

Performance evaluation of metal-coated fiber Bragg grating sensors for sensing cryogenic temperature

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Abstract

A metal recoated fiber Bragg grating sensor has been designed, fabricated and tested to study its temperature response at cryogenic temperature around 15 K. Metals like aluminium (Al), copper (Cu), lead (Pb) and indium (In) are considered for recoating the FBG sensors. Indium recoated FBG (IRCFBG) sensors showed a higher sensitivity at around 15 K compared to Al, Cu and Pb coated FBG sensors. In addition, the IRCFBG sensor was tested for its repeatability, stability and performance in the high magnetic field (8 T). The experimental results of the IRCFBG sensor test revealed a satisfactory performance. They will be reported in this paper.
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1. Introduction

The ability to provide real-time information for superconducting (SC) magnets is an important diagnostic process for the effective design, construction and protection of the SC magnets. There are many parameters like current density, magnetic flux, critical temperature, stress which are involved in an optimised SC magnet design. Knowledge of the temperature and stress distribution inside the SC magnets could help the magnet designer to identify the exact location of the hotspot generated and the direction of its propagation. Based on this information, the magnet designer can improve the design by modifying the material, routing the cooling channel in the required place and so on. Electrical strain gauge (ESG), diodes and many other conventional electro-mechanical sensor systems are consid-

ered. Unfortunately, these sensors are susceptible to the electromagnetic interference (EMI). In addition, the number of sensors required for long SC cables will have to be increased in order to determine the signal distribution. Also, the risk involved in introducing electrical wires inside the SC magnets makes them unsuitable candidate for the needed measurement system.

Use of FBG sensors is very appealing for sensing low temperature and stress in superconducting magnets because of their miniature size and the possibility of accommodating many sensors in single fiber. The main drawback is their low intrinsic thermal sensitivity at low temperatures. This low intrinsic thermal sensitivity is due to the silica's negative thermal expansion coefficient around ~ 120 K. In fact, the intrinsic temperature sensitivity of FBG sensors is proportional to the thermal expansion coefficient of the optical fiber constitutive material – silica, which reduces as the temperature decreases. Approaching cryogenic temperatures, temperature changes lower than a few degrees Kelvin cannot be resolved, since they do not cause an appreciable shift of the wavelength diffracted by a bare FBG sensor.

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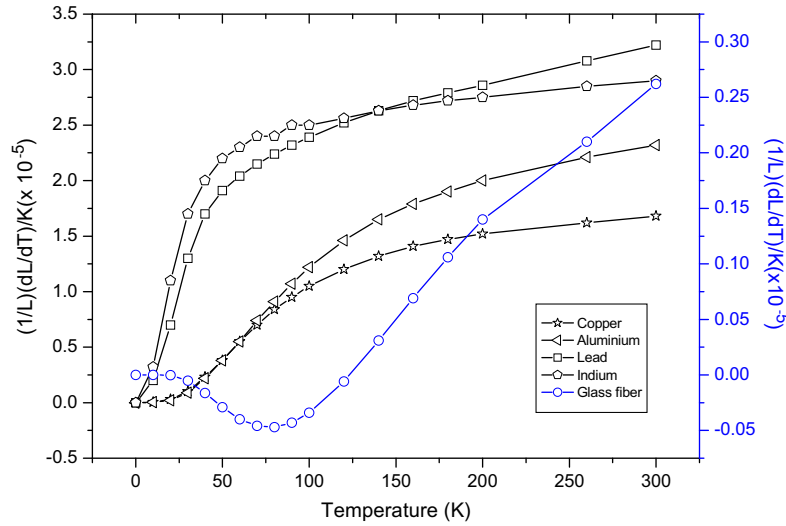


Fig. 1. Thermal expansion coefficient of materials [6].

It has been proposed in [1–4] to attach the bare FBG sensor to different blocks of Teflon, PMMA (poly methyl methane acrylate), and ORMOCER materials to increase the sensitivity at low temperature. But the polymer-recoated FBG sensors are not sensitive enough below 77 K and the sensors were found to exhibit non-repeatability [5].

This paper will focus on the use of metals for recoating the FBG sensors. Fig. 1 shows the thermal expansion coefficient (TCE) of aluminium, copper, lead and indium. These materials are found to have high TCE at cryogenic temperature [6]. This is why they were considered for recoating the FBG sensor.

2. Theoretical background

The Bragg reflection wavelength λ_B of an FBG is given as [7]

$$\lambda_B = 2\Lambda n_{\text{eff}} \quad (1)$$

where the Bragg grating wavelength, λ_B , is the free space center wavelength of the input light which will be reflected by the Bragg grating, n_{eff} is the effective refractive index of the fiber core at the free space center wavelength, and Λ is the grating spacing.

The FBG is sensitive to strain due to linear expansion affecting the grating period and change in refractive index that results from the photo-elastic effect. Similarly, it is also sensitive to temperature due to thermal expansion and the thermo-optic effect of the fiber material. By monitoring the shift in the Bragg wavelength which is characterized by Eq. (2), the temperature and strain can be measured simultaneously [7].

$$\Delta\lambda_B = 2n\Lambda(1 - (n^2/2)[P_{12} - v(P_{11} + P_{12})]\epsilon + [\alpha + (dn/dT)/n]\Delta T) \quad (2)$$

where P_{ij} is Pockel coefficient, α is thermal expansion coefficient, v is Poisson ratio, ϵ is strain, and T is temperature.

3. Sensor design and fabrication

Metals like indium and lead cannot be applied directly to glass fiber which is an insulating material. An intermediate coating layer of aluminium (primary coating layer) is deposited first and then the metal coating (secondary coating layer) can be done. To fabricate the grating elements in the bare fiber, the polymeric coating of the fiber is removed first by a chemical etching process. Then, the fiber surface is cleaned and dried. Finally the grating elements are inscribed into the single mode fiber using the phase mask technique [7]. Fig. 2 shows the dual-layer coated FBG sen-

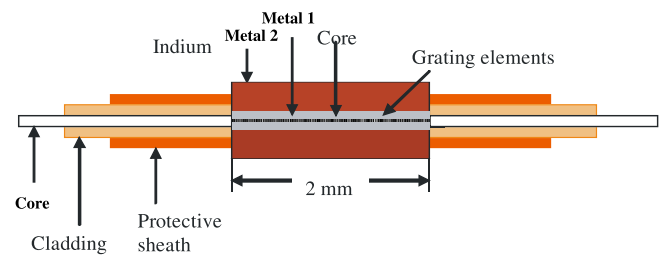


Fig. 2. Dual layer metal coated FBG sensor (DMCFBG).

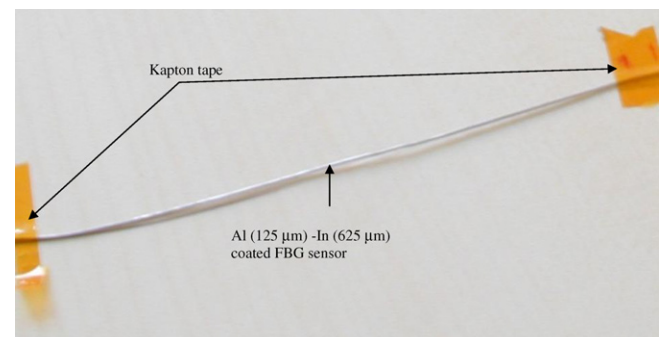


Fig. 3. IRCFBG sensor.

sors (DMCFBG). Coating thickness of the primary layer may be $125\ \mu\text{m}$ and the secondary layer may be $625\ \mu\text{m}$ thick. The bragg wavelength and the grating length can be $1535\ \text{nm}$ and $2\ \text{mm}$, respectively [9].

3.1. Coating technologies [10]

The FBG sensor is recoated by aluminium primary layer and metal secondary layer. Many technologies like dipping,

casting, physical vapour deposition (PVD), and chemical vapour deposition (CVD) are available for the metal coating of a bare fiber.

Selection of an appropriate method is influenced by the parameters such as process temperature and the thickness of the coating material. The thickness of the coating material should be determined, as it plays a vital role in imparting thermal stress which in turn affects the sensitivity of the DMCFBG sensors. It would be good to have a thin coating

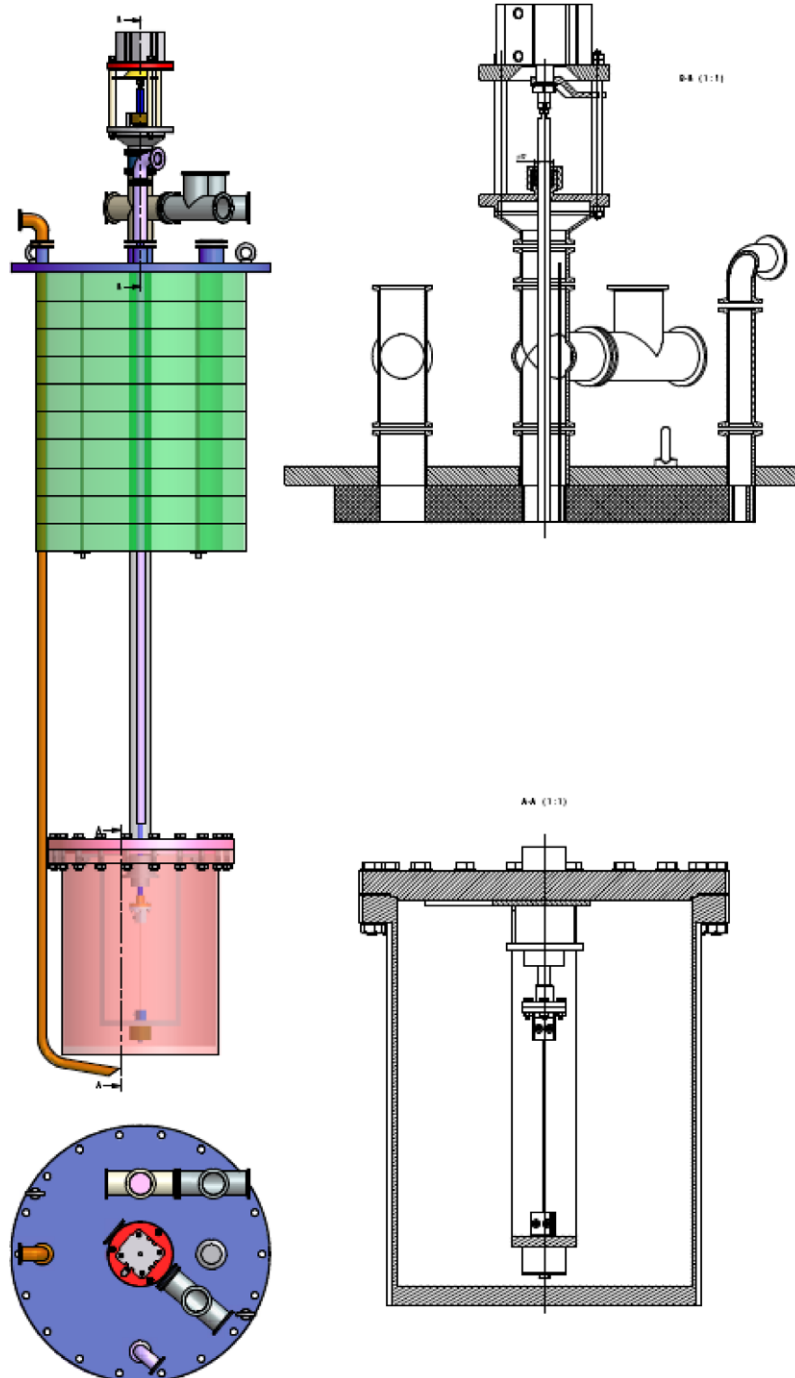


Fig. 4. Design of the testing facility.

to reduce the thermal inertia. But the coating thickness should also be high enough in order to effectively transfer the metal strain to the core of the optical fiber. The process temperature should be lower than the melting point of the bare fiber as an increased process temperature may damage the sensing elements in DMCFBG. The dipping process cannot be used, as the sensor requires uniform coating throughout the sensing element. Dipping process does not guarantee a uniform coating thickness and the formation of bubbles in the coating layer during the process will also affect the sensor operation. Casting gives higher thermal stresses but allows for a virtually limitless amount of material to be deposited as a coating. Furthermore, casting cannot be used with metal having a melting point higher than about 700 °C, as this would cause the destruction of the FBG. PVD also produces appreciable thermal stresses. Consequently, electro-deposition is the best suited technique for depositing the metal onto the fiber, as it can be performed at room temperature, thus avoiding thermal stresses, and it allows for the deposition of a large quantity of metals [8]. Aluminum can be used as the intermediate layer. It may be applied easily to the glass fiber by using Al vaporization technique. This aluminum layer will act like a conductive layer for the electro-deposition of the desired metals. Fig. 3 shows the fabricated dual layer aluminium–indium coated FBG sensor.

4. Experimental setup

4.1. Low temperature measurement

Fig. 4 shows a testing facility which was built to measure the temperature and strain response of the DMCFBG sensors at low temperature of around 15 K. This paper deals only with the temperature characteristic of the DMCFBG sensors and hence care has been taken to ensure that the DMCFBG sensor is mechanical strain free.

The testing facility consists of an upper pneumatic control part and the lower test chamber. The pneumatic controller from FESTO GmbH placed at the top of the setup is connected to the lower test chamber by a connecting rod. The test chamber is then inserted into the cryostat which can be cooled down to 77 K using liquid nitrogen supply and to 4.2 K using liquid helium. The FBG sensor for temperature measurement is left to hang freely inside the chamber to avoid any stress effect other than temperature. When it is planned to measure the strain characteristics of DMCFBG sensor, then the sensor may be attached with the copper beryllium wire that is connected to a FESTO pneumatic controller through the connecting rod. The calibrated TVO temperature sensor and extensometer strain sensors are used as reference sensors. The DMCFBG sensor is connected to the 1550 nm center wavelength ELED light source and the reflected Bragg wavelength is measured by an optical spectrum analyzer. Fig. 5 shows the complete experimental setup.

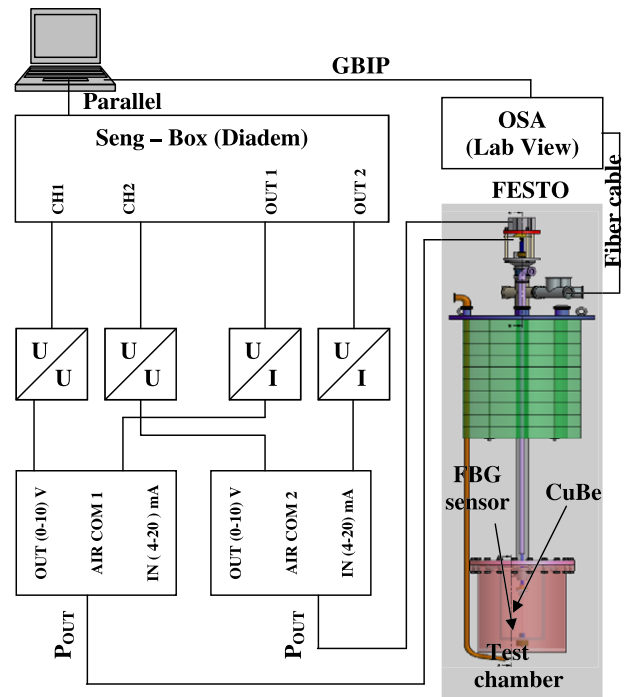


Fig. 5. Experimental setup.

4.2. FBG response in magnetic field

Fig. 6 shows the experimental setup for testing the performance of the DMCFBG sensor in a high magnetic field. The magnet inside the cryostat is made of NbTi material. The magnet is cooled down to 4 K using liquid nitrogen and liquid helium. By applying 12.4 mA current, the magnetic field of 1 T was generated inside the cryostat. The magnetic field can be varied up to 8 T by varying the applied current up to 99.4 mA. The DMCFBG sensor sample is introduced in to the cryostat. A TVO temperature sensor and a Hall Effect sensor are used as reference sen-

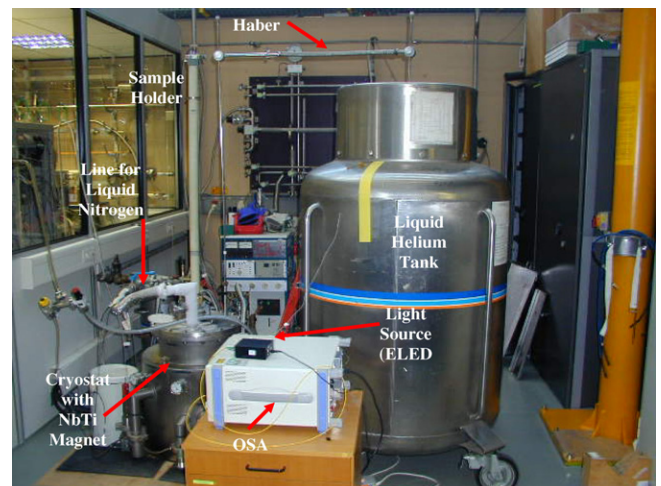


Fig. 6. Experimental setup for the testing IRCFBG sensor response at varying magnetic fields.

sors to measure the temperature and magnetic field respectively. The magnetic field is varied from 1 to 8 T by controlling the current density (J_c) and the sensor response is recorded.

5. Results and discussion

The fiber Bragg grating sensors were coated with different metals like Al, Cu, Pb, and In. The metal-recoated sensors were then installed in the testing facility and the cryostat was cooled down to 4 K from room temperature. Fig. 7 shows the characteristics of the metal-recoated FBG sensors. The total wavelength shift of the aluminium-recoated FBG (ARCFBG) sensor was found to be 6.28 nm, copper-recoated FBG (CRCFBG) sensor reached 7.08 nm, lead-recoated FBG (LRCFBG) sensor 9.41 nm and indium-recoated FBG (IRCFBG) sensor 10.06 nm.

Fig. 8 shows the calculated sensitivities of the ARCFBG, CRCFBG, LRCFBG, and IRCFBG sensors. It is clear from this figure that the IRCFBG sensor reaches a

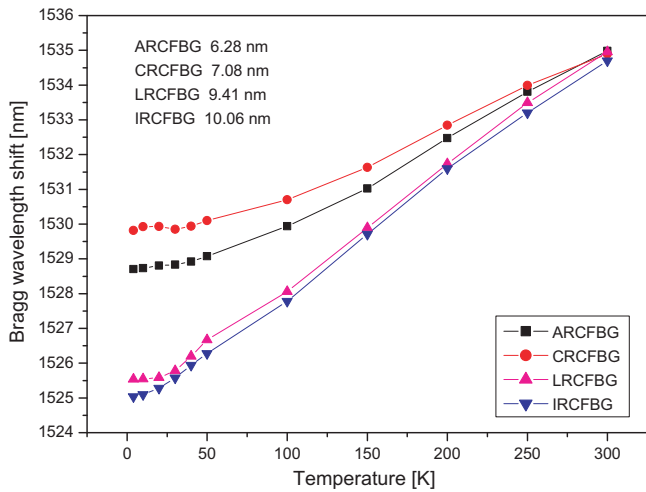


Fig. 7. Temperature characteristics of metal-coated FBG sensors.

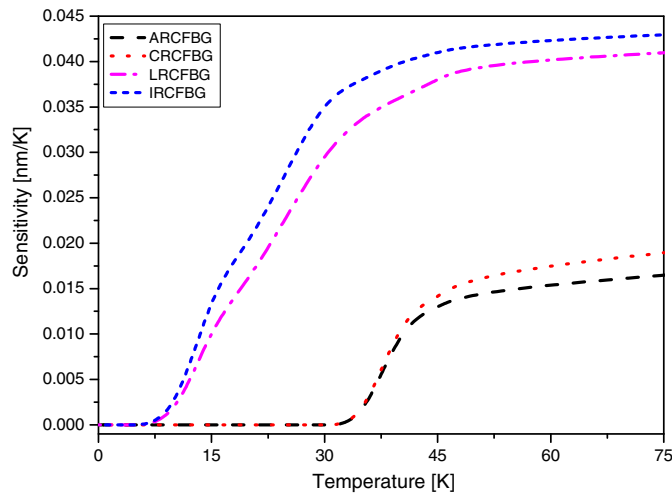


Fig. 8. Sensitivity of different metal-coated FBG sensors.

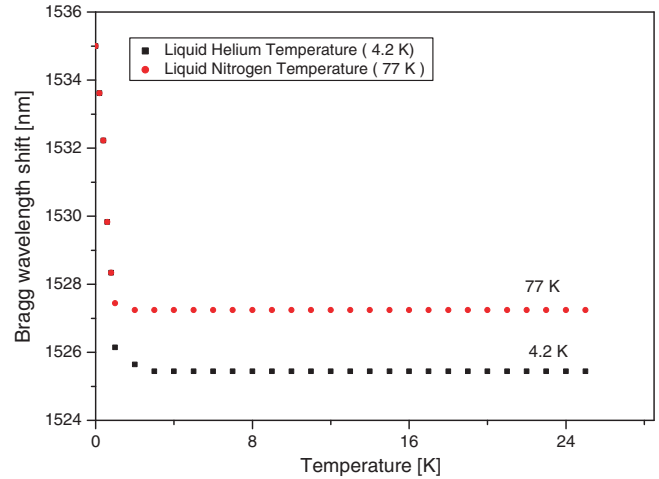


Fig. 9. Stability test of the IRCFBG sensor.

higher sensitivity at lower temperature of about 15 pm shift/Kelvin at 15 K. The IRCFBG sensor was subjected to the further stability and repeatability test. The IRCFBG sensor was dipped into the liquid helium for 24 h. Fig. 9 shows the results of the stability test. It is obvious that the IRCFBG sensors exhibits no change in its characteristic and hence, is stable over the long term.

The IRCFBG sensor was then subjected to a repeatability and thermal cycling test. A series of 3 runs was conducted continuously. Fig. 10 shows that the wavelength shifts of all three runs agree well with each other. It also shows that the IRCFBG sensor has a good repeatability irrespective of the thermal cycling of the sensor. The study was extended to understand the time response of the IRCFBG sensor. The measurement speed was set to 2, 5 and 10 ms and the measurements were made. Fig. 11 shows that the sensor results for 5 ms coincide with the 10ms measurements. Hence the time response of the fabricated IRCFBG sensor is found to be 5 ms.

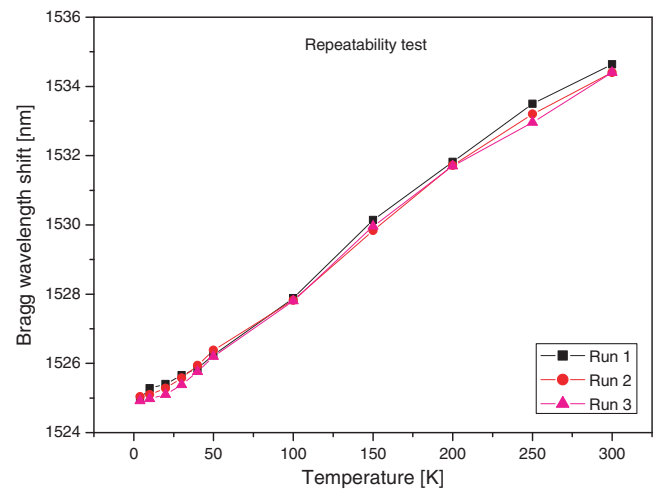


Fig. 10. Repeatability and thermal cycling test of the IRCFBG sensor.

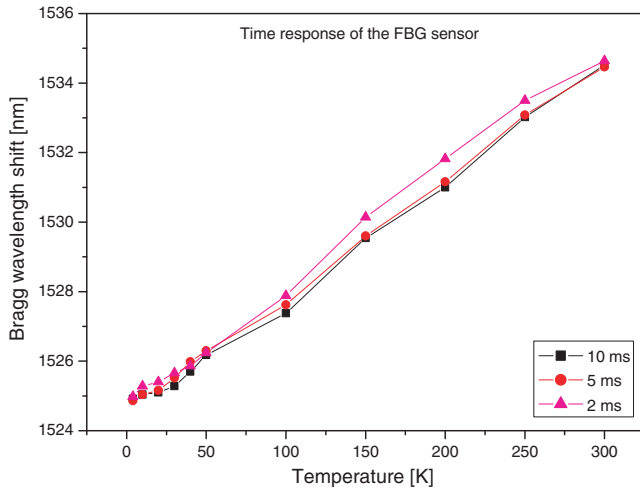


Fig. 11. Time response of the IRCFBG sensor.

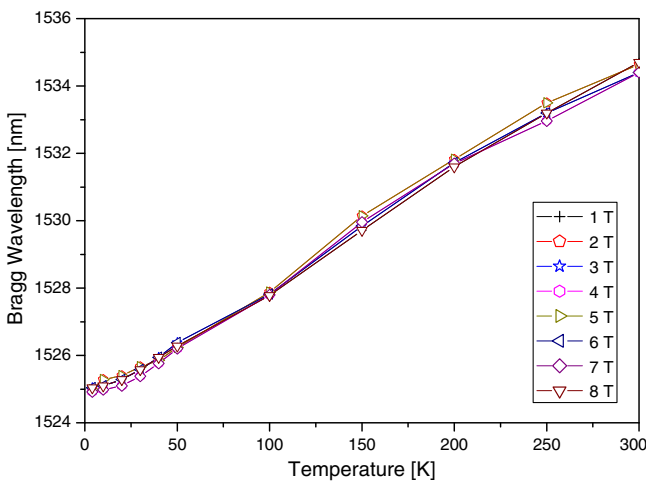


Fig. 12. IRCFBG sensor responses for varying magnetic fields.

The IRCFBG sensor was then subjected to a varying magnetic field from 1 to 8 T. Fig. 12 shows that the sensor performance was not affected by the varying magnetic field.

6. Conclusion

From the above experimental study it can be concluded that the IRCFBG sensor can be used for measuring low temperature of the order of 15 K. It was demonstrated experimentally that the IRCFBG sensor is not affected by the magnetic field of up to 8 T.

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References

- [1] Mizunami T, Tateata H, Kavashima H. High-sensitivity cryogenic fiber-Bragg-grating temperature sensors using Teflon substrates. *Meas Sci Technol* 2001;12:914–7.
- [2] Li XC, Prinz F, Seim J. Thermal behavior of metal embedded fiber Bragg grating sensor smart mater. *Structure* 2001;10.
- [3] Albin S, Fu W, Zheng J, Lavarias AC, Albin J. A cryogenic temperature sensor using fiber Bragg grating. In: Proceedings of ICEC17: cryogenics, section 16 Bournemouth, UK; 1998. p. 695–8.
- [4] Rajinikumar R, Nyilas A, Süsser M, Weiss KP, Narayankhedkar KG, Krieg G. Fiber Bragg gratings for sensing temperature and stress in superconducting coils. *IEEE Trans Appl Supercond* 2006;16(2).
- [5] Rajinikumar R, Nyilas A, Süsser M, Narayankhedkar KG. Investigation of fiber Bragg grating sensors with different coating materials for high sensitivity. *Proc ICEC 2006*;21:467–70.
- [6] Johnson VJ. Properties of materials at low temperature (phase 1). Pergamon Press; 1961.
- [7] Othonos A, Kalli K. Fiber Bragg gratings – fundamentals and application in telecommunications and sensing. Artech House Optoelectronics Library; 1999.
- [8] Rajinikumar R. Design parameter evaluation of di metallic coated FBG sensor for cryogenic applications, Internal Report 2006, Institute of Technical Physics, Forschungszentrum Karlsruhe; 2006.
- [9] Tracton Arthur A, editor. Coatings technology handbook. Marcel Dekker; 2005.
- [10] Lupi C, Felli F. Electrodeposition of protecting coating on optical fibers. In: JSME/ASME international conference on material and processing, Honolulu; October 2002. p. 424–7.