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Superconducting devices based on coherent operation of Josephson junction arrays above 77K

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Abstract. Arrays of Josephson junctions operating coherently at 77K seem to be the ideal candidates for re-shaping the future of the electronics industry. Their advantages over their semiconducting counterparts (higher operating speed, lower power consumption/electronic noise) can be exploited in practice because of their practicality: cooling down to 77K is both cheap and easy to handle. These developments naturally fit into the increasing interest of some semiconductor technologies in lower operation temperatures. Therefore, it looks attractive to link semiconductor and 77K superconductor technologies to improve system level performance. Currently, however, in the vast majority of applications 4.2K superconducting technology is used as it provides significantly superior performances relative to devices build in the 77K technology. Recent significant improvements in the performance of superconducting devices operating as 77K, as well as, in their fabrication technologies may change all that. Several such examples will be considered here. Firstly, when coherency is achieved in large series SQUID-arrays magnetic flux sensors or voltage amplifiers can be build having record values for their output voltage and flux noise sensitivities outperforming even single SQUID-based devices operating at 4.2 K. Secondly, when coherency is achieved in parallel SQUID-arrays placed in a uniform magnetic field B, B-field tuned microwave generators can be build. Large parallel SQUID arrays were also implemented to achieve record values for current amplification at 77K, highly efficient ratchets with unidirectional magnetic vortices motion and integrated nano-magnetic sensors.

1. Introduction
Since Feynman’s prediction [1] that multiple Josephson junction (JJ) devices would eventually improve performance of superconducting devices there has been considerable effort spent to achieve that. Such JJ- or SQUID (Superconducting Quantum Interference Devices) arrays are very attractive in many applications where single-JJ or single-SQUID based devices are routinely used as: magnetic sensors, low-noise amplifiers, THz receivers, analog-to-digital converters, antennas, filters, etc. Because of their practicality (cooling down to 77K is both cheap and easy to handle) and their potential to penetrate the market dominated by the semiconductor technology here my focus is exclusively on arrays operating at 77K.

There are two main challenges for a successful implementation. First challenge is the fabrication reliability of large JJ- or SQUID-arrays. Currently, the most reliable are the bicrystal [2] and the step-edge [3] technologies. JJ- and SQUID-arrays fabricated in the bicrystal technology showed the best results so far. However, this technology lacks the flexibility of the 2D step-edge technology. SQUIDs have been fabricated along 3 different directions in a tri-crystal configuration [4] and therefore M
multi-crystal technology (with M= 4, 5, …) is potentially an interesting direction to explore in the future in order to gain a similar 2D flexibility required for the implementation of complex JJ- and SQUID-arrays architectures. Recently, significant progress has been reported in the area of step-edge junction array technology [5, 6] that offers the advantage of using low cost MgO substrates and the flexibility of implementing complex 2D large array configurations involving many tens of thousands of SQUIDs.

The second challenge is the ability to operate large JJ- or SQUID-arrays coherently at 77K. Recently, coherent operation has been achieved in both large series- and parallel-SQUIDs arrays leading to record values relative to single-SQUID devices for flux sensitivity [7], electromagnetic power radiation in the GHz range [8], current amplification [9] and flux-ratchet tunability [10]. To emphasize that SQUID-arrays at 77K can indeed replace single-SQUIDs operating at 4.2K in many applications, in this report a unified view is given on these four significant results.

It is important to notice that contrary to previous beliefs even a considerable spread in the properties of individual junctions will not affect the overwhelming superiority of arrays over single junctions devices. Indeed, in [7] the intrinsic spread of Josephson critical currents in large arrays has been measured and fitted with a Gaussian distribution characterized by an average standard deviation $\sigma$ of about 12.2% at 77K. This is significantly smaller than at 4.2 K where $\sigma$ values around 25% are typical. Large arrays with additional artificially implemented spread in the SQUID areas/inductances as large as 30% have also been fabricated [7]. The flux-coherence persisted even in this case. This is because in large arrays the gains of a global response by many junctions outweighs the losses due to differences between individual junctions.

2. Series SQUID arrays

SQUIDs being the most sensitive magnetic sensors and amplifiers are routinely used in many areas, among them: medicine (magneto- and cardio-encephalography), research in material science (as magnetometers measuring magnetic properties of materials), geology, astronomy, magnetic imaging applications, electronics, etc. At present, such devices made of low temperature superconductor (LTS) SQUIDs operating at 4.2K are being used in the vast majority of applications due to their superior flux noise performance. This is despite several significant advantages offered by high temperature superconductor (HTS) SQUIDs operating at 77K: low cost and user-friendly cooling procedures, and also potential superiority as magnetic imaging devices due to lesser thermal insulation demand, i.e., reduced separation between the sensors and the room temperature object under study. The question is then: can devices based on HTS SQUIDs and operating at 77K ever get better than their LTS counterparts based on single-SQUIDs and operating at 4.2K?

A very promising approach is to build a series SQUID array (SSA) of N non-interacting SQUIDs operating flux-coherently, because in this case [10-13] the voltage modulation $\Delta V$ linearly scales with N, the dynamic range increases as $N^{1/2}$, whereas the white flux noise $S_\Phi^{1/2}$ decreases as $1/N^{1/2}$. Consequently not only the noise properties of a SSA are superior to a single-SQUID but a much larger $\Delta V$ means their matching to room temperature readout is greatly simplified since the array impedance is N times larger than that of a single SQUID. Moreover, SSAs have the potential of also improving the bandwidth. Some of these predictions have been largely confirmed when large N (typically N is in the range 100-200) SSAs operating at 4.2K have been developed in LTS technology [10-16]. However, flux-coherency and SQUIDs non-interactivity have proved to be very challenging to achieve in large N SSAs made of HTS and operated at 77K. Indeed, it has only been achieved in relatively small N SSAs (N in the range 10-30) [17-18]. With N small, their superiority over single SQUIDs was less spectacular and they could not compete in terms of noise performance with single LTS SQUIDs operated at 4.2 K. Earlier attempts to operate large N HTS SSAs (N in the range 50-130) did not show the expected improvements in magnetic sensitivity, because the flux-coherent mode was not achieved throughout the entire array [19-20].
Recently [7], we reported on the design, fabrication and testing of a new generation of very large (N=484 and N=770) non-interacting SSAs made of YBa$_2$Cu$_3$O$_7$ (YBCO) and operating flux-coherently (see Figure 1). The SSAs were fabricated using the well-established bicrystal technology. To increase field sensitivity SQUIDs are usually connected to rectangular flux-focusers with both their dimensions much larger than the SQUID width (total width of SQUID hole and two junctions). In order not to compromise the number of SQUIDs we could integrate on a standard 10x10 mm$^2$ bicrystal substrate while still implementing flux-focusers for enhanced sensitivity, we developed large area narrow flux-focusers. Their width is identical to the SQUID’s width while they are much longer. Importantly, our results showed that the larger the area of such narrow flux focusers the higher the degree of flux coherence in the operation of SSAs and SQUIDs non-interactivity within the SSAs.

Families of current-voltage characteristics were measured for various fields $B$ and at different temperatures in the range 10 to 89 K. Voltage could be measured along the entire array or different sections of it. From such families, $V(B)$ could be constructed. Large amplitude SQUID-like oscillations with a flux quantum periodicity were observed (see inset in Figure 2). Unlike the case of single SQUIDs, $V(B)$ is amplitude modulated and suppressed to nearly zero within about 20 periods. This is well understood [5] as being a consequence of a slight variation in the periods of individual

![Figure 1. Left: optical micro-picture of a small part of a 770 series SQUID array showing 8 SQUIDs. The array is fabricated by optical lithography after depositing a YBa$_2$Cu$_3$O$_7$ thin film on a SrTiO$_3$ bicrystal. Each SQUID consists of two Josephson junctions connected in parallel. The junctions can be seen as 3 micron-wide narrow bridges (in brown) crossing the bicrystal boundary shown with a horizontal dotted line. Each pair of successive SQUIDs is connected in series via inductive large area narrow flux-focusers (one is highlighted in red). Right: flux density noise $S_{\Phi}$ at 1kHz versus the number of SQUIDs integrated in the 770 SQUID-array. The discontinuous line indicate the theoretical $1/N^{1/2}$ dependence. Typical flux noise levels of optimized HTS SQUIDs at 77K, nano-HTS SQUIDs at 4.2 K and LTS SQUIDs at 4.2 K are also shown as references. Inset: $V(B)$ of the 770 SSA at 83K for 11 different current biases $I$ in the range (-212,-172) $\mu$A with $I$ changing in steps of 4$\mu$A;](image-url)
SQUIDs along the array due to either variation in the SQUID loop sizes or/and non-uniform magnetic field coupling over the length of the array. This affects the coherency of the array at large applied fields. For the 770 SSA $\Delta V$ ranges from 10.8 mV at 77K to 2.2 mV at 86K. The $V(B)$ at 83K is shown in the inset of Figure 2. The SSA’s values of $S_{\phi}^{1/2}$ in the temperature range (40-83)K were about 50 times lower than for optimized single HTS SQUIDs operating at 77K and even lower than those of single LTS SQUIDs operating at 4.2K (see Figure 2). This strongly suggests that HTS SSAs are ideal candidates to replace single LTS SQUIDs in many applications. We found [7] that to a good approximation $\Delta V$ linearly increases with $N$, whereas $S_{\phi}^{1/2}$ decreases as $1/N^{1/2}$ suggesting that flux-coherency and SQUIDs non-interactivity were achieved.

It is important to note that here and in [7] SSA’s were investigated at the most fundamental level, regardless of particularities due to specific applications where such arrays may be used as SQUID-based instruments. Therefore the main goal was to prove their superiority over LTS single-SQUIDs as flux-to-voltage converters. Considering this the array’s sensitivity is given by their flux resolution $S_{\phi}^{1/2}$. On the other hand sensitivity of SQUIDs (or SQUID arrays) used as SQUID-based instruments in various specific applications is measured differently:

a) as EM/gamma/X-rays, particle detectors, gravitational waves detectors, or amplifiers is measured by its noise temperature;
b) as photon energy detectors is measured by its energy sensitivity;
c) as magnetometers is measured by its field resolution $S_B$;
d) as gradiometers is measured in $S_B/m$;

Consequently, a series SQUID array with a record $S_{\phi}^{1/2}$ has the potential to operate with record sensitivity in most applications including magnetometers that measure B (provided the most advanced schemes are used for their input coil coupling, bias reversal, output read-out electronics, magnetic and electromagnetic screening, etc). It is therefore important to stress that the input coil used to measure $V(B)$ in Figure 2 is neither optimally coupled, nor it is optimally designed. Indeed, in our case there is a significant mismatch between the input coil and the SQUID array loops. No effort was made to address this mismatch since our primary goal was to prove SQUID array superiority over single SQUIDs in the most fundamental way possible valid for most applications (not just as magnetometers). For that reason the $V(B)$ data presented should not be used to extract the $B$ field sensitivity of our SQUID array. There are many well-known schemes/techniques to significantly improve this mismatch such as single layer/multilayers flux transformers that are coupled directly or in a flip-chip configuration. Those schemes are routinely used in commercially available single HTS SQUIDs. By using those advanced schemes one can easily translate the record flux noise performance of our SQUID arrays into a record field noise performance when the SQUID-arrays are used as magnetometers. At present we consider the realization of similar coupling schemes for large serial arrays.

3. B-field tunable microwave generators

Since the discovery of the ac Josephson effect, Josephson junctions (JJ), as natural electromagnetic (EM) microwave generators, have always been attractive for applications. In practice, however, single JJs are never used because the power of the emitted EM radiation is too small. Devices consisting of multiple JJs are therefore the only realistic solution. One of the most promising approaches is when an enhanced EM radiation is produced as a result of a coherent flux flow [21] in one-dimensional (1D) arrays [22-27] placed in an externally applied magnetic field $B$. In this case magnetic vortices will enter the array in a form of Josephson vortices. The bias current, $I$, flowing across the array produces a Lorentz force, $F_L$, which drives the Josephson vortices unidirectionally, forming a lattice of vortices moving with a speed, $v$. This is accompanied by an emission of small amplitude linear waves that propagate along the array. In other words EM waves are excited by a (magnetic field induced) chain of propagating magnetic vortices. When the vortex spacing is commensurate with the wavelength of
emitted waves, resonant modes occur. This can be viewed as the phase-locking condition of the vortex velocity and the phase velocity of one of the self-induced modes. The experimental signature of such phase locking between a train of propagating vortices and their induced EM radiation in a JJ array is a series of flux-flow resonances (m=1, 2, 3, 4, etc) in the current-voltage characteristics (IVCs). On a resonant current step, moving vortices couple to their induced linear waves. Further increases of the current do not lead to further linear increases in the vortices velocity, because the energy is consumed in amplifying the linear waves.

Such resonances have been observed by many groups, below 9K, in LTS JJ arrays [22-27]. The associated amplified EM radiation has been measured too, proving that LTS JJ arrays are suitable candidates as B-tunable microwave oscillators [28, 29]. After the discovery of HTS in 1986, it was anticipated that similar B-tunable microwave oscillators could be made of HTS JJ arrays operating at liquid nitrogen temperature. Initially the highest reported temperature for observing stable flux-flow resonances in HTS JJ arrays was 40K, achieved in Bi$_2$Sr$_2$CaCu$_2$O$_{8+x}$ mesa structures based on a 1D array of intrinsic JJs [30]. The first observation of multiple flux-flow resonances at 77K and above (see Figure 2) reported in [8] has been observed in asymmetric parallel arrays consisting of 440 YBa$_2$Cu$_3$O$_7$$_\delta$ JJs fabricated in bicrystal technology. The array consists (see inset in Figure 2) of 22 identical sets of 20 JJ of identical width (3 µm). Within each set all 20 JJ are connected via superconducting loops of identical width (3µm) and monotonically decreasing length from 18µm to 13µm. Recently, in my group [31], a symmetric parallel array was fabricated to investigate whether an asymmetric design is an essential condition for the observation of flux-flow resonances. The parallel array consists of 100 JJ of identical width (3 µm) connected via superconducting loops of identical size: (width, length) = (3µm x 15 µm). It was found that the flux-flow resonances were observed in the temperature range (30-45) K and that their amplitudes were significantly lower than for the asymmetrical design (see Figure 3). One can therefore conclude that an asymmetric design significantly enhances the coherent flow of vortices and transforms it into a very non-linear phenomenon with respect to a monotonically increasing B field. That ultimately leads to a significant amplification of EM.

Figure 2. Families of 15 consecutive current-voltage characteristics (IVCs) of an asymmetric (a) and a symmetric (b) parallel arrays recorded for monotonically increasing B values. In blue (red) are the first (last) IVC within these sets. The position of the high-amplitude second flux-flow resonance (m=2) in (a) and of the low-amplitude first flux-flow resonance (m=1) in (b) are gradually shifted by varying B. Insets show optical micrographs of a small part of the arrays (42 JJs). The asymmetrical geometry introduces a highly preferential direction for the flux flow and strong non-linearities that ultimately leads to a significant amplification of EM.

\[ P = 0.5(I \times I_{step}/I_c)^2 R_0/N \]

where \( I \) is the current, \( I_{step} \) is the step current, \( I_c \) is the critical current, \( R_0 \) is the intrinsic resistance, and \( N \) is the number of JJs. At 77K the device performance improves considerably
providing a $B$-field tunable power of about $0.1 \mu W$ within the range (1.5-25) GHz. By inductively coupling multiple $M$ rows of 1D JJ arrays the power of emitted EM radiation can be further increased. Thus, the design approach reported here shows great promise as a route to realizing high performance B-field tunable HTS microwave oscillators based on flux flow resonances.

4. Vortex-flow superconductor transistors

High temperature superconductor Josephson vortex-flow transistors (JVFT’s) are the most promising candidates for high-frequency amplifying devices in all-superconducting microwave circuits [32-33]. There are two types of JVFTs: ones that are based on a single long Josephson junction (JJ) [34, 35] or JVFT’s based on arrays of JJs [35-38]. A high performance JVFT for practical applications should have a high current gain, $g = \partial I_c / \partial I_{ctrl}$ (where $I_c$ is the device critical current and $I_{ctrl}$ is the control-gate current), a large dynamic range (the range of $I_{ctrl}$ over which a high $g$ can be achieved), small vortex transit times to allow high frequency operation and a relatively large transresistance, $r_m = \partial V / \partial I_{ctrl}$.

In [9] we propose a discrete JVFT based on a parallel array of 440 YBa$_2$Cu$_3$O$_{7-\delta}$ bicrystal grain boundary JJ that combines beneficial aspects of several previous designs. On the one hand, it has a symmetric bias configuration to ensure a large dynamic range, as well as, small vortex transit times; on the other hand it has a certain degree of inductive asymmetry implemented via an asymmetric loop configuration within the array. This asymmetry ensures the bias current produces a net inhomogeneous magnetic field along the array through self-field effects that result in a highly asymmetric $I_c(I_{ctrl})$ curve with high current gains. Of particular interest are JVFT’s operating at 77K due to their low-cost cooling procedures and practicality. There have been several reports of JVFT’s with current gains $g$ as high as 6 at 30K [35], or 5.5 at 50K [37], or 14 at 70K [36], however, in all these cases $g(T)$ rapidly and monotonically decreases with temperature as it approaches 77K. Thus, the highest current gains reported so far at 77K were achieved with discrete JVFT’s having an asymmetric in-line bias distribution (maximum reported values were $g=3.5$ [38]). Our discrete JVFT shows current gains as high as 19, a significant dynamic range of more than 20 $\mu$A at 77 K, and an unusual non-monotonic $g(T)$ dependence in the range (4.7-92)K with a maximum recorded value around 77K. The flux-flow in asymmetrical arrays is significantly altered relative to symmetrical geometries, with a highly preferential flux-flow direction leading to enhanced dynamics (sharp flux-flow resonances, EM amplification). As shown in [9] this novel behaviour can be exploited in a controllable fashion by $B$ leading to record values for current amplification at 77K (see Figure 3). This interesting feature can find applications in developing low-noise fast first-stage current amplifiers in various electronic devices.

Another interesting application of asymmetric JJ-arrays is their functionality as magnetic field-tunable highly reversible vortex diodes (ratchets) as demonstrated in [10]. Thus, at 89 K the ratchet efficiency $\eta = \left[ \frac{V(I+V(-I))}{V(I)-V(-I)} \right] \times 100\%$ could be reversed from +60% to -60% with a change in $B$ as small as 3$\mu$T. Such ratchet designs can be used to control unidirectional vortex flow vortices in superconducting devices, to remove unwanted trapped vortices in superconducting devices without the need to warm them up above their critical temperature, as well as, to build integrated nano-magnetic sensors.

5. Conclusions

Recently, several significant developments have been reported of superconducting devices such as magnetometers [7], B field-tunable microwave generators [8] and superconducting transistors [9] build based on large arrays of JJs- or SQUIDs-arrays. Such devices showed improved performances at 77K a temperature that can be reached with liquid nitrogen (that is cheap and user-friendly). They were fabricated using the bicrystal technology that is both sufficiently reliable and inexpensive. All these features suggest the practically and potential of this HTS 77K array technology to replace LTS single JJ or SQUIDs currently used in many applications. It is remarkable that in all these reports a proof of concept of such devices has been provided with minimal efforts invested into the optimization of their
Figure 3. A set of 35 consecutive IVC at 77K for various values of the control current I_{ctrl} around 1.2 mA. I_{ctrl} is changed in steps of 15 µA. In blue (red) are the first (last) IVC within these sets. In green are the two IVC's for the I_{ctrl} range where a switching behaviour is observed with current gains as high as 19. Inset show highly asymmetric I_{V}(I_{ctrl}) dependencies recorded at 7 different voltages. The steepest slopes of these curves is where the transistor amplifies best.

operation. This strongly suggests that performances of such devices can be significantly improved further. This is exciting as 77K can probably be regarded as the lowest acceptable temperature that would allow superconducting electronics to challenge their semiconducting counterpart on a different, much larger, scale.

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