HTS SQUID-based Magnetometers Less Noisy than their LTS Counterparts?

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October 26, 2015 (STH35, HP101). At present, magnetometers 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 HTS SQUIDs ever get less "noisy" than their LTS counterparts?

A very promising approach is to build a series SQUID array (SSA) of N non-interacting SQUIDs operating flux-coherently, because in this case [1-3] the voltage modulation ΔV 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 ΔV 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 [1-6]. 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) [7-8]. 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 [9-10]. Recently, 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 $YBa_2Cu_3O_7$ (YBCO) and operating flux-coherently (see Figure 1) [11].

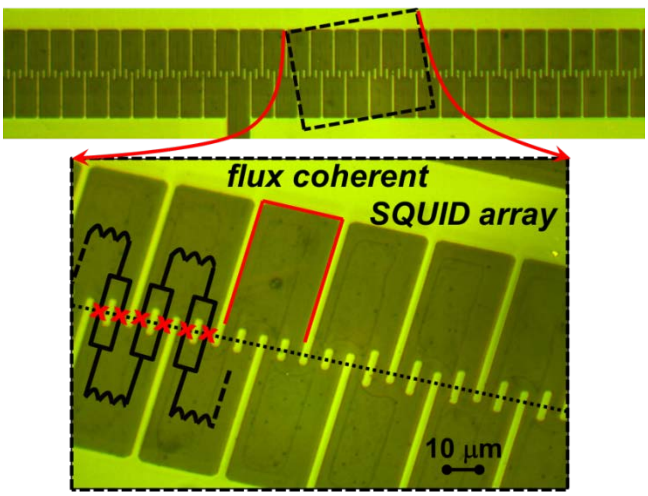

Fig. 1. Optical micro-picture of a small part of a 484 series SQUID array showing 54 SQUIDs and a high resolution picture showing only 11 SQUIDs. The array is fabricated by optical lithography after depositing a $YBa_2Cu_3O_7$ thin film on a $SrTiO_3$ bicrystal. Each SQUID consists of two Josephson junctions connected in parallel. The junctions (schematically represented as red crosses) can be seen as 3 micron-wide narrow bridges crossing the bicrystal boundary shown with a dotted line. Each pair of successive SQUIDs is connected in series via inductive large area narrow flux-focusers (one is highlighted by red U-shape).

The SSAs were fabricated using the well-established bicrystal technology. We choose to vary the individual SQUID loop areas *artificially* by 30% in the 484 SSA in order to investigate to what extent large variations in the SQUID inductances impact on the degree of flux-coherency and voltage modulation depth in large N SSAs. In contrast, all SQUID loop areas were identical for the 770 SSA. 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. Unlike the case of single SQUIDs, $V(B)$ is amplitude modulated and suppressed to nearly zero within several periods. This is well understood [5] as being a consequence of a significant variation in the periods of individual 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 484 SSA ΔV ranges from 10.1mV at 10 K to 0.7mV at 77K with a maximum value of 17mV reached at 40K. For the 770 SSA ΔV 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). Values of $S_\Phi^{1/2}$ in the temperature range (40-83)K were not only overwhelmingly lower than those of optimized single HTS SQUIDs operating at 77K but even outperformed single LTS SQUIDs operating at 4.2K (see Figure 2). This strongly suggests that HTS SSAs are ideal candidates to replace single SQUIDs in many applications. We found [11] that to a good approximation ΔV 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.

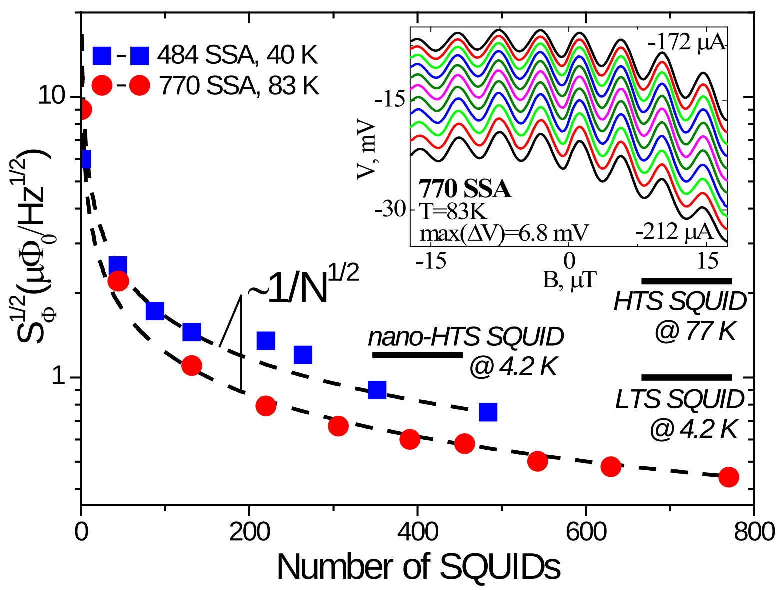

Fig. 2. Adapted from [11]. Flux density noise $S_\Phi^{1/2}$ at 1kHz versus the number of SQUIDs integrated in the arrays of both SQUID arrays. The discontinuous lines indicate $1/N^{1/2}$ dependence. Typical flux noise levels of optimized HTS SQUIDs at 77K, nano-HTS SQUIDs at 4.2 K and LTS SQUIDs at 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) μA with I changing in steps of 4μA;

See also HP102

References

[1] R.P. Welty and J.M. Martinis, "A series array of DC SQUIDs", *IEEE Trans. Magn.* **3**, 2924-2926 (1991).

[2] R.P.Welty and J.M. Martinis, "Two-stage integrated SQUID amplifier with series array output", *IEEE Trans. Appl. Supercond.*, **3**, 2605-2608 (1993).

[3] K.G. Stawiasz and M.B. Ketchen, "Noise Measurements of Series SQUID Arrays", *IEEE Trans. Appl. Supercond.* **3**, 1808-1811 (1993).

[4] V. Foglietti, K. G. Stawiasz, M.B. Ketchen, and R. H. Koch, "Performance of a flux locked series SQUID array", *IEEE Trans. Appl. Supercond.* **3**, 3061-3065 (1993).

[5] K. Li and S. P. Hubbell, "Measurement and simulation of the voltage-flux transfer function of SQUID arrays", *IEEE Trans. Appl. Supercond.* **5**, 3255-3258 (1995).

[6] K. Li and S.P. Hubbell, "High Linear Dynamic Range Magnetometer Utilizing a Large Array of Serially Connected SQUIDs", *IEEE Trans. Appl. Supercond.* **7**, 3217-3219 (1997).

[7] K. Li, S.P. Hubbell, R. Cantor, M. Teepe, "High temperature superconductor transimpedance amplifiers using serially connected Bi-crystal junction SQUID arrays", *IEEE Trans. Appl. Supercond.*, **9**, 4420-4423 (1999).

[8] S. H. Wu, M.H. Hsu, K.L.Chen, J.C. Chen, J.T. Jeng, T.S. Lai, H. R. Horng, H. C. Yang, "A highly sensitive YBCO serial SQUID magnetometer with a flux focuser", *Supercond. Sci. Technol.* **19**, S246 (2006).

[9] S. G. Lee, Y. Huh, G.S. Park, I.S. Kim, Y. K. Park, J.C. Park, "Serial array high Tc SQUID magnetometer", *IEEE Trans. Appl. Supercond.* **7**, 3347-3350 (1997).

[10] C. H. Wu, M. J. Chen, J. C. Chen, K. L. Chen, H. C. Yang, M. S. Hsu, T.S. Lai, Y. S. Tsai, H. E. Horng, J. H. Chen et al., "High quality step-edge substrates for high-T_c superconducting devices", *Rev. Sci. Instrum.* **77**, 033901 (2006).

[11] B.Chesca, D. John, C. Mellor, "Flux-coherent series SQUID array magnetometers operating above 77 K with superior white flux noise than single-SQUIDs at 4.2 K", *Appl. Phys.Lett.* **107**, 162602 (2015).