Tests of operating conditions for metrological application of HTS Josephson arrays

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Abstract. We report on an experimental study of metrological properties of High Temperature Superconductor arrays, made of shunted bicrystal YBCO Josephson junctions, to assess their accuracy. A detailed analysis of measurement errors is presented, mainly based on a direct comparison of an HTS array against a low temperature array. Owing to the high sensitivity of the comparison, we were able to measure the changes in the HTS array voltage on a step at nanovolt level. A precise estimate of the dependence of the HTS array step width on operating conditions was obtained. Differences were observed with respect to the results provided by the usual, low sensitivity, techniques, confirming that the method we adopted is necessary in the study of HTS arrays for metrology. The high sensitivity analysis was applied in the derivation of the temperature dependence of the critical current as well, providing some insights on the behaviour of the HTS array.

1. Introduction
In recent years, a considerable interest has been addressed to metrological applications of non-hysteretic Josephson junctions. Such junctions are suitable to realize ac voltage standards with quantum accuracy, because a single-valued current-voltage relationship is needed to switch sections of the array. Arrays of Josephson junctions with non-hysteretic current-voltage (I-V) characteristic are used for both programmable voltage standard and the synthesis of arbitrary waveform [1]. Particular interest has the possibility of increasing the operating temperature of these devices, to avoid the need of liquid helium for operation and extend their application. Josephson junctions based on High Temperature Superconductor (HTS) technology show intrinsic non-hysteretic behavior. Moreover they have the additional advantage of liquid-nitrogen operation. However, some HTS-specific effects exist, like thermal fluctuations due to the higher operating temperature, that can affect precision measurements.

Among the others HTS junctions, YBa$_2$Cu$_3$O$_7$ (YBCO) shunted bicrystal junctions have proved to be a good candidate. A direct comparison with a niobium programmable voltage array working at 4.2 K, has demonstrated that the steps of an YBCO array operated at 64 K are flat over a wide current range [2].

In this work, we analyze some specific aspects which play a relevant role in the use of these YBCO arrays, i.e. the r.f. signal coupled to the junctions and the working temperature.

2. Experimental
We have investigated Josephson junctions made on commercially fabricated symmetrical bicrystal yttria-stabilized zirconia (YSZ) substrates ([001] tilt) with misorientation angles $\Theta = 24^\circ$. Thin gold films were used as a shunt layer. This guarantees typical interface contact resistivities of the order of $10^8$ $\Omega cm^2$, which are essential for effective shunting of grain boundary junctions. In our layout the inductance of the shunt was comparatively large. The details of the technology of HTS junctions were published previously [3]. For microwave irradiation the array of 100 HTS junctions was embedded into a coplanar transmission line [4] with a characteristic impedance of about 50 $\Omega$ and a PdAu resistor as load. Thin film current leads made from
PdAu allowed independent dc-bias and voltage measurements of the dc current-voltage characteristic and prevent the distortion of the sine wave in the coplanar line.

A source with frequency range from 1 GHz to 20 GHz and 20 mW maximum output power was used for microwave generation. This frequency range was suitable for the measured array, whose characteristic frequency $f_c$ was from 5 GHz to 10 GHz, depending on the temperature. The single junctions were irradiated by means of a small antenna, whereas the array was irradiated through a coupling structure at the end of the coplanar line. To study the effect of temperature, we measured critical currents between 65 K and 83 K, in many cases checking the flatness with resolution of few tens of nV. Within the same temperature range, we analyzed the amplitude of the first step at microwave frequencies $f = f_c$ and multiples.

The step flatness was measured by direct comparison with a Nb/Al-AlO$_x$/Nb SIS junction array at 4.2 K. We have used an operating frequency of 74 GHz for this array and 18.5 GHz for the YBCO array. Owing to the integer ratio of frequencies, the arrays can be set at nearly the same voltage, with a relevant improvement in the comparison sensitivity.

3. Discussion

The comparison of the critical current of the single junction and the array does not show significant disagreement: we know of course that for the latter, some junction of lower quality may decrease the overall temperature dependence of the array. On the contrary, there is a strong difference in the amplitude of the first step with respect to the critical current. In fact we have observed that, even in the best case, this ratio is far lower for the array than for the single junction. We have measured a ratio of 0.2 at 77 K, which still reduces when the resolution is increased at the nV level, when the radiation frequency was twice the calculated characteristic frequency, a situation which corresponded to a value of 0.58 for the single junction.

This discrepancy is not likely to be ascribed to an unoptimized distribution of the microwave signal along the transmission line, as happens in large niobium arrays [5].

![Fig. 1 Profile of the first step observed at 77.3 K, with the YBCO array irradiated at 18.5 GHz (11 dBm). The dotted line shows low sensitivity measurement data (values on right axis), the solid line show the profile of high sensitivity measurements obtained by direct comparison of the YBCO array against a low temperature Nb/Al-AlO$_x$/Nb SIS array (left axis).](image)

Instead, we think, according to [6], that a frequency approximately equal to $4f_c$ could be accepted as real characteristic frequency of the irradiated array junctions. This is presumably connected with the fact that the real characteristic frequencies of the irradiated junctions were much larger than $f_c$ in shunted junctions with large value of $\beta_L = L_s/L_c$, where $L_s$ is the inductance of the shunt and $L_c = \Phi_0/2\pi l_s$ is a characteristic inductance of Josephson junction and $\Phi_0$ is a magnetic flux quantum.
The effect of the temperature can be summarized as follows. For \( T > 77 \text{ K} \), the depression of \( I_c \) causes a step of reduced amplitude, which does not appear up to frequencies > \( 4f_c \). The reduction of \( I_c \) moreover causes a reduction of the characteristic frequency and therefore of the maximum voltage of the steps.

For \( T < 77 \text{ K} \), due to the strong dependence of \( I_c \) on \( T \) (Fig. 2), this leads to a corresponding enhancement of the step width, for instance at 65 K there is a factor 4 on \( I_c \). This causes an increment of both the calculated and effective characteristic frequency, requiring radiating frequencies higher than those we used in our tests.

However, this is promising for a next exploitation of these devices since, using a working temperature (see Fig. 2) slightly below 77 K - say 70 K, where: \( I_c(70 \text{ K}) = 2.5 I_c(77 \text{ K}) \) - we can have an effective characteristic frequency of the array junctions in the range 70 GHz, with an increment in the voltage output.

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