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Flux-coherent series SQUID array magnetometers operating above 77 K with superior white flux noise than single-SQUIDs at 4.2 K

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A very promising direction to improve the sensitivity of magnetometers based on superconducting quantum interference devices (SQUIDs) is to build a series-array of N non-interacting SQUIDs operating flux-coherently, because in this case their voltage modulation depth, $\Delta V$, linearly scales with N whereas the white flux noise $S_\phi$ decreases as $1/N^{1/2}$. Here, we report the realization of both these improvements in an advanced layout of very large SQUID arrays made of YBa$_2$Cu$_3$O$_7$. Specially designed with large area narrow flux focusers for increased field sensitivity and improved flux-coherency, our arrays have extremely low values for $S_\phi$ between (0.25 and 0.44) $\mu\Phi_0/Hz^{1/2}$ for temperatures in the range (77–83) K. In this respect, they outperform niobium/aluminium trilayer technology-based single-SQUIDs operating at 4.2 K. Moreover, with values for $\Delta V$ and transimpedance in the range of (10–17) mV and (0.3–2.5) k$\Omega$, respectively, a direct connection to a low-noise room temperature amplifier is allowed, while matching for such readout is simplified and the available bandwidth is greatly increased. These landmark performances suggest such series SQUID arrays are ideal candidates to replace single-SQUIDs operating at 4.2 K in many applications. © 2015 AIP Publishing LLC.

With recent advances in the fabrication of superconducting quantum interference devices (SQUIDs) made of high temperature superconductors (HTS), the demands of complex designs required in many SQUIDs applications are now starting to be fulfilled. Indeed, while HTS SQUID fabrication in bicrystal1 or multi-crystal2 grain boundary technology reached maturity more than a decade ago, other fabrication methods are recently gaining momentum.3,5 Also, significant is the progress reported in the area of nanofabrication.5–8 At present, however, due to their superior flux noise performances in the vast majority of applications, SQUIDs made of low temperature superconductors (LTS) and operating at 4.2 K are being used. This is despite several significant advantages HTS SQUIDs operating above 77 K offer: low cost and user-friendly cooling procedures (at a time, when the price of liquid He is increasing significantly) and potential superiority as magnetic imaging devices due to a reduced separation between the sensors and the room temperature object under study (because of the decreased thermal insulation demand). Recently, it was shown9–12 that these advantages are particularly significant in magnetoencephalography. Therefore, improving noise properties and sensitivity of HTS SQUIDs has become more relevant than ever.

A very promising direction for improving a magnetometer’s sensitivity is to build a series SQUID array (SSA) of N non-interacting SQUIDs operating flux-coherently, because in this case13–15 $\Delta V$ linearly scales with N, their dynamic range increases as $N^{1/2}$, whereas $S_\phi^{1/2}$ decreases as $1/N^{1/2}$. Consequently, not only the noise properties of a SSA are superior to a single-SQUID but also a much larger $\Delta V$ means their matching for room temperature readout is greatly simplified. Moreover, SSAs have the potential of also improving the bandwidth and the impedance matching as their impedance is N times larger than that of a single SQUID. All these predictions have been confirmed by pioneering research reported in Refs. 13–18 where large N SSAs have been developed in LTS technology. Such LTS SSAs were operated at 4.2 K and typically N is in the range 100–200, but devices with N as large as 7104 have also been designed and tested.18 The primary requirements to achieve coherent flux operation and, consequently, a linear increase of $\Delta V$ with N were found to be: (a) the SQUIDs should be sufficiently identical in critical current $I_c$ and loop inductances $L_i$; (b) the mutual inductance M should be approximately the same between all SQUIDs and the modulation line; (c) there has to be little or no random flux offset between the individual SQUIDs; (d) the mutual coupling between SQUIDs has to be negligible. So far these requirements have proved to be very challenging to achieve in large N SSAs made of HTS and operated at 77 K and above. Consequently, flux-coherent operation at 77 K and above has only been achieved in relatively small N SSAs (N in the range 5–30).19,20 Due to the relatively small value of N, their superiority over SQUIDs is less spectacular, and also they could never compete in terms of noise performances with single LTS SQUIDs operated at 4.2 K. Earlier first attempts to operate large N (N in the range 35–130) HTS SSAs did not show the expected improvements in the magnetic sensitivity due to the flux-coherent mode not being achieved throughout the entire array.21,22 Here, we report on the design, fabrication, and testing of an advanced layout of very large (N = 484 and N = 770) non-interacting SSA made of YBa$_2$Cu$_3$O$_7$ (YBCO) and operating flux-coherently. Consequently, in the temperature range (40–83) K, they have very large values for $\Delta V$.

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The SSAs were fabricated by depositing high quality epitaxial, 100 nm thick c-axis oriented YBCO films on 10 \times 10 \text{mm}^2, 24° and 45° symmetric [001] tilt SrTiO₃ bicrystals by pulsed laser deposition (the films were deposited by Ceraco ceramic coating GmbH). A 200 nm thick Au layer was deposited in situ on top of the YBCO film to facilitate fabrication of high quality electrical contacts for electric transport measurements. The films, with a critical temperature \( T_c \), of 89 K, were subsequently patterned by optical lithography and etched by an Ar ion beam to form large SSAs. In this report, results obtained from two samples are presented: a 484 SSA fabricated on a 45° symmetric [001] tilt SrTiO₃ bicrystal and a 770 SSA fabricated on a 24° symmetric [001] tilt SrTiO₃ bicrystal. In choosing designs parameters, we have been guided by theory\(^2\) and previous reports of optimal HTS SQUIDs.\(^24\) For both samples, all Josephson junctions are 3 \( \mu \text{m} \) wide. The 484 SSA consists of 44 identical sets of 11 SQUIDs each. Within each set of 11 SQUIDs, the length of the SQUIDs’ loops varies monotonically from 13 \( \mu \text{m} \) to 8 \( \mu \text{m} \), while their width is constant at 3 \( \mu \text{m} \). Optical micrographs of small parts of the 484 SSA are shown in Figs. 1(a) and 1(b). The 770 SSA consists of 770 identical SQUIDs characterized by identical SQUID loops of length 13 \( \mu \text{m} \) and width 3 \( \mu \text{m} \) each (see Fig. 1(c)). For both samples, the SQUIDs are connected in series in a serpentine path along the bicrystal boundary.

The reason we choose to vary the SQUID loop areas artificially by 30% in the 484 SSA design was to investigate to what extent large variations in the SQUID inductances \( L \) impact on the degree of flux-coherency and voltage modulation depth in large N SSAs. This fundamental aspect indeed requires further investigations, since previous attempts\(^21,22\) to operate coherently large N SSAs at 77 K failed presumably because of incoherent modulation due to unequal fluxes \( \Phi_{\text{SQUID}} = LB \) threading the SQUIDs. Here, \( B \) is the magnetic field to be measured applied perpendicular to the planar array’s structure via an input coil current. To increase field sensitivity, SQUIDs\(^25\) and SSAs\(^20\) are usually connected to large square/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 10 \( \times 10 \text{nm}^2 \) 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 only their length is much larger. For the 484 SSA, their dimensions are 88 \( \times 9 \mu \text{m}^2 \) while for the 770 SSA they are 160 \( \times 9 \mu \text{m}^2 \). 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.

Families of current-voltage characteristics (\( IVC’s \)) were measured by a 4 terminal method at various temperatures between 10 K and 89 K and for various \( B \) in the range (−40, 40) \( \mu \text{T} \) with a resolution of 0.067 \( \mu \text{T} \) (the case of 484 SSA) or 0.27 \( \mu \text{T} \) (the case of 770 SSA). \( V \) can be measured along the entire array or parts of it (in multiple sets of 44 SQUIDs). From such families of \( IVC’s \) scanned over \( B, V(B) \) for both positive and negative bias currents could be constructed. The \( IV \) of a single SQUID fabricated on the same chip showed the concave resistively \( R_N \) shunted junction (RJ) model-like hyperbolic shape.\(^23\) On the other hand, the shape of the \( IV \)'s for the SQUID arrays near \( I_c \) is convex, which we attribute to the spread of critical current in the array. Apart from this region in the vicinity of \( I_c \), the \( IVC’s \) are well described within the RJ model. The value of \( I_c \) for an array was determined by extrapolating the normal state resistance of the array to zero-voltage on the \( IV \). The intercept point of the current represents the average critical current for the array. A family of 130 consecutive \( IVC’s \) measured at 77 K for the 770 SQUID array is plotted in Fig. 2. Average values across the SSAs of the individual SQUID’s main parameters \( I_c, R_N, \) etc. are shown in the table.
I_c, R_N, L, and $\beta$ are shown in Table I. Here, $\beta = 2Lc/\Phi_0$ with $\Phi_0$ being the flux quanta and $R_N$ is the array’s resistance.

Individual SQUID inductances $L$ were estimated by calculating the SQUID hole perimeter and considering that typically for such bicrystal SQUIDs 1 μm corresponds to 1 pH. For the 484 SSA, individual SQUID inductances were designed to vary monotonically between (20, 30) pH within each set of 11 SQUIDs which gives an average value for $L = 25$ pH.

The dependence of voltage $V$ modulation versus $B$ as well as peak-to-peak voltage modulation $\Delta V$ for both SSAs was also measured in the temperature range (10–89) K. Results for several temperatures are shown on Fig. 2 (left inset), Figs. 3(a) and 3(b), as well as Table I ($T_{max}$ is the temperature, where $\Delta V$ reaches maximum). It is important to stress that both $V(B)$ and $\Delta V(\beta)$ behaviours differ significantly from the case of single-SQUIDs. Therefore, below 70 K, no SQUID oscillations were observed for the 770 SSA due to the fact that at this temperature $\beta = 20$ is quite large and appears to be above a threshold value at which SSA’s flux coherency is lost. Then, $\Delta V(\beta)$ does not reach its maximum at around $\beta = 0.5–1$. Finally, unlike single-SQUIDs, $V(B)$ is amplitude modulated and is suppressed to nearly zero within $7\Phi_0$ periods for the 484 SSA and 10$\Phi_0$ periods for the 770 SSA. Such an amplitude modulated behaviour is well understood as being a consequence of a significant variation in the periods of individual SQUIDs along the array due to either variation in the SQUID holes or non-uniform magnetic field coupling across the length of the array. This affects the coherency of the array at large applied fields. A similar behaviour has been previously observed for both LTS SSA’s and HTS SSAs.

By comparing Fig. 3(a) with Fig. 3(b), one can see that, as expected, the loss of flux-coherence is more pronounced for the 484 SSA than for the 770 SSA. It is remarkable, however, that the 484 SSA shows a significant degree of flux-coherence considering that variations of $L$ within the array as large as 30% have been artificially implemented. The left hand side inset of Fig. 2 shows the $V(B)$ periodic SQUID oscillations for 10 different current biases $I$ in the range (−60, −30) μA and (30, 60) μA with $I$ changing in steps of 5 μA.

FIG. 3. (a) $V(B)$ of the 484 SSA at 40 K for various current biases in the range (−60, −30) μA and (30, 60) μA with $I$ changing in steps of 5 μA; (b) $V(B)$ of the 770 SSA at 83 K for 11 different current biases $I$ in the range (−212, −172) μA with $I$ changing in steps of 4 μA.
ΔV = 10.1 mV reached with the 770 SSA at 77 K for a bias of ±730 μA (see left inset of Fig. 2) is more than 200 times larger than for the best HTS single-SQUID operating at 77 K. Both ΔV = 10.1 mV value for the 770 SSA at 77 K and ΔV = 17 mV value reached with the 484 SSA at 40 K for a bias of ±50 μA (see Fig. 3(a)) are the highest ever reported for HTS SSA.19–22 Such large values for ΔV allow a direct connection of the SSAs to a low-noise room temperature amplifier, while matching for such a room temperature readout is simplified due to their large impedances Rarray in the range (0.3–2.5) kΩ. The use of a magnetic shielding did not lead to a significant increase in ΔV suggesting that SSAs can operate in an unshielded environment.

By performing ultra-high resolution IVC’s of only a part of the 770 SSA, namely, individual sets of 44 successive SQUIDs, the Ic values of the majority of 44 SQUIDs could be identified as multi-peaks in the derivatives dI/dV that correspond to switching of individual SQUIDs from the superconducting state into the resistive state. One example is shown in the right inset of Fig. 2 where 36 peaks have been identified out of the expected 44. The difference can be associated to accidental overlapping of Ic values of 8 individual SQUIDs. Previous such studies in large SSAs could not resolve multipeak structures at temperatures above 30 K.26 Such investigations are important to figure out how the spread of Ic at 77 K compares with that at 4.2 K and understand the impact of it on achieving flux-coherence and optimum flux sensitivity in SSAs. Histograms of Ic were constructed with a Gaussian fitting that produced an average standard deviation of σ = 10.1% for sets of 44 SQUIDs. σ arises to about 12.2% for the entire array. It is important to note that σ is significantly smaller at 77 K than at 4.2 K, where σ = (23.5–25.5)% were found for similar large arrays fabricated using bicrystal technology.26,27 The spread of critical currents in our array, although significantly larger than in the LTS junctions (typically around σ = (2–3)% for 3 μm wide junctions array13), appears not to play a critical role in achieving flux-coherence in large arrays. ΔV on the other hand is expected to decrease rapidly with increasing σ.

The noise of the arrays was measured by directly coupling the output of the SSAs to a low noise preamplifier at room temperature, the output of which was connected to a spectrum analyzer. The arrays were biased by a battery powered current source and operated in a small signal amplifier mode. The output voltage noise VN of the arrays was measured at the point of maximum responsivity, i.e., where the array’s flux-to-voltage transfer function (dV/dΦ) was maximum. If we assume that the noise sources in the SQUIDs are uncorrelated, the theoretical values for the white noise voltage spectral density Sv/1/2 of an N junction SSA should be N1/2 larger than for single SQUIDs,14 i.e., SV/1/2 = N1/2 (16kTRN)1/2. That gives SV/1/2 = 6.6 nV/HZ1/2 for the 484 SSA operating at 40 K and SV/1/2 = 3.25 nV/HZ1/2 for the 770 SSA operating at 77 K (see Table II). Experimentally, however, typical values for SV/1/2 measured in the white region at 1 kHz were a factor of 3–6 times larger: SV/1/2 = 40 nV/HZ1/2 for the 484 SSA at 40 K and SV/1/2 between (8 and 9) nV/HZ1/2 for the 770 SSA in the temperature range (77–83) K (such excess noise is not unusual for YBCO SQUIDs). These values correspond to white flux noises SΦ/1/2 = 1/2(dV/ dΦ) = SV/1/2/(πΔV/θ0) of 0.75 μΦ0/HZ1/2 for the 484 SSA at 40 K and between (0.25 and 0.44) μΦ0/HZ1/2 for the 770 SSA in the temperature range (77–83) K. These values are superior to those of optimized LTS single-SQUIDs operating at 4.2 K which typically have SΦ/1/2 around 1 μΦ0/HZ1/2 (see Fig. 4). Then, the value of SΦ/1/2 = 0.25 μΦ0/HZ1/2 for the 770

### Table I. ΔV, Rarray, and average values across the SSAs of the individual SQUID’s main parameters Ic, RN, LRN, L, β at various temperatures.

<table>
<thead>
<tr>
<th>Array</th>
<th>484 SSA</th>
<th>770 SSA</th>
</tr>
</thead>
<tbody>
<tr>
<td>ΔV</td>
<td>0.7 mV</td>
<td>10.1 mV</td>
</tr>
<tr>
<td>T&lt;sub&gt;max&lt;/sub&gt;</td>
<td>17 mV, 2.5 kΩ</td>
<td>14.5 μA, 10.3 Ω, 150 μV</td>
</tr>
<tr>
<td>L, R&lt;sub&gt;n&lt;/sub&gt;, LR&lt;sub&gt;N&lt;/sub&gt;</td>
<td>25 pH, 0.35</td>
<td></td>
</tr>
<tr>
<td>L, β</td>
<td>0.25 μΦ0/HZ1/2</td>
<td></td>
</tr>
</tbody>
</table>

The noise of the arrays was measured by directly coupling the output of the SSAs to a low noise preamplifier at room temperature, the output of which was connected to a spectrum analyzer. The arrays were biased by a battery powered current source and operated in a small signal amplifier mode. The output voltage noise VN of the arrays was measured at the point of maximum responsivity, i.e., where the array’s flux-to-voltage transfer function (dV/dΦ) was maximum. If we assume that the noise sources in the SQUIDs are uncorrelated, the theoretical values for the white noise voltage spectral density Sv/1/2 of an N junction SSA should be N1/2 larger than for single SQUIDs,14 i.e., SV/1/2 = N1/2 (16kTRN)1/2. That gives SV/1/2 = 6.6 nV/HZ1/2 for the 484 SSA operating at 40 K and SV/1/2 = 3.25 nV/HZ1/2 for the 770 SSA operating at 77 K (see Table II). Experimentally, however, typical values for SV/1/2 measured in the white region at 1 kHz were a factor of 3–6 times larger: SV/1/2 = 40 nV/HZ1/2 for the 484 SSA at 40 K and SV/1/2 between (8 and 9) nV/HZ1/2 for the 770 SSA in the temperature range (77–83) K (such excess noise is not unusual for YBCO SQUIDs). These values correspond to white flux noises SΦ/1/2 = 1/2(dV/ dΦ) = SV/1/2/(πΔV/θ0) of 0.75 μΦ0/HZ1/2 for the 484 SSA at 40 K and between (0.25 and 0.44) μΦ0/HZ1/2 for the 770 SSA in the temperature range (77–83) K. These values are superior to those of optimized LTS single-SQUIDs operating at 4.2 K which typically have SΦ/1/2 around 1 μΦ0/HZ1/2 (see Fig. 4). Then, the value of SΦ/1/2 = 0.25 μΦ0/HZ1/2 for the 770

### Table II. Theoretical and experimental values for Sv/1/2 and SΦ/1/2 of the SSAs.

<table>
<thead>
<tr>
<th>Array, T</th>
<th>484 SSA, 40 K</th>
<th>770 SSA, 77 K</th>
</tr>
</thead>
<tbody>
<tr>
<td>SV/1/2</td>
<td>6.6 nV/HZ1/2</td>
<td>3.2 nV/HZ1/2</td>
</tr>
<tr>
<td>Measured</td>
<td>40 nV/HZ1/2</td>
<td>8 nV/HZ1/2</td>
</tr>
<tr>
<td>SΦ/1/2</td>
<td>0.15 μΦ0/HZ1/2</td>
<td>0.045 μΦ0/HZ1/2</td>
</tr>
<tr>
<td>Experiment: SV/1/2</td>
<td>0.75 μΦ0/HZ1/2</td>
<td>0.25 μΦ0/HZ1/2</td>
</tr>
</tbody>
</table>

![Fig. 4](image-url) Flux density noise SΦ/1/2 at 1 kHz and maximum peak-to-peak voltage modulation ΔV (inset) versus the number of SQUIDs integrated in the SSAs. The discontinuous lines indicate 1/N1/2 dependence. Typical flux noise levels of optimized HTS SQUIDs at 77 K, nano-HTS SQUIDs at 4.2 K, and LTS SQUIDs operating at 4.2 K (Ref. 23) are also shown as references.
SSA operating at 77 K is about 9 times lower than that of best reported values for optimized single HTS-SQUID operating at 77 K.\textsuperscript{24} It is important to stress that the arrays investigated here were not optimized in terms of their geometrical and electric transport properties, including $S_f^{1/2}$. Indeed, theoretical estimations for $S_f^{1/2}$ of optimized SSAs assuming a typical value of $\Delta V_{\text{SQUID}} = 30$ $\mu$V for a single SQUID are significantly lower (see Table II). This is very promising and it should stimulate research for further improvements. To a good approximation, the voltage modulation depth $\Delta V$ linearly increased with $N$, whereas the white flux noise $S_f^{1/2}$ decreased as $1/N^{1/2}$ (see Fig. 4). That strongly suggests that both flux-coherency and SQUIDs non-interactivity were achieved in our large $N$ arrays and at high temperatures. For both arrays, $S_f^{1/2}$ increases for frequencies below 1 kHz, a behaviour known to arise from critical current fluctuations. This $1/f$ low frequency noise can be eliminated by proper modulations techniques (i.e., bias reversal).

In summary, large $N$ SSAs made of YBCO and operating flux-coherently have been fabricated and tested. Their voltage modulation depth and white flux-noise performances in the temperature range (40–83) K are much better than single optimized HTS-SQUIDs operating at similar temperatures and even outperformed single LTS-SQUIDs operating at 4.2 K. HTS SSAs are therefore ideal candidates to replace single-SQUIDs in many applications.

\textsuperscript{1}H. Hilgenkamp and J. Mannhart, Rev. Mod. Phys. 74, 485 (2002).