JOURNAL OF OPTOELECTRONICS AND ADVANCED MATERIALS Vol. 12, No. 10, October 2010, p. 2040 - 2043

Teflon-coated fiber Bragg grating sensor for wide range of temperature measurements

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Cryogenic temperature sensing has been demonstrated using FBGs with polymer coating of various thicknesses and the experimental results have been presented in this paper. Teflon coating applied on Fiber Bragg Gratings which are inscribed in silica fiber (TFBG) with coating thicknesses of 20 and 40 micrometers have been used in the present investigation. The Bragg wavelength was measured in the temperature range from -196°C to 800°C in the case of regular FBGs and TFBGs. TFBGs were found having better linearity and sensitivity compared with the response of regular uncoated FBGs.

(Received September 15, 2010; accepted October 14, 2010)

Keywords: Fiber Bragg grating, Polymer coating, Regeneration. Thermal stability

1. Introduction

In the area of fiber optic sensors, fiber Bragg grating sensors (FBG) have proved to be very successful as substitutes for the traditional fiber-based sensors. Their small size and inconspicuous presence are very promising in applications that require the physical advantages of optical fibers such as, EMI immunity, distributed sensing, light weight, radiation and corrosion tolerance. In addition, FBGs have unique optical advantages to offer such as immunity to intensity fluctuations, polarization changes, and connection losses. These merits arise from the fact that the FBG is a self-referenced linear device in which the information is wavelength encoded. Low-temperature FBG sensors have potential applications in temperature monitoring of super conductive devices, where strong magnetic field exists. Further the magnetic field may be an alternating field [1]. They also find applications in spacecrafts which use liquid hydrogen-oxygen rocket engines whose parts are exposed to a low-temperature and explosive hydrogen atmosphere [2].

It has been suggested that FBGs can be embedded in or bonded to substrates like Teflon to enhance their temperature sensitivity. The substrate should have larger thermal expansion coefficient than that of silica fibers. Bonding a fiber to a substrate to effect greater temperature sensitivity requires the substrate thickness to be much greater than the diameter of the fiber and substrate length to be longer than the FBG. Therefore, the dimensions of this substrate are of the order of several micrometers to millimeters. While the enhancement of FBG temperature sensitivity is significant using these techniques, the flexibility of the optical fiber is sacrificed because of the need for bonding to a rigid substrate.

In this paper, we propose Teflon coating on FBG to obtain a higher sensitivity. The temperature response of TFBG is studied by determining experimentally the Bragg wavelength shift in the temperature range from liquid nitrogen (LN_2) temperature to 800°C for two different thicknesses of Teflon coating. The sensing characteristics of FBGs with and without Teflon coating are compared .It has been observed that TFBGs show greater sensitivity and are therefore very useful in the measurement of wide temperature ranges.

2. Sensor design and fabrication

The FBG was inscribed in the core of SM1500 (4.2/80μm) Fiber using phase mask technique. The fiber was placed in the close proximity of Bragg Photonics phase-mask with a period Λ_{pm}= 1058nm. A Braggstar industrial Line Narrow Excimer laser- (248nm) with pulse energy of 2.56 mJ at 200 hz and having a spatial coherence of 1.5 mm along fiber axis was used to write 3mm long grating. The grating with 90% reflectivity and Bragg wavelength λ_B at 1535.8nm was formed within 30 seconds of exposure. The reflected spectrum of FBG at 1539nm is shown in Fig. 1.

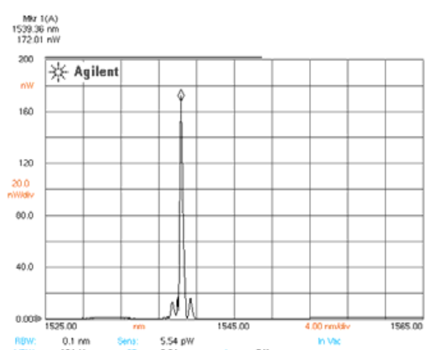

Fig. 1. Trace of reflected spectrum of fiber Bragg grating sensor at 1539nm.

2.1 Coating technologies

Many technologies like Dip-coating, Physical vapor deposition (PVD), chemical vapor deposition (CVD) and Electrostatic Spraying can be used to coat the FBG sensor with polymer layers. Selection of an appropriate method is influenced by the parameters such as process temperature and the thickness of the coating at it plays a vital role in imparting thermal stress. This in turn effects the sensitivity of the TFBG sensor. It would be good to have a thin coating to reduce the thermal inertia. 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 FBG. The dipping process may not be used, as the sensor requires uniform coating throughout sensing element and may not guarantee a uniformity of coating. Formation of bubbles in the coating layer during the process will also affect the sensor operation.

In the present investigation, Electrostatic Spray technique is employed for coating Teflon on the FBG sensor using a spray gun. In the spray gun, the polymer to be coated is atomized and then negatively charged from an electrically charged electrode at the tip of the gun. The charged particles are given their initial momentum from the fluid pressure/air pressure combination. The part to be coated is electrically neutral, making it positive with respect to the negative coating droplets. The coating particles are thus attracted to the surface and held there by the charge differential until cured. Electrostatic spraying offers high transfer efficiency (65 % to 95 %) as well as excellent edge coverage together with strong bonding between the coated surface and the polymer.

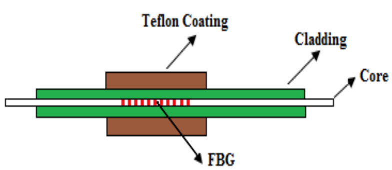

Fig. 2. Teflon coated FBG sensor (TFBG).

The Teflon coating on the FBG is applied by the above method, at a coating temperature of 110°C.The coated FBG is baked at 360°C for 5 hours to get stress-free uniform coating as shown in Fig. 2. FBGs coated with thicknesses of 20 and 40 micron thicknesses are used in the present experimental work [3-4].

3. Theory

The basic purpose of operation of a FBG sensor is to monitor the shift in the wavelength of the reflected light with changes in the grating pitch (Λ) and the effective refractive index (η_{eff}). The Bragg wavelength, or resonance condition of a grating, is given by the expression

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

For an FBG coated with polymer, a change in the temperature causes a change in the grating period. This is due not only to the thermal expansion of the fiber but also to the strain δl/l, induced by the thermal expansion of the coating polymer. In the case of TFBG,the change in Λ will be essentially due to the thermal expansion of the coated polymer, since the thermal expansion coefficient of silica is negligibly small($0.5*10^{-6}$ K^{-1} at room temperature). In addition, the refractive index of the fiber core changes because of the thermo-optic effect. Combining all the above effects, the shift in the Bragg wavelength due to finite temperature change, ΔT, is given as

$$\Delta\lambda_B/\lambda_B=\alpha\Delta T+ (1-p_e)\, \delta l/l+\delta\eta_{eff}/\eta_{eff} \quad (2)$$

where α is the linear thermal expansion coefficient and p_e (for silica fiber=0.22) is the photo elastic constant. For silica fibers α is so small that the effect of the thermal expansion is one order less than that of the thermo optic refractive index change. To increase α, the portion of fiber in which the FBG is written is coated with Teflon. Science its coefficient of thermal expansion α_P is high, it makes the temperature sensitivity of the sensor proportional only to its thermal expansion coefficient.

The strain δl/l, induced by the thermal expansion of the coating polymer can be expressed as

$$\delta l/l =(\alpha_P-\alpha_S)[\gamma E_P/(\gamma E_P+E_S)]\Delta T \quad (3)$$

where α_P is the thermal expansion coefficient of the polymer, E_P and E_S are the Young's moduli of the polymer and silica glass respectively.

4. Experimental setup and discussion

4.1 Low temperature measurement

The schematic of the experimental set-up for sensing the low temperatures with FBG is shown in Fig. 3. A K-type thermocouple with a temperature range -200ºC to 1250ºC was used as the standard against which the response of the FBG (λ_B=1539nm) temperature sensor was compared. The FBG sensing element is inserted into the steel tube and is placed in the liquid nitrogen cryocan, and the tip of the thermocouple is adjusted very close to it for making the temperature measurements accurate.

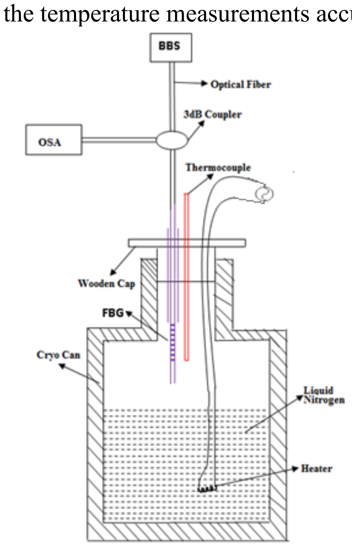

Fig. 3. Experimental setup for measuring low temperature response using TFBG.

The FBG is cooled with the LN2 fumes produced by an 80Ω resister heater placed in the liquid-nitrogen cryocan. The rate of cooling and thus the temperature of FBG are controlled accurately by the application of an AC voltage to it with the help of a dimmer start. The temperature of the FBG as measured by the thermocouple was logged. Simultaneously, a circulator was used to couple light from a Broad Band source to the FBG, and the reflected Bragg peak at each temperature was recorded using an Optical Spectrum Analyzer (OSA) (Agilent)having a resolution of 0.1nm and the peak wavelength was displayed with accuracy of the order of 0.1nm.

The measurement was performed keeping the sensor in thermal equilibrium during each one minute scanning time of the OSA. This experiment was performed without and with Teflon coating on FBG for thicknesses of 20 and 40µm. The response of the sensor is noted by varying the temperature from 25ºC to -196 ºC and -196 ºC to 25ºC, and by repeating the experiment three times. They are shown in Fig.4 and Fig.5.It was observed that the response of the sensor traces exactly while the temperature is reversed. Without coating, the sensitivity and linearity of the sensor are found to be 7.59pm/ºC and 99.2% respectively, whereas, with Teflon coating the sensitivity and the linearity of the sensor are found to be 12.85pm/ºC and 99.2% respectively [5]. The experimental observations are tabulated. It was also observed that the sensitivity has become three times with coating thickness of 40 µm [6].

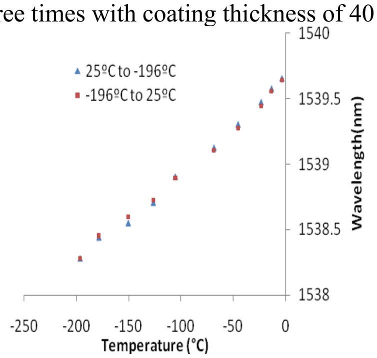

Fig. 4. Temperature response of FBG sensor without Teflon coating.

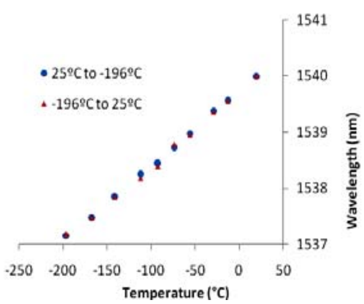

Fig. 5. Temperature response of FBG sensor with Teflon coating.

Table 1.

Coating thickness t(µm)	$\Delta\lambda_B$ (nm) (73 K)	$\Delta\lambda_B$ (nm) (300 K)	Wavelength shift in (nm)
Without coating	1538.22	1539.96	1.14
20	1537.16	1540	2.84
40	1537.6	1541.2	3.6

4.2 High temperature measurement

The schematic of the experimental setup for high temperature measurement using TFBG sensor is shown in Fig. 6. In the experimental setup, the FBG sensor is inserted in the ceramic tube which is then placed axially at the center of a cylindrical Inductive Coil Furnace (ICF). The furnace temperature, *T*, can be ramped up/down in the range 25°C<*T*<1100°C by controlling the current (*I*) flowing through the coils. A Super Luminescent Diode (SLD) broadband source (C-Band: 1524nm-1572nm) connected to port-1 of a 3-port fiber optic circulator is used to launch light into the grating-inscribed fiber which is connected to port-2 of the circulator. The light reflected from the grating is redirected into the OSA connected to port-3. The Bragg grating (λ_B=1535.8nm) in the fiber was thermally treated in the temperature range 25°C<T<850 °C over a span of 3 hrs, and the reflected Bragg peak at each temperature was noted.

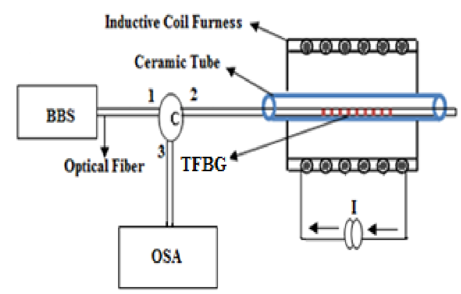

Fig. 6. Schematic of experimental setup for high temperature measurement.

Experimental results on the response and dynamics of reflectivity without Teflon coating on the FBG sensor are shown in Figs. 7 and 8 respectively. It is observed that the response at high temperatures is found to be linear. However the normalized reflected Bragg peak power is constant up to 400°only, and the sensitivity of the system is found to be 12pm/°C[7]. After this temperature, the reflected peak power has decreased exponentially and the grating was completely erased [8-9]. Therefore, this type of sensor cannot be used for high temperature applications. However, experimental investigations on the response and dynamics of reflectivity of the proposed Teflon coated FBG sensor shown in Figs. 9 and 10 has shown that the response is linear and the normalized reflected peak power is constant up to 650°C and later, it decreased with increase in temperature. The FBG was not erased up to 800°C. As the temperature increases, the reflected Bragg peak wavelength also increased linearly. The sensitivity of the TFBG sensor is found to be 14.09 pm/°C with a linearity of 99.8%, which is better than that of the uncoated FBG. This proves TFBG sensor to be a better option for wide range of temperature measurements, and can be used from -196°C to 800°C.

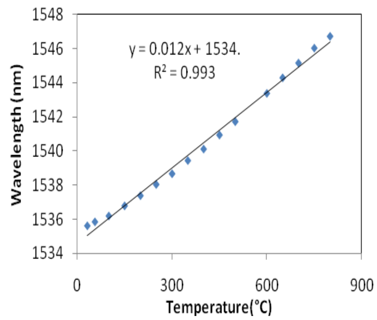

Fig. 7. Response of FBG sensor at high temperatures.

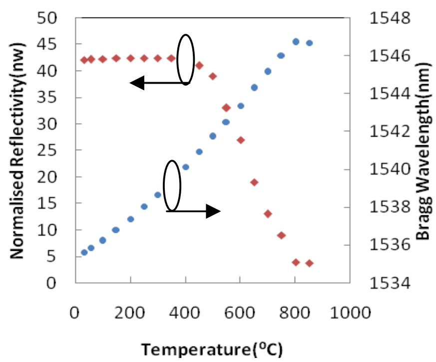

Fig. 8. Typical dynamics of reflectivity of FBG at high temperatures.

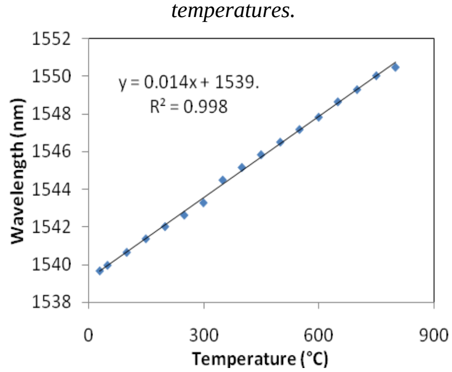

Fig. 9. Response of TFBG sensor at high temperatures.

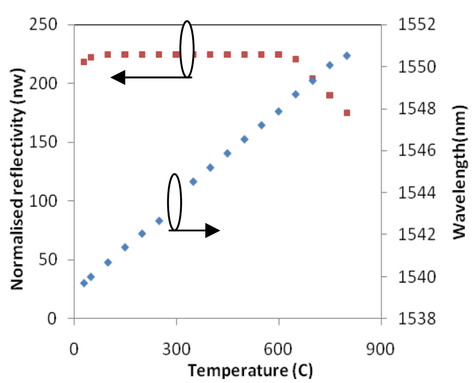

Fig. 10. Typical dynamics of reflectivity of TFBG sensor.

5. Conclusions

We have demonstrated a technique of using Teflon coating on FBGs for high sensitivity temperature measurements. Comparison of the experimental results obtained with the coated and un-coated sensors indicate that the polymers coated FBG has slightly greater temperature sensitivity than the un-coated one in the temperature range from -196°C to 800°C. The sensitivity of Teflon coated FBG reaches 12.85pm/k from -196°C to 25°C and 14.04 pm/K from 25°C to 800°C, three times as large as that obtained with the regular FBGs. Therefore, the polymer-coated FBGs are apparently suitable for both cryogenic temperatures as well as high temperature applications.

Acknowledgements

The authors thank Prof.S.Asokan, IISc Bangalore, India for providing the Fiber Bragg Grating sensors

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