Optimization of the coupling of mm wave power to arrays of high-$T_c$ Josephson junctions

A M Klushin, M He, M Yu Levitchev, V V Kurin, N Klein

1Institute for Bio- and Nanosystems and CNI-Centre of Nanoelectronic Systems for Information Technology, Forschungszentrum Jülich GmbH, Germany
2Department of Electronics, Nankai University, People's Republic of China
3Institute for Physics of Microstructures, Russian Academy of Sciences, Nizhny Novgorod, Russia

a.klushin@fz-juelich.de

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 voltage 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 challenging for applications in quantum voltage metrology. It is important to note that our quasioptical coupling method can be extended up to terahertz frequencies.

1. Introduction

One of the most attractive applications of arrays of synchronized Josephson junctions (JJs) is connected with the development of dc quantum voltage standards. Special interest was aroused by the development of programmable voltage standards (PVS). These devices have attracted much attention because they can be successfully used in ac voltage and power quantum metrology. 10 V PVS have been recently demonstrated using nonhysteretic JJs based on low-temperature Nb and NbN superconductors (LTS) [1, 2].

Similar nonhysteretic junctions are naturally available for high-temperature superconductor (HTS) technology. The main advantage of HTS is a higher operation temperature, which is achieved by low-power cryocoolers and larger characteristic frequencies. However, in comparison to LTS JJs the spread of parameters of HTS junctions is still remarkably high. A very challenging approach relies on bicrystal JJs with external shunt resistors [3]. Shunted bicrystal junctions were fabricated by using Au- YBa$_2$Cu$_3$O$_7$ (YBCO) bilayers deposited in situ on yttrium-stabilized zirconium oxide substrates. With such an array the spread of the junction normal state resistance is kept at only a few percent, whereas the spread of the critical current is still of the typical order of 30 %.

An important requirement for the formation of stable and wide voltage steps is to establish a uniform microwave power coupling over all the junctions. In LTS arrays, a straight-line series array of JJs is embedded along either a micro strip line [1], or the center conductor of a coplanar wave guide [2].
Recently we suggested and successfully implemented a method of irradiating arrays of high-$T_c$ JJs by coupling them to the resonant modes of a millimeter wave Fabry-Perot (FP) resonator [4, 5]. 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 [6].

Here we present the results of the experiments used to study the influences of different layouts of arrays and parameters of FP resonator on the coupling of Josephson junctions to the mm wave irradiation. After the coupling conditions had been optimized, the number of synchronized junctions and the step height were further increased.

### 2. Fabry-Perot resonator system and different designs of high-temperature Josephson junction arrays

The FP resonator was arranged as a hemispherical configuration composed of a plane and a spherical mirror. The substrate was used as the plane mirror with dimensions of 10×10 mm². Both the radius of the curvature and the diameter of the spherical mirror were 25 mm. The millimeter (mm) wave was radiated on the sample through the open end of a standard waveguide arranged in the center of the spherical mirror. The details of the Fabry-Perot resonator construction are described elsewhere [4-6].

The shunted junctions were fabricated using Au–YBaCuO bilayers deposited in situ on bicrystal symmetrical yttrium-stabilized zirconium (YSZ) substrates with a misorientation angle of 24°. The thickness of the YBCO thin film was 300 nm. Details of the deposition process and the technology of shunted GB junctions have been published elsewhere [7].

Figure 1 shows the layout of the HTS array circuit, which is composed by several sub-arrays. From left to right the sub-arrays were numbered 1, 2… 10. 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. Each sub-array includes N Josephson junctions with the width of the bridge $W = 6 \mu m$ crossing the GB. The black lines are HTS thin film. As shown in figure 1, there are three types of array layouts denoted as A, B and C. The whole array circuit is composed of one type or all types of sub-arrays.

### 3. Results and discussions of experiments

#### 3.1. Characteristics of arrays with different designs.

In order to explore the characteristics of different designs shown in figure 1, we fabricated a JJ array circuit composed of 8 different sub-arrays. Each sub-array included 62 JJs. 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.

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 $R_n = 0.1 \Omega$. The current-voltage ($IV$) curves of different types of sub-arrays without (dashed lines) and with (bold lines) mm wave irradiation at $f = 67.2$GHz are shown in figure 2.
3.2. The influence of the junction parameters on the coupling of the external irradiation to the array.

In our previous experiments [3], it was found that the shunted gold layer helps to make the resistance of Josephson junctions more uniform. At the same time, we should take into account the fact that this process may reduce the coupling efficiency both due to the decrease in the resistance of the junctions and the decline of the amplitude of mm-wave bias current penetrating into the Josephson junction in the presence of the shunt layer, i.e. due to the skin effect.

We explored the coupling efficiency of mm-wave power to JJs covered by gold layers with thicknesses of $d_{Au} = 50$ nm (sample I) and $d_{Au} = 30$ nm (sample II). As a figure of merit of the coupling efficiency, we used the amplitude of the critical current or zero step $\Delta I_0$. Arrays with layout B containing 64 Josephson junctions were fabricated. Figure 3 shows the $IV$ characteristics of these two samples at different temperatures. We measured $\Delta I_0$ at approximately equal critical currents $I_c$ and characteristic frequencies $f_c = I_c R_n / \Phi_0$, where $\Phi_0$ is the magnetic flux quantum. Curves (a) and (c) in figure 3 show the $IV$ characteristics of sample I at 78 K and sample II at 79.1 K. At these temperatures, sample I and sample II have critical currents $I_c \approx 0.5$ mA but different resistances. The average resistances of each junction are $R_{n,1} = 0.11 \, \Omega$, $R_{n,2} = 0.18 \, \Omega$ and characteristic frequencies $f_{c,1}$(79 K) = 42.6 GHz and $f_{c,2}$(78 K) = 26.6 GHz as is shown in table 1. We applied external irradiation at frequency $f = 67.5$ GHz to these two samples and obtained the $IV$ characteristics shown in curves (d) and (f), respectively. From these curves we found that $\Delta I_0$,(78K) = 0.3 mA for sample I is larger than $\Delta I_0$,(79K) = 0.06 mA for sample II. Moreover, sample II achieved the small value of $\Delta I_0$,(79K) at an irradiation power of $P_2 = 4.5$ mW, which is much smaller than the maximal available power $P_1 = 11$ mW needed for sample I.

To measure these samples at approximately equal characteristic frequencies, we decreased the temperature of sample I to 74 K to obtain $f_{c,1}$(74 K) = 42.6 GHz, which was comparable to the $f_{c,2}$(79 K) of sample II. Curve (e) shows the $IV$ characteristic of sample I at an irradiation frequency 67.5 GHz.

To show the difference of the $IV$-characteristics more clearly, curves (a) and (c) are shifted by 2 mA and -2 mA on the current axis. As shown in figure 2, curve (a), we can only see a very small modification at the position of the first step under mm-wave irradiation at $f = 67.2$ GHz. 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 illustrate that the mm-wave irradiation power can be coupled effectively to the JJs, and the first steps of height $\Delta I_1 = 0.32$ mA and $\Delta I_2 = 0.31$ mA appeared, as shown in figure 2, curves (b) and (c).
with a power of 11 mW. In spite of increasing the critical current to $I_{c1}(74\,\text{K}) = 0.8\,\text{mA}$ at this temperature the zero step decreased to $\Delta I_{01}(74\,\text{K}) = 0.24\,\text{mA}$ in comparison with $\Delta I_{01}(78\,\text{K})$.

The results obtained cannot be explained by the skin effect because the thicknesses of the gold layers were much smaller than the skin depth equal to 200 nm in our case. To explain the experimental data we use a simulated dependence of the power $P$, required to produce steps, on critical current and reduced frequency $\Omega = f / f_c$ [8]. The simulations were performed for short junctions and in the frame of the resistively shunted junction (RSJ) model. From the simulations [8] we found that the required power is proportional to $P \sim I_c \Omega^2 (0.5 < \Omega < 5)$. Quantities $I_c \Omega^2$ are shown in the table.

From these rough estimations it follows that for the same value of $\Delta I_0$ sample I at 74 K needs power larger by a factor of 2.7 in comparison with sample II. In the experiment, this relation was smaller and equal to $P_1 / P_2 \approx 2.4$. For sample I, the quantity $I_c \Omega^2$ decreased from 3.22 to 1.9 with decreasing $T$ from 78 K to 74 K, which explains the decrease of the corresponding value of $\Delta I_0$ as is shown in the table. We conclude that unnecessarily high values of $\Omega$ should be avoided in order to minimize the irradiation power. An optimal value $\Omega = 1$ is large enough for the steps to approach their full amplitude but not so large that excessive mm wave power is required to produce them. Coincidentally, $\Omega = 1$ also yields the greatest tolerance of step position to variations in critical currents [8, 9].

**Table.** Parameters for sample I and sample II

|       | $d_{Au}$ (nm) | $T$ (K) | $I_c$ (mA) | $R_n$ ($\Omega$) | $f_c$ (GHz) | $\Omega$ | $\Delta I_0$ (mA) | $P$ (mW) | $I_c \Omega^2$ |
|-------|---------------|--------|------------|------------------|-------------|--------|-------------------|--------|--------------|
| Sample I | 50            | 78     | 0.5        | 0.11             | 26.6        | 2.54   | 0.30              | 11     | 3.2          |
| Sample I | 50            | 74     | 0.8        | 0.11             | 43.5        | 1.55   | 0.24              | 11     | 1.9          |
| Sample II| 30            | 79.1   | 0.5        | 0.18             | 43.6        | 1.58   | 0.06              | 4.5    | 1.2          |

**Figure 3.** Current-voltage characteristics of samples I and II without (dashed lines) and with (bold lines) the irradiation frequency of 67 GHz at different temperatures. Samples I and II are covered by gold layers with thicknesses of 50 nm and 30 nm, respectively.
3.3. HTS array of Josephson junctions with step voltages of up to 0.1 V
We present the results of the investigation of the circuits containing 10 sub-arrays of type B. 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 4 shows the current-voltage characteristics 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 figure 4, curve (a), it can be seen 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 $\Omega$. 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

**Figure 4.** Current-voltage 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.

**Figure 5a.** 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.

**Figure 5b.** 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 $\Delta I_0$ of each sub-array.
with resolution better than $5 \mu$V reveals the step height of $\Delta I_1 \approx 0.17 \text{ mA}$.

Figure 5a 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 5a shows all the steps from 10 mV to 100 mV. By investigating each of the sub-arrays as shown in figure 5b, it is found that the average critical current is $I_c = 0.55 \text{ mA}$ with a standard deviation of 19 $\mu$A or 3.5%. The average resistance of one shunted junction is about $0.18 \Omega$ with a standard deviation of 2.5 m$\Omega$ 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.

4. Conclusion
We compared characteristics of three types of arrays and found an 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 a maximum first step at a Josephson voltage of about 0.1 V on the array of 620 bicrystal junctions at a temperature of 79 K. The step height was 0.17 mA at a frequency of 77.465 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 showed that such circuits are challenging for application as a programmable 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 the realization of THz sources and detector arrays. Finally, our approach could be useful for the irradiation of large arrays of niobium Josephson junctions as well. In this 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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