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RAPID COMMUNICATION

Significant reduction of AC losses in YBCO patterned coated conductors with transposed filaments

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Abstract
We report on a first implementation of a design which provides a significant reduction of AC losses in $YB_2Cu_3O_{7-\delta}$ (YBCO) coated conductors (CCs) without mechanical twisting. The conductor is composed of two diffusively bonded silver clad commercial CCs with zigzag patterned filaments partially separated by a dielectric layer. We produced three fully bonded samples with 500 μm wide filaments using three-stage photolithography and wet chemical etching. A tenfold reduction of AC losses at frequencies between 20 and 400 Hz was observed, while transport measurements and magneto-optical imaging showed no degradation of T_c and a low contact resistance of $\simeq 10^{-8}$ Ω cm^2 between Ag and $YB_2Cu_3O_{7-\delta}$.

(Some figures in this article are in colour only in the electronic version)

The dc performance of $YB_2Cu_3O_{7-\delta}$ (YBCO) coated conductors has been greatly improved recently by enhancing the in-field critical current density $J_c(T, B)$ by artificial pinning centers [1]. However, the reduction of high hysteretic losses in CC tapes remains a very important and challenging problem [2, 3], because this requires electromagnetic decoupling of filaments, which is usually accomplished by mechanical twisting [4]. This method has many crucial drawbacks for the flat CC geometry, so different designs [5–10] have been proposed recently to emulate the Rutherford tape architecture, in which the filaments can be magnetically decoupled without twisting the conductor.

In this letter we report on the first implementation of a conductor design [6] shown in figure 1, which provides a significant reduction of ac losses without mechanical twisting. The conductor consists of two patterned CCs with electrically insulated slanted filaments thermally bonded face to face through low-resistance bridges in the silver caps. The silver layers of each CC is partly covered by a thin dielectric layer, leaving two parallel uncovered conducting strips which only connect pairs of filaments from each conductor. The patterned CCs are then thermally bonded together through resistive Ag bridges so that each filament is electrically connected with only two filaments in the other CC. Here the electrical conduction paths alternate along the tape in a zigzag pattern, providing complete filament decoupling. Thus, the hysteretic and eddy current losses at fields $B > \mu_0 J_c d/\pi$ are reduced by the large factors $W/w \gg 1$ and $(W/w)^2 \gg 1$, respectively, where d is the YBCO film thickness, $w \gg d$ is the filament width, and W is the width of the tape. Since the silver cap on each filament remains intact, the electromagnetic and thermal stability for each individual filament does not deteriorate significantly as compared to the standard two-sided conductor, although the dielectric layer between the patterned conductors impede heat exchange between them. The loss reduction in our conductor occurs even though the ends of all filaments remain electrically connected, both through the YBCO current pads and Ag cap layers. The resistive bridges result is a small dc resistance R_0 yet the diffusion thermal bonding used in this work enabled us to minimize R_0 as compared to soldered and striated CC [8].

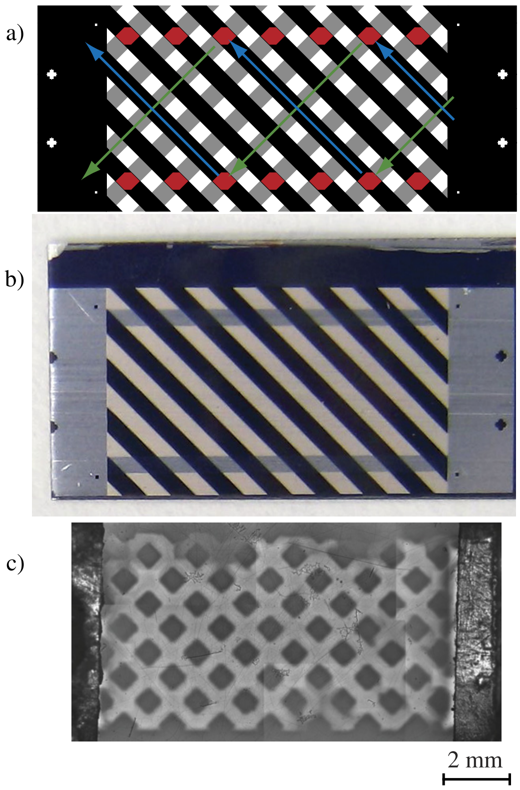

Figure 1. (a) Sketch of two bonded CCs where the filaments in the top layer (black) and the bottom layer (gray) are only connected through the resistive silver bridges (red). Alternating current paths are shown with blue (upwards) and green (downwards) arrows. (b) A photograph of a patterned half of the conductor after three photolithography stages. Shiny stripes correspond to the silver-coated YBCO filaments, yellowish regions show the dielectric photoresist coating and black regions correspond to the buffer layer; (c) magneto-optical image of trapped flux in a fully bonded conductor N1 (field cooled at 120 mT down to 10 K). The lighter regions show superconducting filaments, and the hair-like lines are defects in the MO indicator film.

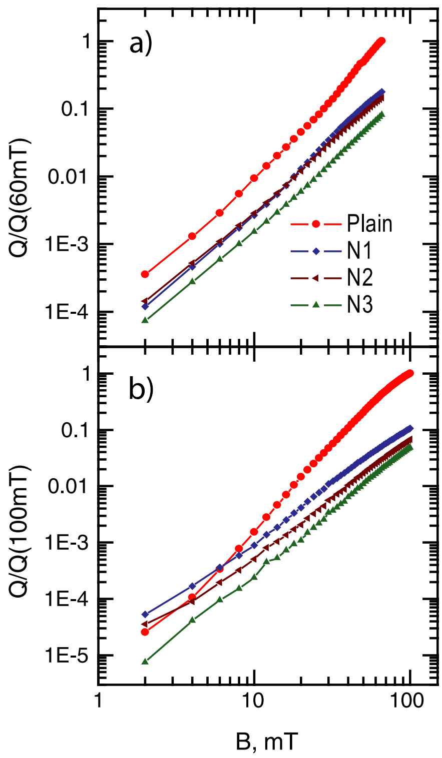

Figure 2. Losses for three patterned samples at 400 Hz (a) and 55 Hz (b) normalized to the maximum Q of the controlled sample.

We used YBCO tapes made by the metal-organic deposition on RABiTS from American Superconductor. These 4 cm wide tapes with a 75 μm thick Ni-5% W substrate, 250 nm Y_2O_3–YSZ–CeO_2 buffer layer, 0.8 μm thick YBCO layer, 3 μm thick Ag cap layer had $J_c(77\ \mathrm{K}) = 2.5$–$3\ \mathrm{MA\ cm^{-2}}$ in self-field [11]. Silver to silver thermal diffusion bonding regimes were optimized with respect to the bonding temperature, time and pressure, reducing the contact resistance to $5 \times 10^{-9}\ \Omega\ \mathrm{cm}^2$, close to best values reported in the literature [12].

Three photolithography stages and wet chemical etchings were used to pattern 14 mm × 19 mm pieces cut from the CC tape. First, the sample was covered with the resist AZ 1518 [13] and then the quartz mask was used to produce 1 cm long patterned region of width 6 mm with 500 μm wide slanted filaments spaced by 500 μm. The silver layers uncovered by the resist were etched away by water solution of ammonium hydroxide and hydrogen peroxide in ≈1 min. Then YBCO layer was dissolved by 1% HNO_3 and the photoresist was removed with acetone. After each photolithography step the resist was hard baked for 30 min at 115 °C. At the second stage ≈1.2 μm of the silver layer uncovered by the resist was etched away everywhere but the resistive bridge regions. At the third stage the reverse photolithography with AZ 5214E resist was applied to the same mask as for the second stage so that the insulating photoresist was filled in everywhere but the steps in the resistive bridges shown in figure 1(b). The patterned CCs were glued to a home-built holder with thin glass plates and placed into X–Y–Z-rotation stage in which the resistive bridges between the conductors were aligned by superimposing the pair of two cross-shaped marks on each glass under the microscope. Then samples were pressed together and diffusively pre-bonded at 115 °C for 120 min. in air followed by the final thermal bonding under the same conditions. Three bonded samples N1, N2 and N3 with the same dimensions were made under the nominally same conditions.

The magnetization ac loss power $Q(H)$ at 77 K of the bonded samples and an unpatterned control two-sided CC of the same dimensions were measured by the setup described in [14]. AC fields up to 100 mT and frequencies from 10 to 400 Hz were applied perpendicular to the tape. Figure 2 shows the field dependencies of $Q(H)$ for samples N1, N2, and N3, and the control sample. AC losses of patterned samples at high fields drop by ≈10 times as compared to $Q_c(H)$ of the control sample for all frequencies from 10 to 400 Hz. The difference between samples N1, N2 and N3 may result from macroscopic variations of J_c along the tape, quality of thermal bonding, etc. The observed loss reduction $Q/Q_c \approx 0.1$ is consistent with the qualitative estimate $Q/Q_c \simeq (L - L_p)^2/2LW + (w/W)^2 N L_p \sqrt{2}/L \approx 0.1$, assuming no significant degradation of local J_c during

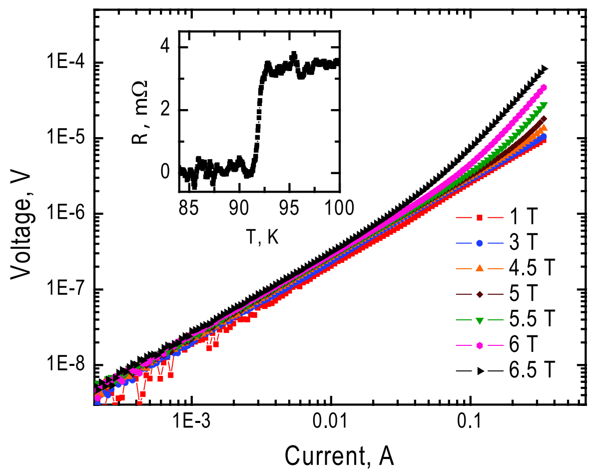

Figure 3. V–I characteristics of patterned sample N1. The resistive transition at $H = 0$ is shown in the inset.

patterning and thermal bonding. The first term in Q/Q_c describes hysteretic loss ratio for the unpatterned part of the sample, and the second term is the loss ratio for the patterned part with fully decoupled filaments at $B > \mu_0 J_c d/\pi$. Here $W = 6$ mm, $w = 0.5$ mm, $N = 4$ is the number of filaments across the sample, $L = 14$ mm is the total length of the conductor, and $L_p = 10$ mm is the length of the patterned part.

Magneto-optical (MO) imaging was used to check the filaments alignment and the YBCO superconducting properties in all bonded samples. MO images, like the one shown in figure 1(c), revealed a rather uniform critical state of trapped flux in the filaments imaged through the 75 μm thick Ni–W substrate. This technique showed a good filament alignment in all bonded CCs. MO imaging also revealed current-blocking defects, probably microcracks, which appear when two patterned CCs were pressed together during thermal bonding. These defects are visible at some of the filament ends, which nevertheless remain electrically connected through the silver cap. Although these defects reduce the global I_c of the conductor, they do not affect the hysteretic losses determined by the local J_c in the decoupled filaments.

Our four point transport measurements showed no reduction of T_c in samples N1, N2 and N3. DC voltage–current (V–I) characteristics were measured in fields up to 7 T for all 3 bonded samples and one control sample. The typical V–I curves for sample N1 shown in figure 3 exhibit the ohmic part $V = R_0 I$ at low I due to the resistive bridges followed by a raise of V above I_c. Here the dc power $Q = IV = 3.52$ μW dissipated due to the bridge resistance at $I = 0.335$ A $< I_c$ and 3 T results in $Q/2Lf = 2.93$ μJ m^{-1} cycle^{-1} at $f = 60$ Hz.

Several key parameters, such as the YBCO/Ag contact resistance r_i and the current transfer length ℓ between YBCO and Ag can be extracted from the ohmic part of $V(I)$. Here $\ell = (d_n r_i/\rho_n)^{1/2}$ is the length over which the current flows around a current-blocking defect in a filament through the Ag cap layer of thickness d_n and resistivity ρ_n. Such current sharing results in excess resistance $R_l \approx 2(\rho_n r_i/d_n)^{1/2}/w$ [15]. Taking into account the serial and parallel connections between filaments shown in figure 1(a), we obtain the resistance per bridge $R_b \approx 4R_0 = 71$ $\mu\Omega$ for sample N1. Here $R_b = R_a + R_i$ comprises the resistance $R_a = (2\rho_n d_n + r_{ia})/A$ of the silver cap, the Ag/Ag interface resistance r_{ia}, and R_i caused by the interface resistance between YBCO and Ag. Taking $\rho_n(77\text{ K}) = 4.7 \times 10^{-8}$ Ωcm extracted from our transport measurements on single filaments and the resistive bridge area $A = 2.3 \times 10^{-3}$ cm^2, we obtain that $R_a = 3 \times 10^{-8}$ $\Omega \ll R_b$ is negligible, and the observed bridge resistance $R_b \approx R_i$ is dominated by the YBCO/Ag contact resistance. In turn, $R_i^{-1} \simeq A/2r_i + R_l^{-1}$, is determined by two parallel resistances, where $2r_i/A$ is the contact resistance of two YBCO/Ag interfaces, and R_l comes from the current sharing in the Ag cup in two regions of length ℓ away from the contact area [15]. The condition $R_b^{-1} = A/2r_i + R_l^{-1}$ then gives a quadratic equation for r_i, which allows us to express r_i in terms of the observed R_b and other relevant parameters:

$$2r_i = \frac{\alpha A R_b}{1 + \alpha - \sqrt{1 + 2\alpha}}, \qquad (1)$$

where $\alpha = 4A\rho_n/R_b w^2 d_n$. From equation (1) we found $r_i \approx 2.4 \times 10^{-8}$–$1.16 \times 10^{-7}$ Ω cm^2 for all three samples. For sample N1 with $r_i = 1.16 \times 10^{-7}$ Ω cm^2, we obtain $l = 198$ μm, consistent with previous measurements on CCs [16]. Since ℓ is smaller than the filament width, the current sharing resistance $R_l \approx 270$ $\mu\Omega$ gives a relatively small contribution to R_b, but it can become important for narrow filaments $w < \ell$.

In summary, we have implemented a new CC conductor architecture, which provides a significant reduction of ac losses in patterned CCs. The results of this work indicate that further optimization of the bonding process and the reduction of the filament size can produce much more substantial loss reduction.

Acknowledgments

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References

[1] Foltyn S *et al* 2007 *Nat. Mater.* **6** 631
Mele P *et al* 2008 *Supercond. Sci. Technol.* **21** 032002
[2] Sumption M D, Barnes P N and Collings E W 2005 *IEEE Appl. Supercond.* **15** 2815
[3] Ashworth S P and Grilli F 2006 *Supercond. Sci. Technol.* **19** 227
[4] Carr W J Jr 2001 *AC Losses and Macroscopic Theory of Superconductors* (London: Taylor and Francis)
[5] Malozemoff A P *et al* 2001 *International Patent Publication* WO 01/08169A2 Feb. 1
[6] Gurevich A, Larbalestier D C and Thieme C L H 2003 'YBCO coated conductors with reduced ac losses', AFOSR STTR proposal (unpublished)
[7] Amemiya N *et al* 2004 *Supercond. Sci. Technol.* **17** 1464
[8] Tsukamoto O, Sekine N, Ciszek M and Ogawa J 2005 *IEEE Trans. Appl. Supercond.* **15** 2823
[9] Barnes P, Levin G, Varanasi C and Sumption M 2005 *IEEE Trans. Appl. Supercond.* **15** 2827
[10] Oberly C, Razidlo B and Rodriguez F 2005 *IEEE Trans. Appl. Supercond.* **15** 1643

[11] Rupich M W *et al* 2003 *IEEE Trans. Appl. Supercond.* **13** 2458
[12] Ekin J W *et al* 1988 *Appl. Phys. Lett.* **52** 1819
[13] Herrmann J *et al* 2000 *Physica* C **341** 2493
[14] Pamidi S *et al* 2007 *IEEE Trans. Appl. Supercond.* **17** 3179
[15] Ekin J W 1978 *J. Appl. Phys.* **49** 3406
Kuršumović A *et al* 1999 *J. Appl. Phys.* **86** 1569
Levin G A, Barnes P N and Bulmer J S 2007 *Supercond. Sci. Technol.* **20** 757
[16] Polak M, Barnes P N and Levin G A 2006 *Supercond. Sci. Technol.* **19** 817