An Improved Low Temperature Sensing Using PMMA Coated FBG

D.Sengupta*, M.Sai Shankar, P.Saidi Reddy, R.L.N Sai Prasad, K.S.Narayana, P.Kishore

Department of Physics, National Institute of Technology, Waranagal-506 004, India
*Corresponding author e-mail: guuptasengupta@gmail.com

ABSTRACT

Fiber Bragg Gratings have been shown to have a much improved thermal sensitivity when coated by Polymethyle methacrylate (PMMA) at cryogenic regime has been proposed. The PMMA has large thermal expansion coefficients and acts as driving elements. It is coated on the FBG at room temperature and the FBG is under compression at lower temperatures. This allows a much wider tuning of Bragg grating as fiber can stand at more compression than tension. An overall sensitivity of 0.039nm/K in the 1550nm wavelength regime has been achieved and the Bragg wavelength has been tuned upto 8.97nm in the temperature range 77K to 303K.

Keywords: Bragg grating, PMMA coating, Low temperature sensitivity, Strain.

1. INTRODUCTION

In the area of fiber optic sensors, there has been extensive research on fiber Bragg grating (FBG) sensors and is suitable substitute of traditional optical sensors. FBG's sensor is small in size, immune to EMI, light weight and the possibility of accommodating many sensors in a single fiber. Extreme circumstances such as low temperature, strong electromagnetic fields or explosive environment FBG sensors are useful. FBG also find potential applications in space vehicle for the measurement of fuel level kept at cryogenic temperature and structural health monitoring of the vehicle. The temperature sensitivity of the FBG is typically 13pm/^{0}C at 1550nm regime [1]. At low temperature the sensitivity of the FBG decreases because of decrease in coefficient of thermal expansion of optical fiber. There are many technique reported to enhance the cryogenic temperature sensitivity of the FBG. The FBG can be attached to a substrate of higher thermal expansion than the fiber. Such a scheme has been reported for cryogenic temperature sensing by epoxy bonding an FBG on PMMA, AL, lead and Teflon substrate [2-4]. However this method of bonding is not compatible in applications for its large dimension and slow response to fast change in temperature. Also Thermally induced strain depends on the property of the epoxy used between FBG and the substrate.

In this paper, we propose PMMA as coating material on the FBG to obtain a higher sensitivity. The temperature response FBG's with two different coating thickness is studied by determining experimentally the Bragg wavelength shift between 77K to 303K temperatures. It is observed from the comparison study that PMMA coated FBG has higher sensitivity.

2. PRINCIPLE

The Bragg reflection wavelength λ_B of an FBG is given as

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

Where the Bragg grating wavelength λ_B is the free space centre wavelength of the input light that will be back reflected from the Bragg grating, n_{eff} is the effective refractive index of the fiber core at the free space centre wavelength and Λ is the grating spacing.

The normalized temperature sensitivity at room temperature is

$$\frac{\Delta\lambda_B}{\lambda_B \Delta T} = (\alpha + \xi) \qquad (2)$$

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Where α is the thermal expansion coefficient of the fiber equal to 0.55×10^{-6} for silica and ξ is the thermo optic coefficient equal to 8.3×10^{-6} for Germania doped fiber. Therefore temperature sensitivity of an FBG depends mainly on the thermo optic coefficient.

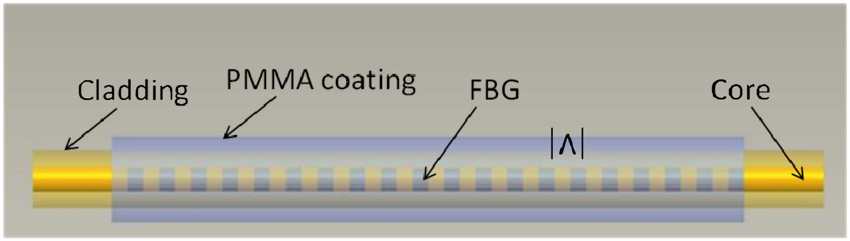

Fig. 1. Schematic figure of PMMA coated FBG

For a metal/polymer coated FBG a change in the temperature causes a change in the grating period. This is not only due to the thermal expansion of the fiber but also effect of strain induced by the thermal expansion of the coating polymer. The normalized strain sensitivity is

$$\frac{\Delta\lambda_B}{\lambda_B \Delta\varepsilon} = (1 - P_e) \qquad (3)$$

Where P_e is photo elastic coefficient and Δε is the induced strain.
If the coating polymer on the FBG is PMMA whose thermal expansion coefficient of PMMA $\alpha_{PMMA}=6.1 \times 10^{-5}$ is two order higher than silica. Then

$$\Delta\varepsilon = \Delta T \alpha_{\text{PMMA}} ,$$ where ΔT change in temperature.

Assuming the induced strain in the FBG is due to PMMA and is proportional to its thermal expansion for a limited temperature range.
Considering thermo optic coefficient to be linearly dependant on temperature for a limited range and the photo elastic constant is independent of temperature. Then the normalized temperature sensitivity of a PMMA coated FBG is

$$\frac{\Delta\lambda_B}{\lambda_B \Delta T} = ((1 - P_e)\alpha_{\text{PMMA}} + \xi) \qquad (4)$$

The equation (4) shows, temperature sensitivity of a PMMA coated FBG is higher than uncoated FBG.

3. EXPERIMENTAL PROCEDURE

Two separate uniform FBG's were inscribed in a photosensitive fiber SM1500 (4.2/80μm) using phase mask (Λ_{pm}=1058) technique. A Bragg star industrial line narrow excimer laser (248nm) with pulse energy of 2.56mJ at 200Hz and having a spatial coherence of 1.5mm along fiber axis was used to fabricate these 3mm length uniform gratings. These gratings were formed with 35s with approx. 95% reflectivity and the reflected Bragg wavelength of the FBG's are 1543.14nm and 1543.44nm at 30^0C.

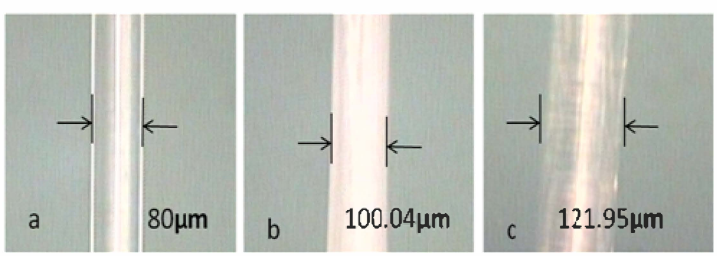

Fig.2. Diameter of (a) bare FBG (b) and (c) coated FBG

Out of many coating techniques (physical vapor deposition, chemical vapor deposition, electrostatic spraying etc.) for coating FBG's with PMMA, a simple dip coating technique is employed for the purpose. To achieve different coating thickness, the FBG's were dipped into two different concentrated PMMA solutions and were lifted from the solution at a uniform speed to avoid non uniform coating thickness. In this experimental work 10.02µm and 20.97µm thickness PMMA coated FBG's are used fig.2.(b) and fig.2.(c). The thickness of the coated FBG was calibrated using an image analyser and with the help of MATLAB 7.1 code with reference to the uncoated FBG fig.2(a).
It was observed that the centre wavelength of the PMMA coated FBG's were blue shifted from their reflected Bragg wavelength. This is due to built-in strain caused by volume contraction of the coating during the polymerization process.

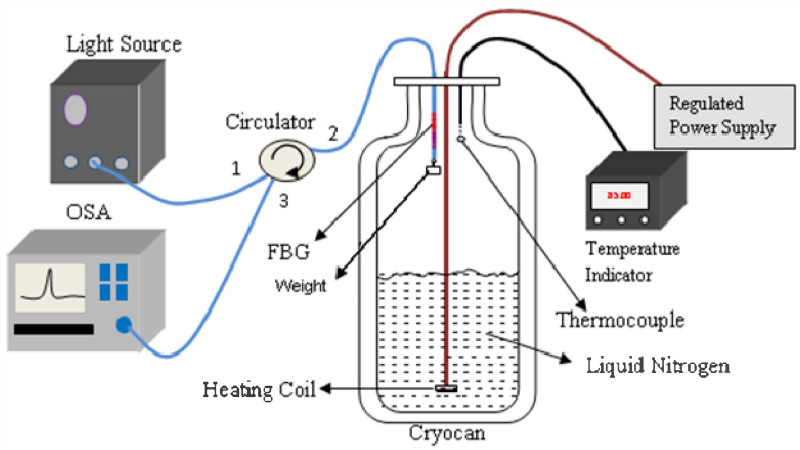

Fig.3.The schematic experimental setup

The schematic experimental setup is shown in figure 3. The FBG and the thermocouple were fixed within the neck of a cryocan (BA – 3). During the experiment, to avoid bending or creeping effect on the FBG due to large thermal expansion of PMMA a small weight of 0.5gm was attached to the coated FBG's. A 'K' type thermocouple with a temperature range -200^0 C to 1250^0C was used as the standard against which the response of the FBG temperature sensor was compared. A circulator and a broadband source of 1550 nm central wavelength having 50nm, 3dB bandwidth were used. The spectral shift of Bragg wavelength and the reflection spectrum was observed with an optical spectrum analyser (Agilent 86142B). The resolution of the optical spectrum analyser was 0.1 nm, and the peak wavelength was displayed to the order of 0.01 nm. The temperature was varied with the help of a heating element dipped in the Liquid nitrogen (LN2) and is controlled by a variable AC voltage source connected to it. A temperature indicator indicates the temperature. Simultaneous measurement of Bragg wavelength shift due to temperature difference and temperature were logged. The experiment was conducted using the bare FBGs first and repeated after the PMMA coating was done on the same FBGs.

4. RESULTS AND DISCUSSION

The temperature response from 303K to 77K of an uncoated FBG, 10.02 µm and 20.97µm PMMA coated FBG is shown in fig.4. Compare to uncoated FBG, 20.97µm PMMA coated FBG shows high temperature sensitivity and is 5.6 times higher than bare FBG sensor. The Bragg wavelength shift of the bare FBG is less for this temperature range mainly due to the thermal expansion coefficient of the silica is less and decreases at cryogenic temperature. The Temperature response curve of 20µm thickness PMMA coated FBG is nonlinear and the linearity follows 5th order polynomial equation ($y= -9E\text{-}11x^5+9E\text{-}08x^4-3E\text{-}05x^3+0.005x^2-0.457x+1546$, $R^2= 0.999$). This is because of the thermal expansion coefficient of silica is not same at all the cryogenic level.

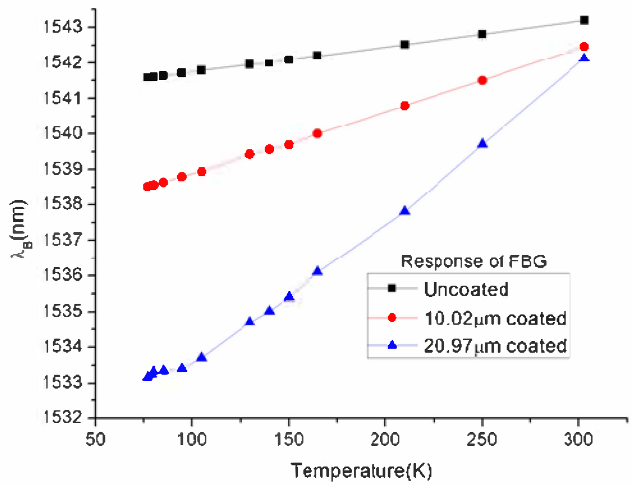

Fig. 4. Temperature response of bare, 10.02 μm and 20.97μm PMMA coated FBG sensors

The temperature sensitivity of FBG varies at different low temperature range shown in table 1.The temperature response of the bare and PMMA coated FBG sensors are nearly linear above 150 K.

Table 1

Temperature(K)	Temperature sensitivities of FBG (pm/K) with different PMMA coating thickness		
	Un coated FBG	**10.02μm coated FBG**	**20.97 μm coated FBG**
303-150	7.19	18.16	43.92
150-95	6.34	16.36	37.69
95-77	6.65	15	10.78

The repeatability of the 20.97μm thickness PMMA coated FBG were examined and a series of 3 trial runs was conducted fig.5. The wavelength shifts of all three trial runs agree well with each other. It also shows that the PMMA coated sensor has a good repeatability irrespective of the thermal cycling of the sensor.

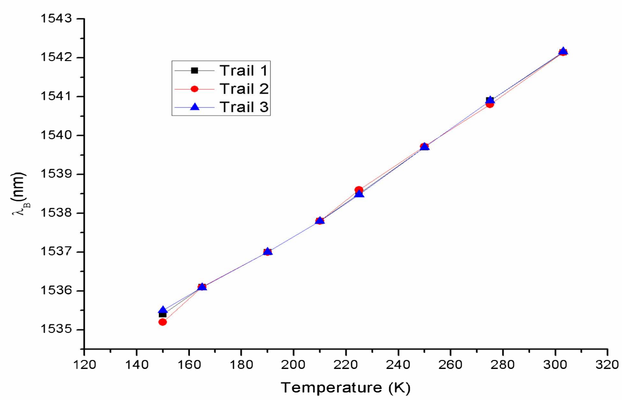

Fig. 5. Repeatability test of the 20.97μm coated FBG sensor

At 150K and below, generation of small peak along with the central peak (λ_B) in the reflection spectrum of the FBG is observed. This is due to the structural transition of germanium induced defect and inhomogeneous thermo elastic strain at the ends of FBG sensors.

The total shift in Bragg wavelength of uncoated and PMMA coated FBGs for a change in temperature from303K to 77K is shown in Table 2. A decrease in reflected Bragg wavelength radiation power also observes during this transition. This is due to the coating of the fibre froze, and induced micro bending in the coated region.

Table 2

The response of FBG temperature sensor from 300K to 77K temperature

	Un coated FBG	**10.02µm coated FBG**	**20.97 µm coated FBG**
Total shift in Bragg wavelength(nm)	1.62nm	3.95nm	8.97nm
Loss of power of reflected Bragg wavelength(nW)	43.52nW	122.69nW	146.87nW

As FBG sensors are wavelength readout, fluctuation in the power level does not affect the measurement and is especially advantageous for such low-temperature sensing. The improper binding between the optical fiber surface and PMMA coating produce less compression on the FBG. This will decrease the temperature sensitivity of the FBG. The response time of the sensor is determined mainly by the heat capacity and thermal inertia of the coating material. For fast response and high sensitivity, optimum coating thickness is required because the coating thickness should also be high enough in order to effectively transfer the PMMA coating strain to the core of the optical fiber. Since the temperature response of the PMMA coated FBG is higher than bare FBG, It can be useful to monitor the thermal radiation at cryogenic regime with a low sensitive spectral measurement system.

5. CONCLUSION

We demonstrated an FBG coated with PMMA material having large thermal expansion coefficient to enhance the thermal sensitivity of the sensor operated between 303K to 77K. The sensitivity of the PMMA coated FBG with coating thickness 10.02µm, 20.97µm and a bare FBG are compared. An overall 5.6 times higher sensitivity is observed in 20.97µm coated FBG than bare FBG. The coated FBG sensor can be easily packaged and can be useful to measure discrete cryogenic liquid level present in cryocan.

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