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On the verge of high temperature superconducting fibers

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ABSTRACT

High temperature Type II superconducting materials were fabricated as fibers with a melt-draw technique. The yttrium barium copper oxide and bismuth strontium calcium copper oxide fibers maintained core diameters of 100–200 μm and overall diameters of 300–600 μm. Material characterization demonstrated both material and process compatibility. A fiber with yttrium barium copper oxide core and cladding holes is proposed as a compact and an efficient cooling design. Demonstration of fibers with Type II superconducting core materials and the potential integration with current state of the art technologies represents the first step in achieving the over-arching desire for superconducting wires with conventional geometries.

1. Introduction

Superconductivity has teased scientists, for a little over a century, with the hope of miracle solutions to electric power transmission, transportation, and magnetic energy storage [1]. Although superconductivity has enabled technologies such as Magnetic Resonance Imaging (MRI), applications are often relegated to the laboratory due, in part, to the lack of traditional cable designs, expense, and/or the requirement of elaborate cryogenic cooling schemes [2]. A Powder-in-Tube (PIT) method has shown to be a robust process for the fabrication of Nb_3N, Nb–Ti, and MgB_2 wires with Ag sheaths, but the requirement of liquid helium cooling has limited their acceptance in most applications [3]. $Bi_2Sr_2Ca_2Cu_2O_{10-x}$ (BiSCCO) wires are also fabricated via PIT processes, but require additional drawing steps, as well as rolling processes and thermal treatments to produce the superconducting tape that is eventually integrated into the final cable structure. Apart from the performance of the often referred to first generation HTS tape technology (1G), the material cost of the silver sheath/tape has been cost prohibitive in most applications.

The most recent tape technology, second generation (2G) or coated conductor, is more cost-effective and employs nickel or nickel alloy as opposed to silver in tape manufacturing. A thin film of $YBa_2Cu_3O_{7-x}$ (or another variant) is deposited on the nickel tape and textured through an epitaxial process to achieve the biaxial alignment required for high critical current densities, J_c [4]. Two different manufacturing processes are used depending on the crystalline nature of the metallic tape: Ion Beam Assisted Deposition (IBAD) or Rolling Assisted Biaxially Textured Substrate (RABiTS). Although the coated conductors are a definite improvement over 1G technologies, the complex manufacturing processes and design requirements are still relatively expensive and the path to an industrial process more adequate for the mass production is still unclear. The discovery of high temperature superconductors and recent improvements in cable designs and manufacturing methods seem to be promising, but a truly novel and multi-disciplinary approach is necessary for superconductors to experience the revolution seen with semiconductors and fiber optics [1,5,6].

In an effort to actually integrate semiconductor devices into optical fibers, researchers have demonstrated that conventional fiber optic materials and processes can readily be adapted to other materials such as metals, semiconductors, ceramics, etc. [7–9]. Furthermore, photonic crystal fibers (PCFs) and random hole fibers (RHFs) have been investigated as "templates" for a myriad of materials and applications such as the incorporation of magnetic nanoparticles for magnetic sensing, semiconductors for devices, and gas and liquids for chemical sensing [10]. Our ongoing innovation in the field of fiber optic and semiconductor technologies has inspired the demonstration of a radically new superconducting fiber design.

2. Materials and methods

Sample preparation. All the superconducting material core fibers were prepared by a melt-draw technique on a custom-made fiber drawing system [9,11]. The fiber drawing system has chucks, which are used to clamp the silica preform and can spin together or separately at precisely controlled speeds. The second chuck can also be moved linearly to draw the fiber from the preform when heated and softened by a hydrogen–oxygen torch over 1600 °C. The superconducting powders used in this study

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were yttrium barium copper oxide (1-2-3), 99.5% (metals basis) and bismuth strontium calcium copper oxide, (2-2-1-2), 99.9% (metals basis) and purchased from Alfa Aesar.

First, a fused silica substrate tube (GE214, OD=8 mm, ID=3 mm) was fused with a core processing tube (GE214, OD=12.75 mm, ID=10.5 mm). The chosen superconducting powders were then placed in the processing tube and melted via an oxy-hydrogen flame to the appropriate melting temperature. A smaller diameter fused silica rod (GE214, 8 mm) was used to push the ceramic melt into the substrate tube forming a preform with a ceramic core. Finally, the preform was drawn into a fiber [11,12].

The holey superconductor material core fibers were then fabricated using a similar process as described in the previous section, but included several fused silica tubes displaced around a "core" fused silica tube containing the superconducting material. First, a fused silica handle tube (GE214, OD=6 mm, ID=3 mm) was fused with the "core" processing tube (GE214, OD=12.75 mm, ID=10.5 mm). The superconducting powder was then placed in the handle tube. The "core" processing tube was then inserted and centered in an overclad tube (GE214, OD=12.75 mm, ID=10.5 mm). Smaller fused silica tubes (GE214, OD=3 mm, ID=1 mm) were then displaced around the "core" tube in the annulus between the overclad tube. A section of this preform was then heated to approximately 2200 °C to allow the overclad tube to "naturally" collapse on the small tubes. As the superconducting powder melted, this structure was drawn into a fiber. A "two stage" process was also evaluated in which the superconducting powder was melted independently and allowed to flow into the drawn structure upon fiberization. This approach lends itself to direct implementation into standard draw tower production.

Characterization. Polished fiber cross sections were characterized with a scanning electron microscope (SEM, LEO 1550) and an optical microscope (Olympus BX51). Energy dispersive spectroscopy (EDS) chemical composition and mapping were performed with an attached IXRF system, Inc. Iridium Microanalysis System at an accelerating voltage of 20.0 kV.

3. Results and discussion

Fig. 1(a) shows a 350 μm fiber with 110 μm yttrium barium copper oxide (YBCO) core material and fused silica cladding. Furthermore, a fiber with a 200 μm bismuth strontium calcium copper oxide (BSCCO) core with a fused silica cladding and overall diameter of 650 μm can be seen in Fig. 1(b).

The basic system capability was investigated to assure the feasibility of the manufacturing approach and material systems. Elemental mapping, Fig. 2(a) and (b), shows the well-defined core and cladding regions in both YBCO and BSSCO core fibers. Although the synthesis route was relatively crude compared to the state of the art fiber optic manufacturing techniques, the limited cross-diffusion of the material components clearly demonstrates the feasibility of this approach. Fibers with more traditional dimensions of 125–300 μm have been demonstrated, but difficulties relating to sample preparation limited our characterization of larger samples. Nevertheless, the optimal fiber geometry will most certainly require further study and experimental analysis.

The basic "self-contained" and "efficient cryogenic cooling" fiber design is demonstrated in the optical micrograph in Fig. 3. We have just begun to address the challenges related to the development of these fibers and have demonstrated the feasibility of this concept with a lead core fiber in a separate manuscript due for submission. Our current research is focused on the theoretical thermal analysis of the system to determine the optimum fiber designs and operating conditions, as well as unique insulating coating and cladding materials, and packaging schemes. Furthermore, controlled cryogenic liquid delivery techniques, concepts and components are being investigated to demonstrate the practicality of deployment. In this particular YBCO core sample, there appears to be a slight amount of material interactions at the core cladding interface due to the challenges of the manufacturing process, but it is likely that this can be eliminated if necessary in future studies.

The current intricacies and complex nature of the synthesis of YBCO and BSCCO materials exhibiting superconductivity present the most significant challenges at this stage of our research. Prior work with various high temperature superconductors suggests that post-processing treatment in an oxygen environment allows for structural rearrangement and enhancement of superconductivity and an increase in the critical current density, J_c [13]. Therefore, our current studies are focused on gaining a comprehensive knowledge of material interactions during the draw down process, as well as developing an online and/or post-process annealing techniques. Once established, these fabrication schemes can be readily implemented in our process to generate superconductivity in our fibers.

Our approach represents the first step in achieving the overarching desire for superconducting wires with conventional geometries. Furthermore, the supporting methodologies, such as splicing, cable designs, etc., and infrastructures that are in place for optical fibers can also be readily adapted to superconductor core fiber designs. Superconducting optical waveguides have also been of large interest for ultrasensitive, ultra-fast and ultralow noise light detectors, but to date, have only been evaluated theoretically [14,15]. Current efforts to fiberize long fiber lengths

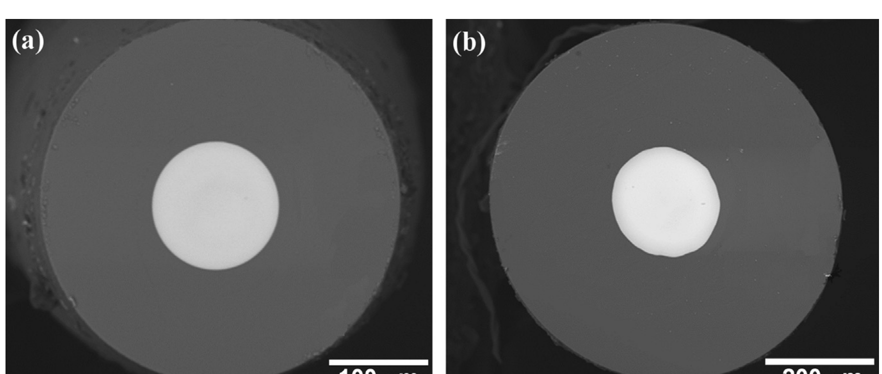

Fig. 1. Backscatter scanning electron micrographs (SEM) of optical fibers with a high temperature superconducting core and fused silica cladding. (a) 110 μm YBCO core and 350 μm fiber diameter. (b) 200 μm BSSCO and 650 μm fiber diameter.