Ultra-Low Heat Leak YBCO Superconducting Leads for Cryoelectronic Applications

Robert J. Webber, Jean Delmas, and Brian H. Moeckly

***Abstract*—We report on High Temperature Superconductor (HTS) DC current leads developed for the specific purpose of delivering small currents ($<$100 mA) to cryocooled electronic devices operating at 4 K, with significantly reduced heat leak. Multi-stage cryocoolers can provide a suitable platform for niobium-based superconducting electronics at 4 K; the necessary multiple parallel biasing of the circuitry can result in total currents of several amps, which can produce substantial thermal loading of the cryocooler when conventional resistive leads are used. Our approach has been to adapt the comparatively mature technology of high-current second-generation (2G) YBCO-coated conductor tape to low current needs by splitting the tape into electrically isolated narrow lines by ion milling. Performance issues discussed are: obtained critical currents, thermal conductance of the composite conductors, line-to-line electrical isolation, resistance of the joints and robustness. Operation as a current lead between the first and second stage of a Gifford-McMahon cryocooler is reported.**

***Index Terms*—Cryocooler, cryoelectronics, current leads, YBCO tape.**

I. Introduction

TYPICALLY, low temperature superconductor (LTS) electronic devices operating at temperatures of 4 to 5 K produce little heat of their own (e.g. 1.2 mW for a 6,000-junction Rapid Single Flux Quantum (RSFQ) circuit [1]). The dominant heat leak into the 4 K environment for any such system that is conventionally wired is from all the electrical connections that link the cryogenic electronics to the outside world at ambient temperature. This includes input, output and bias supply lines; heat leaks from these sources will typically be more than an order of magnitude higher than the heat generated by the device itself [2]. A single-channel satellite receiver using an RSFQ circuit was demonstrated in [3], however, if the system were to be expanded to multiple frequency channels, the number of channels (and chips) that could be accommodated by a single cryocooler would be limited by the heat loads from the conventional DC wiring.

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As a recap, the heat leak per unit current between 2 stages of a cryocooler is calculated for normal metal leads below:

A. Normal Metal Leads

Consider delivery of DC current from a warm temperature T_1 to a cold temperature T_0 by a wire that is thermally isolated at temperatures T in-between. For materials with a finite electrical resistivity, the dimensions of the conductor can be optimized to give a minimum total heat leak into the cold end. This results from the conflicting dimensional requirements of low Joule heating (short, fat wire) with low conductive heating due to the end-to-end temperature difference $T_1 - T_0$ (long, thin wire). The optimized minimum heat leak into the end at temperature T_0, per unit current, is given by [4]:

$$\left[\frac{\dot{Q}}{I}\right]_{\min} = \left[2\int_{T_0}^{T_1} k(T)\rho(T)dT\right]^{0.5} \quad (1)$$

where:

- $\dot{Q}$ is the heat leak into the cold end at temperature T_0
- I is the current flowing in the wire
- $k(T)$ is the thermal conductivity of the wire
- $\rho(T)$ is the electrical resistivity of the wire

The ideal material would thus have a small $k\rho$ product in the range of temperature T_0 to T_1, however, in normal metals, for which thermal transport is dominated by the electronic contribution, a low thermal conductivity is always accompanied by a proportionately high electrical resistivity. Metals tend to follow the Wiedemann-Franz "law" [5]:

$$k\rho = LT \quad (2)$$

where:

- L is the Lorenz constant $(2.45 \times 10^{-8}\ \mathrm{W\Omega K^{-2}})$
- T is the absolute temperature

So, for a "Wiedemann-Franz metal" wire, the minimum heat leak into a station at temperature T_0 for a current I flowing from temperature T_1 is given by [2]:

$$\left[\frac{\dot{Q}}{I}\right]_{\min} = \left[L\left(T_1^2 - T_0^2\right)\right]^{0.5} \quad (3)$$

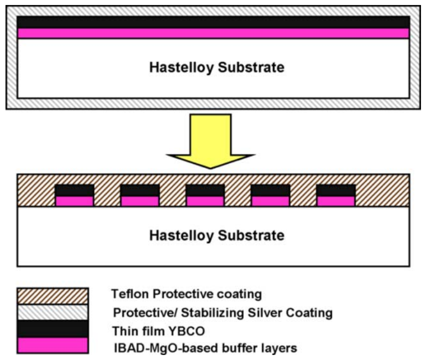

Fig. 1. Schematic drawing of cross-section of high-current YBCO tape transformed into a multi-line ribbon lead.

For $T_1 = 50$ K (typical first stage temperature of a 2-stage cryocooler) and $T_0 = 4$ K, the minimum heat load is 6.5 $\mathrm{mWA^{-1}}$, or twice this number if both supply and return currents are included.

The niobium-based analog-to-digital converter of [2] requires a total of about 1 A of biasing currents, which, if supplied by perfectly optimized Wiedemann-Franz metal conductors from 50 K would see an additional heat load of about 13 mW into the 4 K stage. In practice, the figure would be higher because in a real system of multiple bias lines, each line would not be accurately optimized for its specific current.

On the other hand, HTS leads offer the possibility of delivering current from a 50 K stage to the 4 K environment with significantly lower heat leak than conventional leads. Indeed, products are now commercially available that can carry 10–10,000 A for LTS magnet applications [6], with much better than ten times the thermal performance of normal metal leads. However, no HTS solution is available for the small currents suitable for biasing LTS electronics. The RSFQ circuits described in [1], [2] and [3], use >20 independently adjustable bias currents per chip with a typical r.m.s. value of 35 mA, but with some lines carrying ~100 mA; the total current is approximately 1 A per chip and it is this application that we target here.

II. The Conductor Cable Concept

A multi-line array of low current capacity and low heat leak YBCO leads was patterned on a commercially available second-generation (2G) tape designed to carry ~200 A of current. See Fig. 1. First-generation BSCCO tape cannot be patterned in this way since the superconductor is multifilamentary and embedded in silver alloy. Harshavardhan *et al.* [7] produced samples of thin-film YBCO on flexible substrates of yttria-stabilized zirconia (YSZ) suitable for RF signal transmission to LTS electronics. However, cables fabricated from such materials, though highly promising electrically and thermally, are not readily available. For our DC application, the 2G tape has suitable properties for cable fabrication using the methods outlined here.

In order to make electrically isolated lines, we rely on the MgO buffer layer to provide the insulating barrier between superconductor and metallic substrate. Another key factor that makes this approach feasible is the use of a relatively thin (50–100 μm) tape of low thermal conductivity Hastelloy as the substrate. (See Section V-B) The stabilizing silver layer is removed in the thermally isolating region of the conductor but is left intact at the contact pads for the formation of low resistance electrical joints, since a high quality inter-metallic bond is relatively difficult to achieve between YBCO and silver [8], [9].

Attributes sought for this ribbon cable are as follows:

(i) Number of lines per ribbon: 10–20
(ii) Maximum working current per line ~200 mA
(iii) Heat leak per line <1/10 optimized normal metal leads at 35 mA nominal current.
(iv) Electrical joints to normal metal wires should be of a low enough resistance to conform with (iii) and should be thermally sunk well enough to prevent Joule heating from propagating to cause the superconductor to become normal.
(v) Line-to-line isolation and line-to-ground isolation should be good enough to prevent significant current leakage away from the device at 4 K. For RSFQ circuitry this can be relative low due to their inherent low impedance.
(vi) Mechanical robustness
(vii) Ability to withstand exposure to moisture without degradation

III. Methods of Line-Patterning

Initially, different methods of patterning were explored for general feasibility; 50 mm-long lengths of 10 mm-wide tape supplied by Theva were patterned with lines from 100 to 1000 μm in width. The critical currents of the individual lines were measured in LN_2 by wire-bonding the samples to copper printed circuit boards. The results are summarized below:

A. Laser Ablation

Several 50 mm-long samples with varied line-width were fabricated by Tai-Yang, Inc. Subsequent tests in LN_2 showed relatively poor line-to-line isolation and a rapid fall-off in critical current with decreasing line-width. This effect is believed to be caused by oxygen depletion in the edges of the YBCO lines due to the high temperatures produced by the laser. In principle this technique should be able to produce good isolation and high critical current as shown by Levin *et al.* [10], who used post-ablation oxygen annealing to improve isolation from the metal substrate and possibly restore the edge critical current density.

B. Optical Lithography and Wet-Etching

A 25 mm-long sample was fabricated by the CIRFE of the University of Waterloo, again with variable line widths. In this case, the lithographic equipment limited the maximum length, although Hazelton *et al.* have developed a photolithographic process for long lengths but with uncertain line isolation [11]. The critical currents of the lines were consistent with the bulk critical current density down to 100 μm widths, which indicates that there is negligible edge damage. Line-to-line isolation was also excellent i.e. of the order of megohms.

C. Ion Beam Milling

50 mm-long samples were fabricated by M.I.T.'s Lincoln Laboratory and Superconductor Technologies, Inc. (STI); crit-

Fig. 2. Mask for ion-beam milling 100 mm-long by 12 mm-wide YBCO tape sample. Lines are darker at each end showing the region of silver coating.

Fig. 3. 100 mm-long by 12 mm-wide tape with 22 lines of various widths and separations. 24-pin connectors are soldered directly to the silver-coated pads.

ical currents were somewhat variable, but did achieve results consistent with the bulk critical current density for line-widths down to 100 μm. Line-to-ground resistance was also quite dependent upon the exact milling parameters but values of megohms were demonstrated.

For further development we chose ion beam milling as the method of patterning; critical currents for 100 μm-lines were demonstrated to be as good as by wet-etching, but STI had the ability to pattern 100 mm-long samples, which is seen as an advantage, both from a thermal point of view and when considering compatibility with dimensions of cryocoolers.

IV. Fabrication of 100 mm-Long Ion-Beam-Milled Cables

STI patterned several 100 mm-long samples according to the mask layout shown in Fig. 2. The samples of Section III above were made from tape with a 0.5 μm-thick silver coating; the wire-bond joints had a tendency to break away due to poor adhesion of silver to the YBCO. For the 100 mm-long samples we chose 12 mm-wide tapes with a 3 μm-thick layer of silver and a Hastelloy substrate of only 50 μm thickness manufactured by SuperPower, Inc.. The YBCO thickness is only 1 μm, so without the silver layer, the thermal conductance of the substrate dominates the heat leak, hence the relatively thin substrate of 50 μm is an advantage.

The array of 22 lines varied in width from 25 μm to 300 μm. In addition, a series of lines separated by gaps ranging in size from 25 μm to 100 μm were patterned in order to explore leakage resistance as a function of line-to-line gap. At both ends of the sample the 3-micron layer of silver was left intact over each line to provide a good soldering pad and a length of stabilized superconductor next to the joint.

The films were patterned using conventional contact photolithography and inert Ar ion milling. We developed procedures to mount the tapes to Si wafers in order to keep them flat during processing. Following etching of the YBCO, dielectric, and silver layers, the contact areas were masked with photoresist and the rest of the silver was removed using a wet etch. In order to protect the finished tapes, a Teflon coating was spun on, removed from the contact areas, and cured.

End connections were made by soldering MIN-E-CON 24-pin single row connectors directly to the silver-coated pads using Cerrobend which melts at 70°C; the low soldering temperature prevents scavenging of the silver. See Fig. 3.

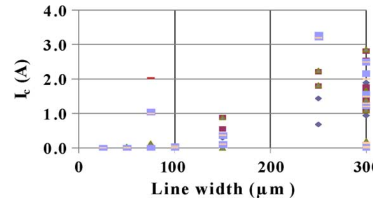

Fig. 4. Critical current vs line-width for ion-beam milled 100 mm-long samples measured in liquid nitrogen.

V. Measured Characteristics of 100 mm-Long Cables

A. Current Carrying Capacity Per Line

Critical currents for all the patterned lines were measured in liquid nitrogen for three 100 mm samples. The results as a function of line width are shown in Fig. 4. As the line width decreases below $\sim$ 150 μm the critical current drops dramatically. This effect is not completely understood, but may be related to the fine structure of the YBCO layer. Critical currents of well over 1 A are, nevertheless, carried by lines of 250 μm. This would give a large margin over 200 mA and would also accommodate the required number of lines. As Fig. 4 shows, there was also considerable variation in performance from one similar line to another; however, the choice of a 250 μm line width would appear to allow sufficient margin to support this.

Interestingly, there seems to be a trend of reduced critical current close to the edge of the tape. This could be accounted for, perhaps, by a variable YBCO layer thickness during original manufacture or uneven milling depths, which in turn could be caused by an uneven thickness of the silver layer.

B. Heat Leak per Line

Given that silver has been removed from the tape in the region of a temperature gradient, and that the YBCO layer is very thin, the heat leak for this lead is dominated by the thermal conductance of the Hastelloy substrate. The efficiency of the lead will be determined by the size of the line-width and line-to-line insulating gap, which sets the cross-sectional area of substrate necessary to carry an individual line. We therefore measured the thermal conductivity of the 50 μm-thick substrate with and without the YBCO conductor; the difference was negligible.

Using the Hastelloy thermal conductivity values measured by Lu *et al.* [12], if we were to assume a line length of 100 mm, a line width of 250 μm and a line-to-line gap of 25 μm, then the predicted heat leak per line carrying 35 mA to 4 K is about 1/10 of the value of an optimized normal metal.

C. Electrical Resistance of Joints

From a thermal budget point of view, our requirement is that the Joule heating from the joint at the 4 K end should be small compared to the heat leak per line from the HTS composite line itself. Secondarily, the Joule heat from the warm-end joint should not be responsible for significantly degrading the critical current of the line by "hot-spot" propagation (potentially a problem in vacuum).

The joints were considerably more robust than the wire-bonded ones and had measured resistances in liquid

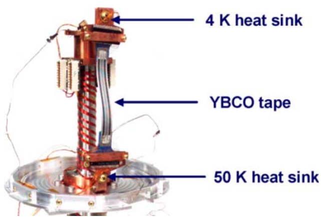

Fig. 5. 22-line patterned tape with connectors mounted between the first and second stage of a 2-stage Gifford-McMahon cryocooler.

nitrogen of $\sim$ 1 $m\Omega$, which is approximately 1/3 of the resistance of our wire-bonded joints. This resistance includes the contribution from the flying copper lead to the connector, but not the connector joint resistance itself; the resistance of the connector joints was about 5 $m\Omega$ in LHe. For currents of 35 mA, this represents 6 μW per line or about 20% of the conductor heat leak, which is acceptable.

D. Line-to-Line and Line-to-Ground Resistance

Measurements showed no correlation between line-to-line separation and line-to-line resistance down to a gap of 25 μm. Leakage resistance values varied, however, from hundreds of Ohms to megOhms, in all cases the path was through the Hastelloy substrate. The load resistance of the RSFQ devices for which these leads are intended is about 1 Ω, so a leakage resistance of 100 Ω would result in 1% leakage current, which may be acceptable. However, the reasons for the variability of the leakage to substrate ground are not understood at the time of writing, but could be caused by redeposition of metals during milling or perhaps pinholes in the buffer layer.

E. Mechanical Robustness

The unpatterned YBCO tape is inherently robust, and can sustain bending in a circle of diameter 1 cm without significant degradation of its critical current. The soldered joints used for the 10 cm-long samples are not what one would call robust and further work is needed to achieve an acceptable level of immunity to breakage, e.g. by the use of encapsulation.

F. Immunity to Degradation by Moisture

Bare YBCO has a well-known tendency to be degraded by exposure to water or, worse still, acids. We coated the bare YBCO with a liquid Teflon suspension which protected our samples from any detectable damage from water condensation which occurred during warm-up of the samples. Although we did not deliberately expose them to water, they certainly condensed water on the tape surfaces in-between repeated critical current measurements, which yielded unchanged values in liquid nitrogen.

VI. Performance in Vacuo on Cryocooler

Each end of a pre-tested lead with connectors was glued to copper foil heat sinks, which were bolted to the first and second stages of a Sumitomo SRDK-101D Gifford-McMahon cryocooler (See Fig. 5). Preliminary results showed that with the warm-end temperature at 77 K, the critical current of one of the 300 μm-wide lines was 80% of that measured in LN_2. This indicates that the control of hot-spot propagation is reasonable in the absence of direct liquid nitrogen cooling and silver layer stabilization. With the warm end held at 50 K, 90% of the 300 μm-lines carried currents of over one Amp.

VII. Conclusion

This method of patterning tape that has been manufactured for carrying $\sim$200 A of current has, indeed, been shown to have the potential to be used to deliver multiple DC biasing currents from 50 K to cryocooled devices at 4 K with approximately 1/10 of the heat leak of conventional normal metal wires carrying a nominal 35 mA each.

End joints between the HTS lines and normal conductors have been fabricated with a resistance low enough to make their Ohmic heating sufficiently small at the designed operating currents.

The leakage resistances of the lines vary over orders of magnitude, but are high enough to prevent significant leakage currents when biasing low impedance circuits.

Individual lines of a patterned multi-line cable have shown encouraging current carrying capacity in vacuo bridging the first and second stage of a cryocooler.

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