High-Temperature Superconductor Cryogenic Current Comparator

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***Abstract*—NIST is developing a cryogenic current comparator (CCC) to operate at 77K, using high-temperature superconductor (HTS) ceramic shielding material and an HTS-based superconducting quantum interference device (SQUID) detector. The shielding properties of at least two polycrystalline oxide HTS materials appear sufficient for use in a high-accuracy CCC. A measurement of current-linkage error, a figure of merit for CCC devices, is made for one type of HTS CCC. The design of a second HTS CCC which uses improved magnetic shielding is described.**

I. Introduction

I. K. HARVEY developed the original CCC concept [1] for operation at liquid helium temperature. This early design consisted of a tube which provided superconducting magnetic shielding between internal ratio windings and an external magnetic detector. Currents in the windings set up nearly cancelling shielding currents on the surface of the tube, and a ratio balance at any integer ratio of currents could be detected and maintained using appropriate windings. Liquid helium temperature overlapped-tube CCC devices [2] used in several laboratories are capable of comparing small currents (25–50 μA) with an uncertainty of a few parts in 10^9, due in part to the magnetic shielding of type-I superconducting materials. CCC devices are often used for quantized Hall resistance (QHR) measurements to provide accurate scaling of resistance values to industrial standards at the 1 Ω and 10 kΩ levels.

The HTS technology available today does not allow a shielding geometry suitable for producing a CCC with this level of accuracy. However, a simple design with reasonable magnetic shielding using straight tubes could allow the CCC to be constructed more easily and provide an intermediate level of ratio accuracy. NIST is constructing a CCC with ratio windings enclosed in two parallel HTS tubes. The HTS-based SQUID will be directly coupled to the magnetic field between the tubes.

II. HTS Magnetic Shielding

Meissner-effect shielding of magnetic fields by HTS ceramics has been shown to be similar to shielding in Nb-based type-II superconductors [3]. In bulk metallic type-II superconductors, flux is expelled completely if the field near the surface is below the lower critical field. The HTS ceramics differ from the metals in that strongly superconducting regions (or grains) in the polycrystalline material form Josephson junctions at grain boundaries. This allows a magnetic field to penetrate between the grains if the Josephson lower critical field ($H_{J_{c1}}$) is exceeded. Above this critical field value, HTS ceramics can exhibit flux creep, and the shielding efficiency is strongly dependent on thickness [4].

HTS magnetic shielding at 77K is implemented using tubes or crucibles because of limits on the fabrication of complex shapes of the HTS ceramic oxides. Magnetic fields which are set up by localized sources on either the interior or exterior of a shielding tube are exponentially attenuated with distance in the tube interior. The strength of the magnetic field inside a tube of radius r falls off at least as far as $\exp(-1.84z/r)$, where z is the distance within the tube as measured along the axis [5].

Tubes made from $YBa_2Cu_3O_7$ (YBCO) and $Ba_2Sr_2CaCu_3O_8$ (BSCCO) superconducting oxides are effective as magnetic shields. The $H_{J_{c1}}$ field strength for YBCO is on the order of the typical field generated in the CCC interior, near a current-carrying winding of small diameter. However, the effective magnetic shielding in tubes of the bulk material can be sustained at fields much higher than $H_{J_{c1}}$. Irreversible shielding loss and remnant magnetization in tubes occur at fields above about 2500 A/m for pure YBCO [6]. In long YBCO tubes, a shielding factor $S = H_{\text{external}}/H_{\text{internal}}$ of at least 10^6 can be achieved for moderate fields [7]. Bulk shielding is less strongly maintained for BSCCO than for YBCO [8], but a shielding factor of more than 10^6 has been measured in a thick-walled BSCCO tube produced for NIST.

III. BSCCO CCC Measurements

We have constructed a CCC from two BSCCO tubes of 100 mm length, as shown in Fig. 1(a). Both BSCCO tubes had been milled flat on the side facing the SQUID to improve the uniformity of the field generated by shielding currents. Two CCC windings consisting of 12 turns of twisted-pair copper wire were passed through the tubes. The wire for each winding was of diameter 0.25 mm and was insulated. A YBCO RF-SQUID in a 4-mm-diameter electrically insulated probe was placed between the BSCCO tubes on the long CCC axis, and could be moved along the axis. The RF-SQUID flux-sensing area is about 2.5×10^{-7} m^2 and its flux noise is less than 2.5×10^{-4} $\phi_0/\sqrt{\text{Hz}}$, where ϕ_0 is the flux quantum of magnetic field. The measured CCC sensitivity was approximately 270 $\mu\text{A}/\phi_0$ for a single turn.

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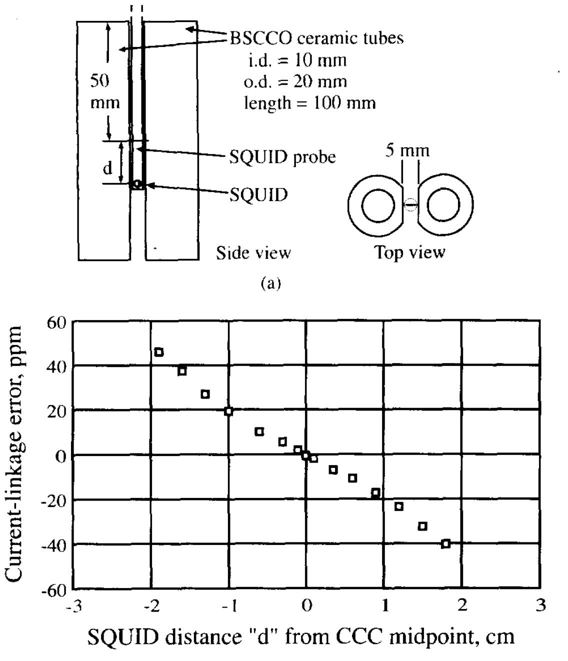

Fig. 1. (a) BSCCO tubes and a YBCO RF-SQUID in the CCC configuration, windings not shown. (b) Measurements of the current-linkage error for two windings of the BSCCC CCC as a function of the position of the SQUID.

The current-linkage error is defined as $E = \epsilon/N_1 I_1$ for a CCC winding of N_1 turns carrying current I_1, where ϵ is a factor proportional to I_1. The error E is the fraction of the full signal measured with an opposing winding of N_2 turns carrying a current $I_2 = N_1 I_1/N_2$. Within 1 mm of the BSCCO CCC midpoint, the measured current-linkage error passed through zero [see Fig. 1(b)], showing that for these windings, the unshielded sections at the two ends produce opposing and approximately equal fields. Each measurement has a relative standard deviation of about 8×10^{-7}. Near $d = \pm2.0$ cm, E falls off somewhat faster than the inverse of the square of the distance to the nearer end. The dipole field from the unshielded, opposing windings at the ends of the CCC should fall off as the inverse of the cube of distance, but the superconducting tubes may focus the end-effect field.

IV. YBCO CCC Design

A second HTS CCC is being constructed at NIST using the YBCO material because of its superior shielding properties. A new design for the tubes is used (see Fig. 2). This figure shows two tubes having a rectangular cross section and made from 99.9% pure YBCO. The YBCO CCC will be assembled with a thin insulating layer between the two rectangular tubes. Holes for the windings are bored along the 152 mm axes, and a circular aperture for a SQUID probe is bored through at right angles to the long axis, leaving a minimum 6-mm wall thickness of YBCO material on all sides of the SQUID aperture. A narrow slit is then cut to connect the entire length of the SQUID aperture to the adjacent exterior surface. This

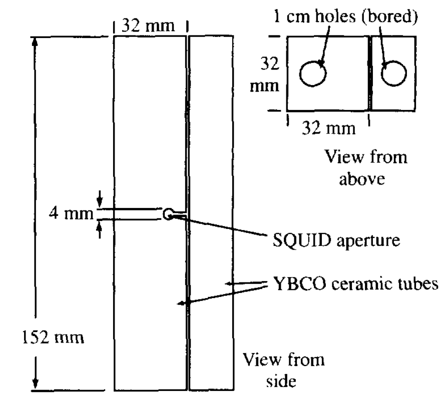

Fig. 2. YBCO tubes in the CCC configuration.

slit provides a path for the surface current to circulate around the SQUID, which senses the signal flux set up by the currents in the windings. HTS CCC sensitivity will improve when SQUIDS coupled by flux transformers made of HTS material are available. This CCC uses a 4-mm-diameter probe with a 90° bend; the design should be mechanically stable since the SQUID can be firmly anchored in the aperture.

The small cylindrical SQUID aperture should provide some shielding from magnetic fields, except for external fields directed along the aperture axis. This geometry is similar to the superconducting flux focuser common in SQUID design. A two-dimensional flux focuser in a uniform magnetic field increases the perpendicular flux per unit area in the aperture. The effective cross-sectional area of the aperture in a uniform field can be as great as the geometric mean of the areas of the aperture and flux focuser [9]. This effect is not likely to greatly increase the signal flux which is set up by the surface current and is not free to move into the aperture.

V. YBCO CCC Sensitivity and Noise

It is possible to predict the CCC sensitivity and noise limit from the RF-SQUID flux noise, the RF-SQUID flux-sensing area, and a calculation of the signal flux. The YBCO tube has a square cross section, and it is reasonable to take the current flowing around the SQUID aperture to be at least 25% of the total shielding current. This fraction of current flowing around a circular current loop gives a CCC sensitivity of 100 $\mu A/\phi_0$ for a single turn winding of the CCC.

A measure of the environmental magnetic noise in our laboratory can be taken from data points obtained in 10-min BSCCO CCC measurements in a standard magnetically shielded cryostat. The measurements were described earlier (see Fig. 1), and give a total noise which is equivalent to $8\times10^{-10}T/\sqrt{Hz}$. This noise represents changes in external magnetic fields, motion of the SQUID, and other noise sources. With the RF-SQUID field resolution of $2\times10^{-12}T/\sqrt{Hz}$, this level of environmental noise shows that additional shielding factor of approximately 400 will be required to achieve the best noise performance. The design of the YBCO CCC includes a 200 mm long thick-film HTS tube enclosing the CCC which will reduce both end-effect current-linkage errors and environmental noise.

A SQUID flux noise of $2.5\times10^{-4}\ \phi_0/\sqrt{\text{Hz}}$ is quoted for the HTS-based RF-SQUID. This gives a CCC noise limit of 25 nA/$\sqrt{\text{Hz}}$ for a single turn of the YBCO CCC. At very low frequencies, SQUID detectors exhibit additional noise ($1/f$ noise). The noise spectrum for these RF-SQUID's in a magnetically shielded dewar shows no added $1/f$ noise component above about 0.2 Hz. For a resistance ratio measurement of 1000–100 Ω, 1 mA of current in a 300 turn primary winding would result in a relative uncertainty due to the base SQUID flux noise of 1.1×10^{-8} in a 60 s measurement. At the QHR step near 12.9 kΩ, the current is limited to about 50 μA for most samples. With a turns ratio of 826 to 64, the QHR step resistance could be compared to a 1000 Ω resistor. The YBCO CCC would be limited to a relative uncertainty of at least 7.8×10^{-8} for a 60 s measurement. This level of random uncertainty is comparable to the best room-temperature measurement systems. However, both of these measurements can be made using liquid helium temperature CCC systems with lower uncertainty.

VI. Conclusion

HTS ceramics appear to have sufficient shielding capability to provide effective magnetic shields for constructing an HTS CCC. Since the HTS materials are brittle and cannot be formed into complex shapes, it is impractical to use conventional shielding and winding geometries. Measurements with an HTS CCC constructed using two 100 mm BSCCO tubes and a YBCO RF-SQUID indicate that noise and current-linkage error can be made to contribute less than one part in 10^6 to the ratio uncertainty. A YBCO-tube CCC enclosed in a superconducting external shield is being constructed. This CCC design should provide higher attenuation of noise, lower current-linkage error, and improved coupling of signal flux. The YBCO CCC will operate at 77K with a planned noise limit of 25 nA/$\sqrt{\text{Hz}}$ for a single turn.

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