate uniform power on the Josephson junction arrays. We demonstrated a full synchronization of about 200 HTS junctions and achieved a Josephson voltage of 30 mV at 74.4 GHz. Metrologically relevant flat steps with a height of about 150 μA were measured at liquid nitrogen temperature [21].

Here, we present the results of experiments used to study the influences of different layouts of arrays on the coupling of Josephson junctions to the mm wave radiation in the FP resonator. After the coupling conditions were optimized, the synchronization of the full array located on the substrate was attained.

III. RESULTS AND DISCUSSION

A. Fabry-Perot Resonator System

The FP resonator was arranged in a hemispherical configuration with plane and spherical mirrors as shown in Fig. 1 [22]. A sample with an array of high-temperature Josephson junctions was placed between the two mirrors, parallel to the plane mirror. The radius of the curvature of the spherical mirror was equal to 25 mm or 50 mm.

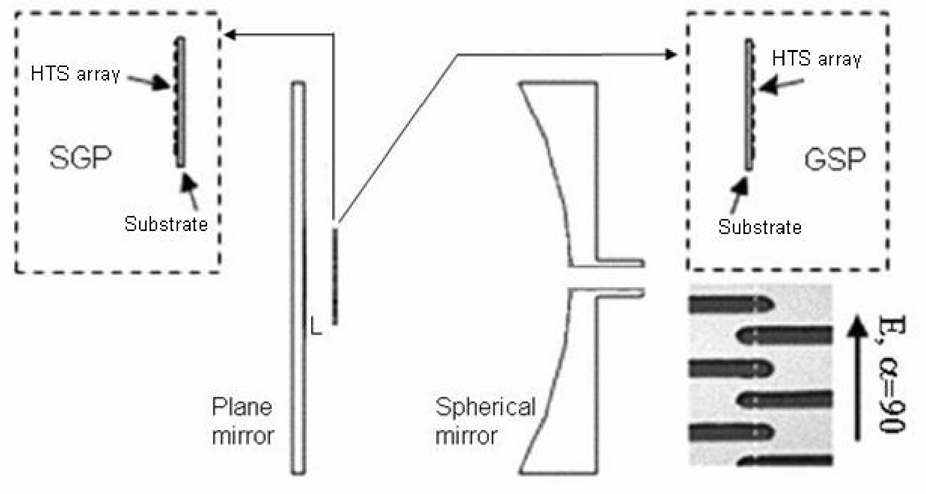

Fig. 1. Schematic of the hemispherical Fabry-Perot resonator with the HTS array placed at distance L from the plane mirror. The inserts at the top show two different types of irradiation schemes of the HTS arrays in the FP resonator: the HTS array placed facing the spherical mirror is denoted as Grids-Substrate-Plane mirror (GSP) structure; the HTS array placed facing the plane mirror is denoted as Substrate-Grids-Plane mirror (SGP) structure. The insert at the bottom right side shows the layout of the HTS array circuit. The grain boundary (GB) is marked as a dashed line. The angle α between the strips and the electric field vector *E* is 90°.

The insert at the bottom right in Fig. 1 shows the layout of the HTS array circuit. The grain boundary (GB) is marked as a dashed line and is located in the middle of a bicrystal substrate with dimensions 10×10 mm^2. The GB divides the substrate into two equal parts. The metallized parts (light areas at the low right insert of Fig. 1) are extended over a length of up to 4 mm and form a grid composed of metal strips. The two sub-grids below and above the GB are connected in the middle of the substrate with the bridges crossing the GB, forming a series array of junctions with a lateral size of 6 mm. The width of each junction is 6 μm. The shunted junctions were fabricated using Au-$YBa_2Cu_2O_{2-x}$ bilayers deposited in situ on bicrystal symmetrical yttrium-stabilized zirconium substrates with a misorientation angle of 24°. Details of the deposition process and the technology of shunted GB junctions were published previously [23].

Two different types of irradiation schemes of the HTS arrays in our FP resonator system can be used. In the first case, the HTS array can be placed facing the spherical mirror. We denote this case as the Grids-Substrate-Plane mirror (GSP) structure. In the second case, the HTS array can be placed facing the plane mirror and is denoted as the Substrate-Grids-Plane mirror (SGP) structure. In this paper the results obtained with the SGP structure will be reported. Experiments described recently [22] showed that a larger area of the uniform field can be achieved and thus the step height increased compared to the GSP structure. Moreover, we can move the grids close to the plane mirror only when the SGP structure is used.

B. Characteristics of Arrays with Different Designs

In order to experimentally explore the characteristics of three different designs shown in Fig. 2, we fabricated a JJ array circuit composed of 8 different sub-arrays [24]. From left to right the sub-arrays were numbered 1, 2… 10. Each sub-array included 62 Josephson junctions with the width of the bridge w = 6 μm crossing the GB. The black lines are YBCO thin films. The grain boundary (GB) is marked by a dashed line and located in the middle of a bicrystal substrate and also in the middle of the sub-arrays. Sub-arrays 1, 2 and 7 were made according to the design of type A, sub-arrays 3, 4 and 8 according to the design of type C and sub-arrays 5 and 6 according to the design of type B.

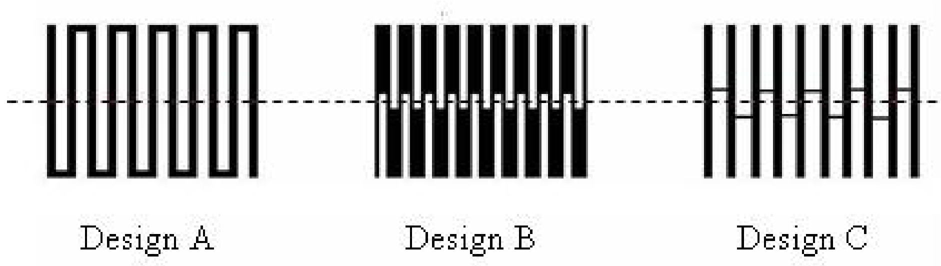

Fig. 2. Three different designs of Josephson junction arrays. The YBCO circuit is black, the GB is marked by the horizontal dotted line.

At a temperature of 74 K, the critical current was $I_c = 0.5$ mA for the sub-arrays of type A and C and the resistance of each junction was $R_n = 0.13\ \Omega$. For the sub-arrays of type B, the critical current was $I_c = 0.8$ mA at 74 K and the average resistance of each junction $R_n = 0.1\ \Omega$. We have observed a very small modification at the position of the first step under mm-wave irradiation at $f = 67.2$ GHz of the array of the type A. This means that the mm-wave irradiation power is very difficult to couple to the JJs sub-arrays with layout A. On the contrary, the *IV*-characteristics of sub-arrays with layouts B and C indicate that the millimeter-wave irradiation power can be coupled effectively to the JJs, and the first steps of height $\Delta I_1 = 0.32$ mA and $\Delta I_1 = 0.31$ mA appeared, respectively.

C. Array of Josephson Junctions with Step Voltages up to 0.1 V

We present the results of the investigation of the circuits containing 10 sub-arrays of type B [24]. Two samples were fabricated and successfully tested. On one sample, a maximal Josephson voltage of 100 mV was observed and on the second 90 mV. Figure 3 depicts the current-voltage characteris-

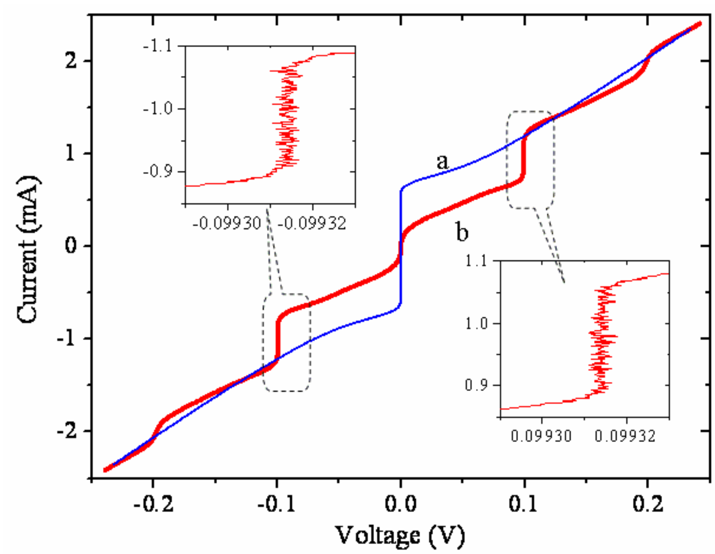

Fig. 3. *IV* characteristics of JJ array of 620 HTS junctions at 79.2K: (a) without and (b) with external mm wave irradiation at 77.465GHz. Enlarged portions demonstrate the amplitude and the steepness of the steps.

tics of the first JJ array of 620 junctions at 79.2 K without (a) and with the external mm wave irradiation at a frequency of 77.465 GHz (b). From Fig. 4, curve (a), one finds that the Josephson junctions in the array have an average critical current of $I_c = 0.53$ mA and that the average resistance of the shunted junction is 0.18 Ω. The resulting characteristic voltage $V_c \approx 0.1$ mV is optimum for the observation of the first voltage step under mm-wave irradiation. Enlarged portions of the *IV* curves demonstrate the amplitude and the steepness of the step. The measurement of the first step at a voltage of about 0.1 V with resolution better than 5 μV reveals the step height of $\Delta I_1 \approx 0.17$ mA. This relatively high-noise-level measurement doesn't imply that in metrological application the step voltage would have similarly limited accuracy.

Figure 4a shows the current-voltage characteristics for different HTS arrays measured at the same frequency, power and temperature. The curves are labeled by numbers from 1 to 10, each denoting the number of the sub-array included in the circuit. One sub-array with 62 Josephson junctions produced a step at a voltage approximately equal to 10 mV. Figure 4 (a) shows all the steps from 10 mV to 100 mV. By investigating each of the sub-arrays as shown in Fig. 4 (b), it is found that the average critical current is $I_c = 0.55$ mA with a standard deviation of 19 µA or 3.5%. The average resistance of one shunted junction is about 0.18 Ω with a standard deviation of 2.5 mΩ or less than 1.5%. The zero and first step heights show that the irradiation power decreases from the middle to the sides of the array.

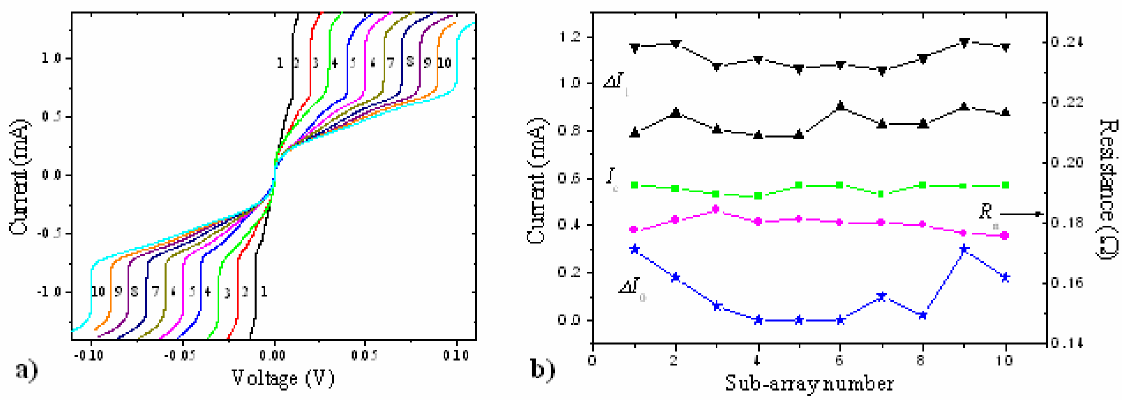

Fig. 4 **(a)** *IV* characteristics of different HTS arrays at 79.2 K with external irradiation frequency $f = 77.465$ GHz. The curves labelled from 1 to 10 denote the numbers of the sub-arrays of type B included in the arrays.

(b) Parameter distribution in the 10 sub-arrays: ▲,▼ - boundaries of the first steps, ■ - critical current of the sub-array, ● - average resistance (right axis) of junctions in the sub-array, ★ - zero step height ΔI_0 of each sub-array.

IV. CONCLUSIONS

We compared characteristics of three types of meander arrays and found a presumably optimal design to achieve steps at higher voltage with better irradiation power coupling efficiency. We confirmed that the quality of the bicrystal junctions we used is very good because the spread of the critical currents was about 3.5% and the spread of the normal resistance was no more than 1.5%. These parameters approach the best results typical of the advanced technology of low-temperature superconductor (Nb, NbN) Josephson junction arrays. With this optimal design, we achieved for the first time uniform microwave energy coupling to all junctions the array, resulting in a maximum first step at a Josephson voltage of about 0.1 V for the array of 620 bicrystal junctions at a temperature of 79 K. The step height was 0.17 mA at a frequency of 77.5 GHz. Sub-arrays containing a smaller number of junctions were also synchronized at the same frequency and power. Steps from 0.01 V to 0.1 V were observed. Our results show that such circuits could be considered for application as a programmable dc voltage standard. It is important to note that our quasioptical coupling method can be extended up to terahertz frequencies. In addition, our approach appears very promising for THz sources and detector arrays. Finally, this approach could be useful for the irradiation of large arrays of niobium Josephson junctions as well. In that case, it may be possible to achieve a substantial simplification of the technology of niobium arrays and an increase of the irradiation frequency.

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