Development of Strain Measurement in Superconducting Magnet Through Fiber Bragg Grating

Hongjie Zhang, Fanping Deng, Qiuliang Wang, Luguang Yan, Yingming Dai, and Keeman Kim

***Abstract*—Temperature and strain responses of fiber Bragg grating sensors were measured in cryogenic environment. With temperature from room temperature down to 77 K or 4.2 K, the temperature response was found to be relatively linear above 100 K, and the temperature sensitivity decreases with the decrease of temperature, and to approximately zero for temperature less than 50 K. Technologies were developed to eliminate the multi-peaks in strain experiment, so the strain response was measured at 77 K, and was found to be linear at constant temperatures.**

***Index Terms*—Cryogenic temperature, fiber Bragg grating sensors, strain response, temperature response.**

I. Introduction

THE design and development of large superconducting magnets is strongly influenced by the strain and the temperature which they experience during operation. High field superconducting magnets usually work in extreme circumstances such as low temperature, strong electromagnetic fields. Standard sensors with electrical connections like resistance thermometers and strain gauges can not work well inside the magnets. Fiber Bragg Grating (FBG) sensors are immune from electromagnetic interference, and with light weight, small size and low power consumption, and then they will have potential applications to temperature and strain monitoring of superconducting devices. The applications of FBG sensors in various fields are expected such as health monitoring of cryogenic spacecraft tank structures [1]–[4], temperature and stress measuring in superconducting coils [5], and microscopic damage detecting of composite materials [6].

So it is necessary to study the character of FBG sensors at cryogenic temperature. By far, we have designed and set up a calibration system employing fiber Bragg gratings, and measured their temperature response over the temperature range from 298 K down to 4.2 K, and strain response at 77 K.

The Bragg reflection wavelength λ_B of an FBG is given as

$$\lambda_B = 2n\Lambda, \tag{1}$$

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where n is the refractive index of the core, and Λ is the grating period. With the variation of temperature and strain, both n and Λ change.

The Bragg wavelength shifts $\Delta\lambda_\varepsilon$ and $\Delta\lambda_T$ of an FBG, in response to a strain change $\Delta\varepsilon$, and a temperature change ΔT, are given as

$$\begin{aligned} \Delta\lambda_\varepsilon &= K_\varepsilon \Delta\varepsilon \\ \Delta\lambda_T &= K_T \Delta T, \end{aligned} \tag{2}$$

where K_ε and K_T are the strain and the temperature sensitivity respectively. K_ε is determined by the Poisson ratio of the fiber, the photoelastic coefficient and the effective refractive index of the fiber core, and K_T by the thermal expansion coefficient and the thermo-optic coefficient.

As the temperature experiment was performed, the FBG sensors were placed freely experiencing only thermal effect, so the thermally induced wavelength shifts can be obtained, and the wavelength shifts induced by strain can also be investigated at each constant temperature.

II. Experiment

The experiments include two parts: temperature measurement and strain measurement.

A. Temperature Effect Measurement

To characterize the thermal behavior of FBG sensors, the experimental setup was designed and built as shown in Fig. 1. An acrylate coating FBG sensor with the wavelength of 1530 nm and a bare FBG sensor with the wavelength of 1560 nm were selected. To verify the cryostat temperature, a Rhodium-iron (Rh/Fe) resistive thermometer was also used. A Cu-sheet was used to balance the environment temperature.

The experiment at liquid nitrogen temperature (77 K) was carried out at first. On the basis of it, the temperature experiment in liquid helium environment (4.2 K) was conducted subsequently. When the temperature response from 286 K to 77 K was tested, the liquid nitrogen was used as cooling media for controlling the temperature. With the evaporation of the liquid nitrogen, the temperature of the cryostat increased 2 K per minute, allowing enough time for temperature equilibrium between the FBG and the resistive thermometer. Liquid helium was used to control the temperature during the measurement from 298 K to 4.2 K. The evaporation of the liquid helium in the dewar was very slow, the temperature increased slowly also. The temperature of the cryostat was monitored by resistive thermometer and the reflection

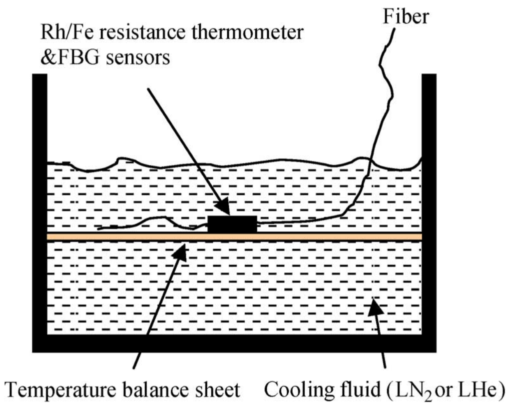

Fig. 1. Cryogenic system for temperature response measurement.

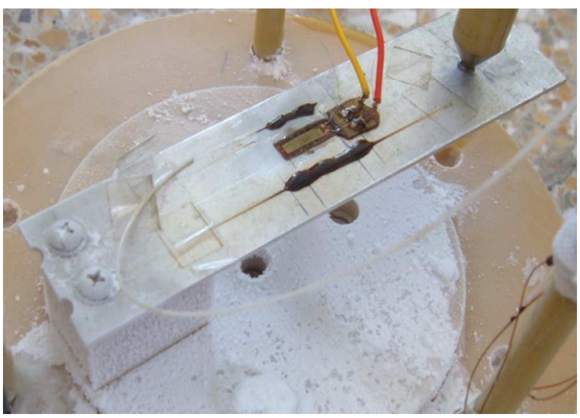

Fig. 2. Experimental system for strain measurement.

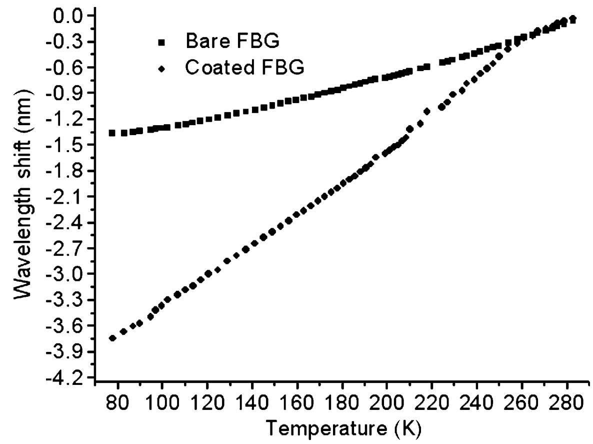

Fig. 3. Temperature response of FBG sensors from 286 K to 77 K.

TABLE I
TEMPERATURE SENSITIVITIES OF FBG AT DIFFERENT TEMPERATURES

Temperature (K)	Temperature sensitivities of coated FBG (nm/K)	Temperature sensitivities of bare FBG (nm/K)
286~210	0.02157	0.00825
210~200	0.01991	0.00684
200~100	0.01593	0.00482
100~80	0.01526	0.00449

spectra of the FBG sensors were observed by FBGSLI demodulator made by Micron Optics Corporation.

B. Strain Measurement

The experimental setup for strain measurement in cryogenic environment is shown in Fig. 2. Two acrylate coating FBG sensors with the wavelength of 1540 nm and 1555 nm were selected. The FBG sensors and the resistive foil strain gauge (RFSG) were bonded on an aluminum cantilever as closely as possible, so that they can sense the same strain. Tensile load was applied to the cantilever about 75 μm/m in steps to a maximum of 600 μm/m. Tensile strain was measured by RFSG bonded on the surface of the cantilever, and the reflection spectra of the FBG sensors were measured using FBGSLI demodulator. Comparing the strain of RFSG and the wavelength shifts of the FBG sensors, the strain response of the FBG sensors can be obtained.

During the experiment, it was found that the single central peak in the reflection spectrum of the FBG sensor was split. This makes the determination of the wavelength more difficult. This problem was attributed to the structural transition of germanium induced defect [7]. We studied this phenomenon from the viewpoint of mechanics, and found that the different thermal expansions between the FBG, substrate and adhesive bring inhomogeneous thermoelastic strain at the ends of FBG sensors. Two technologies were developed to eliminate the multi-peaks of strain response. One of them was that a bare FBG with the grating of 10 mm was used, and the length of the adhesive plastered to it was elongated twice to 20 mm, so that the whole grating could sense homogeneous strain, a better single peak was acquired in cryogenic environment. The other was that a coated FBG with a longer grating of 15 mm was used and was plastered normally. The coating material is soft, and the thermoelastic strain can be decreased and the uniformity can be improved. The pleasant results can be obtained as well.

III. RESULTS

The measured FBG wavelength shift as a function of temperature from 286 K to 77 K is shown in Fig. 3. The curves with solid squares and solid circles represent the results of the bare FBG and the acrylate coating FBG respectively. It is clear that the thermally-induced wavelength shifts of both FBG are relatively linear from 286 K to 100 K. As temperature decreases, the wavelength shift depends nonlinearly on temperature. The temperature sensitivities (K_T) of two FBG sensors for the temperature range from 286 K to 80 K are calculated and listed in Table I, The temperature sensitivity from 286 K to 210 K for the bare FBG is 8.25 pm/K [8], this agrees with earlier result [9]. That of the acrylate coating one is 2.157×10^1 pm/K which is much higher than that of the bare. The coated FBG sensor shows higher temperature sensitivity, if the effect of the thermal expansion is large enough, the temperature sensitivity of the FBG sensor should be proportional to the thermal expansion coefficient [10], so the coating materials with high thermal expansion coefficient can be used to improve the sensor sensitivity at low temperatures.

Fig. 4 shows the temperature response from 298 K down to 4.2 K. The curve with solid squares represents the result of the bare FBG, the one with solid circles represents that of the coated

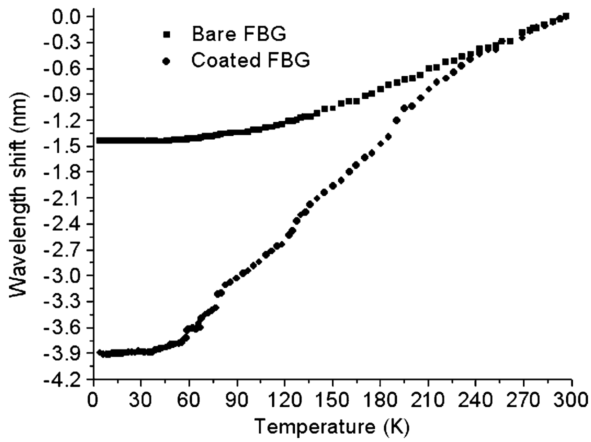

Fig. 4. Temperature response of FBG sensors from 298 K to 4.2 K.

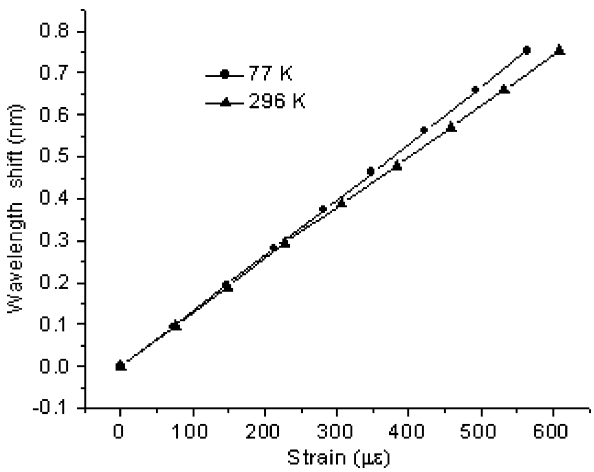

Fig. 5. Wavelength shift versus strain of 1540 nm-FBG at 296 K and 77 K.

FBG. It is found that the temperature responses of the FBG sensors are approximately linear above 100 K, it agrees well with Fig. 3 during corresponding temperature range. The temperature sensitivity decreases with the decrease of temperature, because the thermal expansion coefficients of many materials decrease. The wavelengths of FBG sensors do not change approximately below 50 K. If the FBG sensors are expected to be used below liquid nitrogen as temperature sensor, the substrate with a large thermal expansion coefficient is effective [10].

The strain response of the FBG sensors was investigated at liquid nitrogen (77 K) and ambient temperatures respectively. The wavelength shifts of FBG sensors with different wavelengths versus strain are shown in Figs. 5 and 6. The wavelength shift shows good linearity with the strain at constant temperature. Linear fits are made corresponding to equation,

$$\Delta\lambda_{\varepsilon} = A + B \cdot \Delta\varepsilon. \quad (3)$$

The exact parameters of the linear fits are calculated and listed in Table II. It is found that the strain sensitivity is not equal at different temperatures. The relative error of it is within 8.1%, and the strain sensitivity at 77 K is higher than that at 296 K. The sensitivities at other cryogenic temperatures will be tested in our next work to confirm the result. But, the FBG sensor is

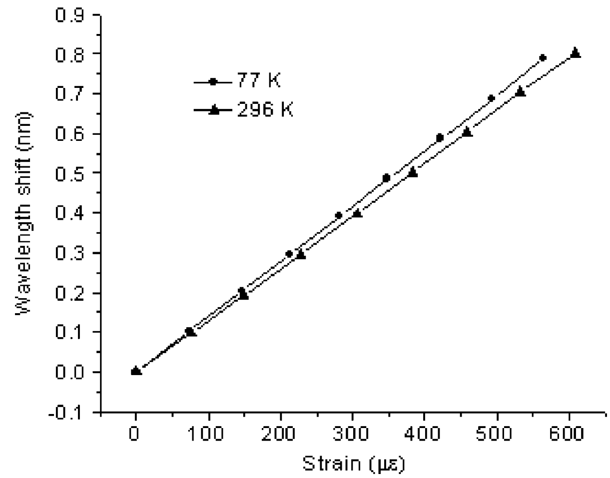

Fig. 6. Wavelength shift versus strain of 1555 nm-FBG at 296 K and 77 K.

TABLE II
LINEAR FIT OF THE FBG STRAIN RESPONSE

	1540nm FBG		1555nm FBG	
	296K	77K	296K	77K
A (nm)	0.00529	-0.00127	-0.0312	-6.276E-4
B (nm / (μm/m))	0.00123	0.00133	0.00132	0.00139
Fit standard error	0.00416	0.00113	0.00251	0.00112

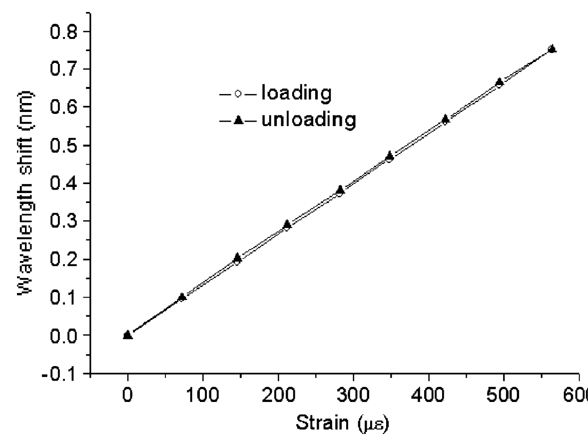

Fig. 7. Wavelength shift versus loading and unloading strain of 1540 nm-FBG at 77 K.

a precise strain sensor in cryogenic applications for its linear strain response at constant temperature. i&

Additionally, the loading and unloading strain experiments were carried out at 77 K. There is no significant deviation in the experiment results, as seen in Fig. 7, showing stable strain sensitivity of FBG sensor at cryogenic temperature.

IV. Conclusion

Temperature and strain responses of fiber Bragg grating sensors were measured at cryogenic temperatures. Temperature measurements were completed over the range from room temperature down to 77 K and to 4.2 K respectively. It was found that the temperature response is relatively linear above 100 K. Temperature sensitivity decreases with the decreasing temperature, to approximately zero for temperature less than 50 K. A substrate with a large thermal expansion coefficient can enhance the temperature sensitivity, so the thermal applications of FBG sensors can be extended in cryogenic environment. Technologies were developed to eliminate the multi-peaks of strain response, as a result, the strain response at 77 K was also obtained. It shows good linearity at constant temperatures. The experimental results can be used to monitor the health of high field superconducting magnets. It proves that the FBG sensor is a precise strain sensor for cryogenic applications.

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