MULTI-PURPOSE FIBER OPTIC SENSORS FOR HIGH TEMPERATURE SUPERCONDUCTOR MAGNETS*

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Abstract

Optical fibers can be imbedded within new high temperature superconductor (HTS) magnets to monitor strain and temperature, to detect quenches, and, in the case of AgX/Ag/$Bi_2Sr_2CaCu_2O_x$, (Bi2212) wire magnets, to serve as a heat treatment process monitor for wind-and-react (W&R) manufacturing. The W&R process requires that the optical fibers be installed before the Bi2212 heat treatment, one important issue is whether the fibers survive the 890 °C heat treatment so as to monitor the heat treatment and to serve subsequently as a low temperature monitor. Here, Au-coated optical fibers are attached to Bi2212 wires and processed with the typical reaction cycle. The Bi2212 superconductor is then evaluated for performance degradation due to the presence of the fiber and the fiber is evaluated for performance degradation due to the heat treatment and viability as a heat treatment process monitor. Two approaches to fiber optic sensing are used: a fiber Bragg grating and Rayleigh scattering.

INTRODUCTION

Magnets using high temperature superconductors are showing great promise for many applications, including high field magnets, magnets for high energy physics, fusion reactors, and power applications. The development and operation of HTS magnets is limited, however, because appropriate sensors and diagnostic systems are not yet available to monitor the manufacturing and operational processes that dictate success. Fiber optics can be used as sensors in HTS magnets to monitor temperature and strain and to detect a quench. In additional, for magnets in nuclear radiation, optical fibers may be viable radiation dosimeters.

During normal operation, the magnets, and thus optical fibers, will be operating at cryogenic temperatures. Their performance at these temperatures is discussed elsewhere [1]. In the experiments described below we focus on the use of these sensors for magnets based upon $Bi_2Sr_2Ca_1Cu_2O_8$ (Bi2212) wires. Superconducting Bi2212 is extremely brittle after processing, thus a sensitive wind-and-react processing method is used, where the maximum temperature reaches 890 °C in a 100% oxygen atmosphere. Figure 1 shows a typical heat treatment process for Bi2212 wire; note that for the partial melt stage, it is critical that the entire magnet reach the melt temperature, T_P, and remain there for the minimum time needed to achieve the partial melt that subsequently results in well-connected, dense, superconducting Bi2212 grains. We propose that optical fibers be imbedded within the magnet and used as heat treatment monitors to ensure the entire magnet has reached thermal equilibrium. After processing, these fibers will be used as operational sensors operating at cryogenic temperatures. Here we evaluate the survivability of the optical fibers at high temperature and determine if the presence of the fiber compromises the Bi2212 performance to examine their viability as process monitors .

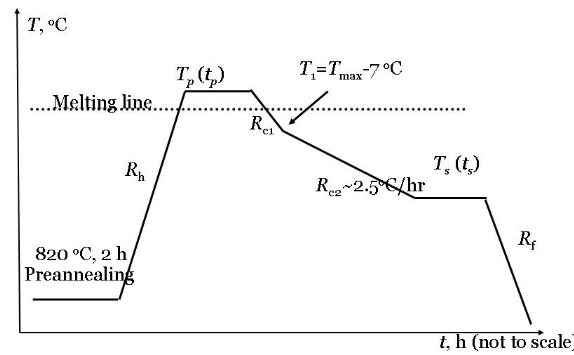

Figure 1: Typical temperature- diagram for Bi2212.

For temperature and strain monitoring, there are multiple sensing methods available; here we investigate fiber Bragg gratings (FBGs) and Rayleigh scattering. An FBG is a permanent, periodic refractive index perturbation written into an optical fiber by exposure to UV light. When a broad spectrum of light passes down the fiber and reaches a grating, all wavelengths of light will transmit, but only a certain wavelength will be reflected. The reflected wavelength is the Bragg wavelength, λ_B, where the governing equation is

$$\lambda_B = 2n\Lambda$$

where n is the index of refraction and Λ is the spacing (pitch) of the grating. If a fiber is exposed to a change in temperature or strain, the grating pitch also changes, resulting in a change in λ_B. Micron Optics [2] has developed a commercially available interrogation system which transmits light and interprets the reflected spectrum to determine λ_B at positions along the fiber where the gratings were created.

Another promising sensing method is Rayleigh backscattering, which relies on naturally occurring perturbations of the refractive index along the fiber. These perturbations are a random but static property of the fiber and occur in even the highest-quality optical fibers. If a region of a fiber is subject to a change in temperature or strain, the reflected spectrum from that region changes. Luna Innovations [3] has developed a commercially available Optical Backscatter Reflectometer (OBR) which can detect and process these changes, creating a

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distributed temperature or strain sensor. The OBR can achieve a spatial resolution as small as 2 mm, but at a cost of requiring a relatively high processing time, where the length of fiber being monitored increases the processing time proportionally. A balance between monitoring length, spatial resolution, and processing time is required for each sensing application. Improved algorithms and more computing power will reduce processing times.

In these experiments, metal-coated fibers are studied for two reasons. First, the fibers can be physically damaged by handling and the coating affords protection. Second, the fibers do not have sufficient temperature or strain response at extremely low temperature and their sensitivity is enhanced by having a more sensitive material bonded to them.

Here we describe experiments to determine the mutual compatibility of gold-coated optical fibers and Bi2212 under heat treatment, use Rayleigh OBR to evaluate fiber survivability and optical properties after heat treatment and lastly use FBGs to monitor the Bi2212 heat treatment process.

FIBER/Bi2212 COMPATIBILITY

A 25 cm segment of commercially available Au coated SMF-28 fiber was placed inside the Nextel insulating sheathing surrounding a piece of Bi2212 round wire manufactured by Oxford Superconducting Technology. The entire sample was then heat treated in pure oxygen using a TYLAN Tytan II furnace, according to the process described in Figure 1, where total heating time is approximately 90 hours and peak temperature, T_P, is 890 °C. Another piece of Bi2212 was treated in the same cycle to serve as a reference sample. After heat treatment, the critical current, I_C, was measured at 4.2 K in a background magnetic field of 5 T. This was compared to the control sample to determine performance degradation of Bi2212 due to presence of the Au coated optical fiber. Additionally, cross sections and a side view of the sample were examined under a scanning electron microscope (SEM) to look for any flaws in the fiber. Energy-dispersive X-ray spectroscopy (EDS) analysis was performed to look at the chemical composition of the fiber, Au coating, and Bi2212 wire after heat treatment.

I_C tests performed on the 25 cm co-sintered Bi2212 and fiber revealed only a 2% performance degradation, which is well within the typical scatter for Bi2212 wires. Table 1 shows the I_C values for the Bi2212 with fiber and without fiber (control) for two electric field criteria.

Table 1: I_C as a function of electric field criteria

Sample	1 μV/cm	0.1 μV/cm
Bi2212 w/ fiber	279 A	231 A
Bi2212 (control)	284 A	235 A

SEM/EDS analysis showed diffusion of Au from the fiber and Ag from the Bi2212 matrix. Figure 2 illustrates the chemical compositions of locations around the Bi2212 and fiber. It is believed that, during heat treatment, the two metals diffusion bonded, forming a Ag-Au eutectic. This is potentially a positive effect for magnet monitoring as it creates excellent thermal and strain contact between the optical fiber and the Bi2212 wire.

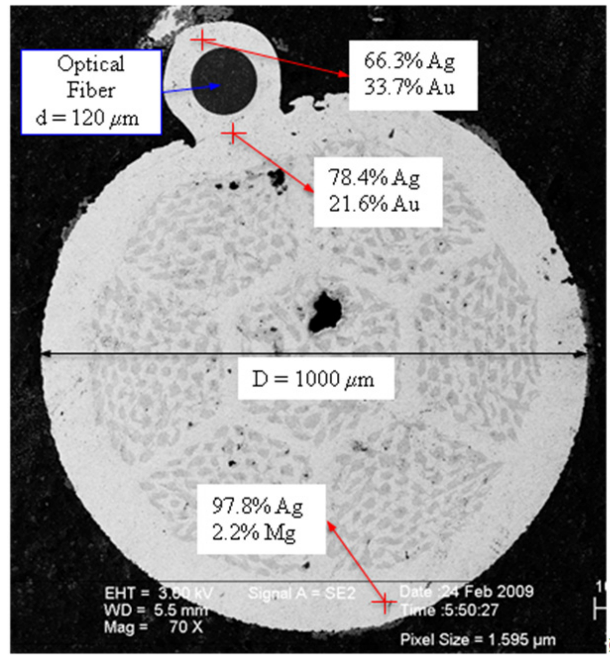

Figure 2: SEM/EDS analysis of a co-sintered, 1 mm diameter Bi2212 wire and an Au coated SMF28 optical fiber.

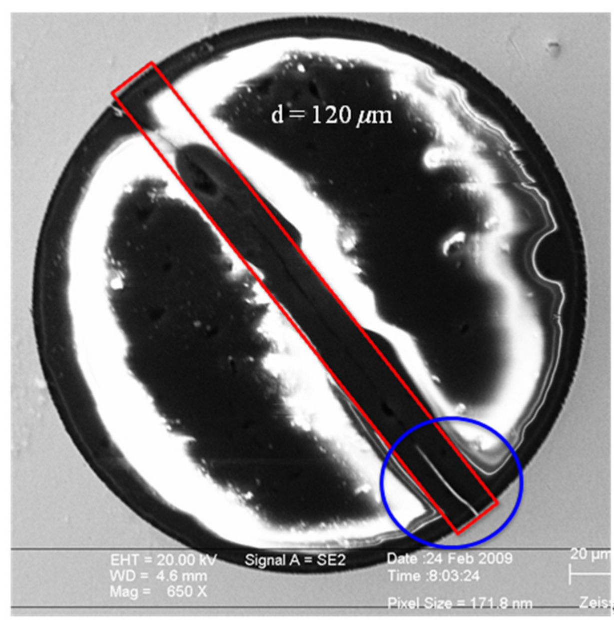

Figure 3: SEM image of an optical fiber after heat treatment. The red rectangle is added to show a crack in the fiber. The blue circle highlights diffusion of surrounding material into the crack during heat treatment

SEM analysis, seen in Figure 3, reveals that a crack in the optical fiber. It is believed that this crack occurred before or during the heat treatment due to the presence of Au/Ag in the crack. As a result of this crack, additional SEM was performed on as-received and heat-treated fibers; cracking was found in the heat-treated fibers, while no cracks were discovered in the as-received fibers. EDS analysis of the side of the Bi2212 wire found leakage of Sr from Bi2212; this is undesirable and likely degrades I_C. No reduction in I_C was found, however, so the leakage is not considered significant in this case.

RAYLEIGH OBR

Three Au-coated optical fibers were heat treated according to the Bi2212 process: one straight sample in contact with Bi2212 wire (30 cm long), and two fibers wound around a cylindrical form, with diameters of 3 cm and 9 cm, respectively. These samples were then sent to Luna Technologies for Rayleigh backscatter analysis to determine if the high heat treatment temperature, the presence of Bi2212, or the coil winding degraded the optical transmission properties of the fiber.

Testing on both the straight sample in contact with Bi2212 wire and the cylindrically wound fibers showed that light can still be transmitted/reflected and fibers can be used as sensors after heat treatment [ref Luna report]. This is a clear demonstration that optical fibers can perform as sensors in Bi2212 magnets.

FIBER BRAGG GRATING

FBGs were tested for their heat treatment process monitoring capabilities. A Micron Optics os4200 temperature FBG sensor was inserted into a furnace and the temperature was ramped from room temperature to 900 °C with a 5 °C/min ramp rate, held for 10 minutes, and then ramped back to room temperature. The heat treatment survivability was examined.

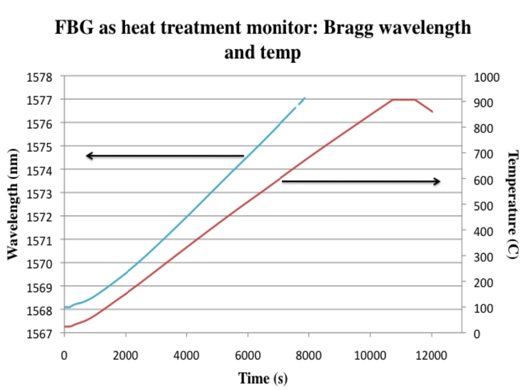

Figure 4: FBG and thermocouple data from heat treatment process monitoring test

During the heat treatment process monitoring, erasure of the grating occurs at ~665 °C. This is not unexpected as it has been reported previously [4]. Above this temperature, the fiber can no longer be used as a sensor as there is no reflective index perturbation to be measured. Figure 4 shows the fiber optic data obtained from the Micron Optics sm125 interrogator, as well as thermocouple temperature data. It is seen that the fiber optic data stops at ~665 °C, thus Type I FBGs do not survive Bi2212 heat treatment. Additionally, the optical fiber was very brittle after HT and could not be handled.

Recent developments in optical fiber technology have resulted in a new type of FBG, known as a chemical composition grating (CCG), which survives up to 1000 °C [5]. CCGs are formed by thermal processing Ge-F-doped fibers with traditional FBGs; between 500 - 800 °C the traditional FBGs are erased; at ~1000 °C, new CCGs form in their place, with the same Bragg wavelength and optical properties. Future work on FBG sensors for Bi2212 magnets will evaluate CCGs.

SUMMARY AND FUTURE WORK

It was shown that Bi2212 performance was not degraded due to the presence of Au-coated optical fiber. Although cracks were found in the heat treated fibers, which may have been pre-existing or a result of the heat treatment, optical testing showed that the fibers still transmit and reflect light. Thus, the fibers survive the heat treatment and Rayleigh scattering is a viable option for fiber optic sensing of Bi2212 magnets. FBGs did not survive Bi2212 heat treatment, but CCGs may provide an effective solution.

Future work includes performing more SEM analysis on heat treated fibers to look for cracks and examining Bi2212/Au coated fiber interaction. Furthermore, additional fiber coating material options need to be explored. CCGs will be tested for their sensitivity and viability as heat treatment process monitors. It is also anticipated advanced Rayleigh scattering algorithms will allow for faster processing times without losing resolution or monitoring length.

REFERENCES

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