Improvement of Sensitivity to Temperature of Optical Fiber Sensor at Cryogenic Temperature

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Monitoring the temperature inside superconducting magnets is an effective way to detect failures and prevent damage to the magnet. It is possible to measure the multipoint temperatures with one optical fiber sensor thread. The sensor is suitable for measuring the temperature inside cryogenic equipment because of its low heat invasion and high voltage insulation in comparison with the resistance temperature sensors such as CERNOX, thermocouples, etc. However, there have been almost no cases where the optical fiber sensors have actually been used at cryogenic temperature. Investigations where therefore carried out into optical fiber temperature sensors that can be used at cryogenic temperature, to monitor the temperature inside superconducting magnets.

Keywords: optical fiber sensor, cryogenic equipment, measuring temperature, superconducting magnet

1. Introduction

Maglev [1-4], magnetic bearings [5-7], motors [8-10] etc. using superconducting magnets are being developed for practical application by many research groups throughout the world. The superconducting magnet is a very important component in these devices. If the magnetic function fails, the whole system will be affected.

Therefore, in order to prevent failure, it is necessary to detect failures inside the equipment at an early stage. This requires multipoint measurement.

When using conventional resistance temperature sensors however, such as thermocouples, CERNOX or platinum sensors, multiple sensors and measurement lines are needed for multipoint measurement. This in turn can cause heat invasion in the superconducting magnet making it impossible to keep the magnet in a cooled state.

When using an optical fiber temperature sensor, however, it is possible to measure multipoint temperatures with a single sensor, as shown in Fig 1.

Although optical fiber temperature sensors for use at room temperature are already available on the market, the purpose of this study is to develop a sensor for use at cryogenic temperatures below 50K (-223 °C).

There are two types of optical fiber temperature sensors, a distribution measuring type [11-12] and a multipoint measuring type [13].

In a past study, “the FBG (fiber bragg grating) type” multipoints measuring type sensor was adopted for experimentation. Temperature measuring tests were performed by cooling a room to about 10K, producing a satisfactory level of reproducibility. Trials revealed however that the sensitivity of wavelength shift to temperature fell at temperatures below 50K, although it was possible to restore sensitivity by applying coating [14-15].

Further trials were conducted to discover ways to enhance sensitivity by improving the optical fiber coating material and method and to test the sensor’s ability to measure the temperature of the superconducting magnet. The results of these trials are reported in this paper.

2. Enhancing sensitivity by improving the optical fiber coating material and method

2.1 Selection of the coating material

Past proposals to bond the stainless steel tube to the FBG sensor [16], included coating the FBG component with a metal such as aluminum, copper, lead or indium [17-18], inter alia. The highest sensitivity was obtained with a sensor coated with both aluminum and indium. These studies however did not attempt to predict the change in FBG wavelength shift due to modification of the coating material properties.

This study therefore undertook to predict wavelength shift based on the thermal expansion coefficient and Young’s modulus of the materials, and to examine a method to improve sensor sensitivity to temperature at cryogenic temperatures. Results confirmed that the thermal expansion coefficient of the coating material influences sensitivity and that the rate of heat conduction influences the stability of the output.

Various materials have to date been tested as a coating material, enabling the collection of their characteristics. The sensitivity of acrylic resin-coated optical fiber was about 6.4 times higher than optical fiber without coating. Nevertheless, temperature differences between the object of the measurement and the FBG component, and mea-
measurements were unstable, due to low thermal conductivity of the acrylic resin.

The acrylic resin was coated with metal to improve thermal conductivity. Nickel and copper were tried, since they have high thermal conductivity. Tests showed stabilized measurements but the metals had a low thermal contraction rate which interfered with the thermal contraction of the acrylic resin, which in turn meant that sensitivity did not improve with either nickel or copper.

When employing an optical fiber as a thermal sensor, measurement stability is a prerequisite. Consequently another metal with high thermal conductivity was selected as a coating material and tested.

In each case where the optical fiber was coated with nickel, silver, sensitivity did not improve. With copper however, sensitivity improved about 1.8 times compared to optical fiber without coating [14-15].

In this paper, zinc was selected as the coating material, because of its superior thermal expansion properties compared to copper, and because the coating process is simple.

2.2 Selection of the coating method

There are two methods for applying zinc coating: sputtering and electroplating. Two samples were prepared using each method. These samples were then tested and compared to determine their influence sensitivity.

The sputtering method applies zinc which then adheres directly to the optical fiber.

Three kinds of metal were used in the electroplating method. After sputtering titanium first to enhance zinc adhesion to the optical fiber, copper was then used as a pole in the plating process. Finally, the optical fiber was electroplated with zinc.

2.3 Experimental methods

Two optical fiber sensors each treated with one of the above measures were placed on a cooling plate in the cryogenic equipment. Resistance temperature sensors were also placed on the same plate for comparison.

A vacuum was formed inside the cryogenic equipment, then it was cooled with a cryocooler from room temperature down to about 10 K. The cryocooler was then stopped and the equipment was left to return to room temperature naturally.

While the equipment returned to room temperature after cooling, the temperature and wavelength from the coated FBG component were measured.

2.4 Results of the experiments

Figure 2 and 3 show the experimental results.

The sensitivity to temperature of the optical fiber coated by sputtering fell in comparison to non-coated optical fiber.

The sensitivity to temperature of the electroplated optical fiber increased by about 3 times compared to non-coated optical fiber, and the FBG wavelength shift remained stable with the changes in temperature.

2.5 Analyses and discussions

The results obtained in the experiment and observations, lead to the following considerations:

2.5.1 Optical fiber sensor made using the sputtering method

Touching the sputtered surface after coating left traces of powdered zinc on the fingers.

It is thought that this is due to the surface of the zinc being rough and porous, and thus easily detached. Consequently interfacial peeling occurred during the cooling and causing the coating to lose its effectiveness. The worsening of sensitivity of the coated fiber compared to non-coated fiber is thought to be due to the interfacial peeling, which meant that the coating inhibited the thermal contraction of the FGB component.

2.5.2 Electroplated optical fiber sensors

It is thought that zinc adherence to the optical fiber, thereby fixing it in place, can be achieved by sputtering.
titanium as a foundation. Furthermore, it is deemed that sensitivity improved because the coating layer thickness could be made thicker through electroplating than with the sputtering method.

Zinc has high thermal expansion, and copper has high thermal conductivity. It was thus assumed that coating the optical fiber with layers of these metals could stabilize output and sensitivity.

3. Thermometry in the thermal simulator

The optical fiber sensor studied in this report is intended to be used in the thermometry of the superconducting magnet.

Past studies reported that the fiber is able to measure the temperature of the superconducting magnet from when electricity is supplied until the temperature of the superconducting magnet rises, and also when the fiber receives the same vibration as that received by the running magnetic levitation vehicle.

This report confirmed the ability of the optical fiber sensor to measure the temperature of the conduction cooling superconducting magnet. A thermal simulator was used which has a conduction cooling coil made with stainless steel and which can imitate the distribution of temperature in the cryostat. Experiments were performed to test the performance of the electroplated optical fiber sensor.

Experiments were then conducted to test the performance of a Brillouin scattering type optical fiber sensor and a Rayleigh scattering type sensor which were the subject of a previous study.

3.1 Experimental methods

Figure 4 shows the temperature measuring points of the optical fiber temperature sensor in the thermal simulator. The figure illustrates the installed the electroplated optical fiber sensors, Brillouin scattering type sensors, Rayleigh scattering type sensors and a CERNOX thermometer to measure the temperature of the imitation coil surface (about 1210 mm in width and about 610 mm in height) and the refrigeration machine cold head. This set of sensors were then cooled in a refrigerator and the temperature was measured.

3.2 Results of the experiments

Figures 5, 6 and 7 show the experimental results. These figures show the relationship between the temperature and the wavelength shift or frequency shift of the optical fiber at the coil surface measuring point (Cx6 in Fig.4), in the cooling process from about 290K to about 60K.

![Graph showing temperature and wavelength shift](image1)

Fig. 5 Temperature and wavelength shift at the coil surface measuring point (the electroplating method type optical fiber sensor)

![Graph showing temperature and frequency shift](image2)

Fig. 6 Temperature and frequency shift at the coil surface measuring point (the Brillouin scattering type optical fiber sensor)

![Graph showing temperature and frequency shift](image3)

Fig. 7 Temperature and frequency shift at the coil surface measuring point (the Rayleigh scattering type optical fiber sensor)
3.3 Analyses and discussions

It was confirmed that each type of optical fiber sensor, namely the electroplated type, Brillouin scattering type and Rayleigh scattering type, was able to measure the temperature of the conduction cooling coil surface without any problems, in the range from about 290K to about 60K.

4. Conclusions

The zinc coated surface obtained through sputtering is rough and porous and is easily removed. When interfacial peeling occurs, the coating inhibits the thermal contraction of the FGB component and reduces sensitivity.

When the zinc coating is applied through an electroplating process, after sputtering a titanium foundation prior to the zinc plate, the zinc then adheres better to the optical fiber and prevents its removal. Sensitivity is then improved because the coating layer can be made thicker than in the sputtering method. Zinc has high thermal expansion, while copper has high thermal conductivity. By coating the optical fiber with these metals in layered form, output can be stabilized and sensitivity improved by about 3 times.

Confirmation was also obtained that electroplated, Brillouin scattering type, and Rayleigh scattering type optical fibers, are able to measure the temperature of the conduction cooling coil in the thermal simulator. It was confirmed that each type of optical fiber sensors is able to measure the temperature of the conduction cooling coil surface without any problems, in the range from about 290K to about 60K.

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