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Investigation of the embedded fiber bragg grating temperature sensor

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Abstract. An embedded fiber Bragg grating (FBG) sensor, which fabricated in IMS, for temperature sensing was proposed. The temperature responses of the in-fiber Bragg gratings (FBGs) have been investigated. It was found that these responses ranged from 10.6 pm/°C to 12.0 pm/°C. The temperature sensitivity of the FBGs was 0.2°C. The strain responses remained temperature independent over a temperature range of 20 – 180 °C. The results obtained are in agreement, within the experimental error, with predictions based on material parameters. Although the temperature response is nonlinear over the temperature range 20 °C to 180 °C, in practical systems the temperature response of the sensor may be assumed to be linear within the temperature range 20 °C to 80 °C.

Keywords: Fiber Bragg Grating (FBG), sensor, strain, temperature sensor

1. Introduction

The Fiber Bragg Grating (FBG) first presented by Hill *et al.* [1] in 1978 is a structure on an optical fiber in which the refractive index of a fiber core is periodically modulated with a pitch Λ (Figure 1).

The index modulation is induced by exposing the fiber to an interference pattern formed between interfering ultraviolet (UV) beams of light by double-beam or phase mask technique. The center wavelength of the reflection λ_B is named "Bragg wavelength". The Bragg wavelength is

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

where n is the effective refractive index of the fiber core. The FBG forms a distributed reflector, acting as a narrow band channel dropping spectral filter in transmission, and as a narrow band reflection filter. The typical bandwidth of the reflected light is about 0.1 nm to 0.3 nm. The reflected Bragg wavelength is dependent upon the pitch of the grating, and is sensitive to strain and temperature according to the relationships:

$$\Delta\lambda_B = \Delta\lambda_{BT} + \Delta\lambda_{BS} = \lambda_B(\alpha+\xi)\Delta T + \lambda_B(1-\rho_\alpha)\Delta\varepsilon \tag{2}$$

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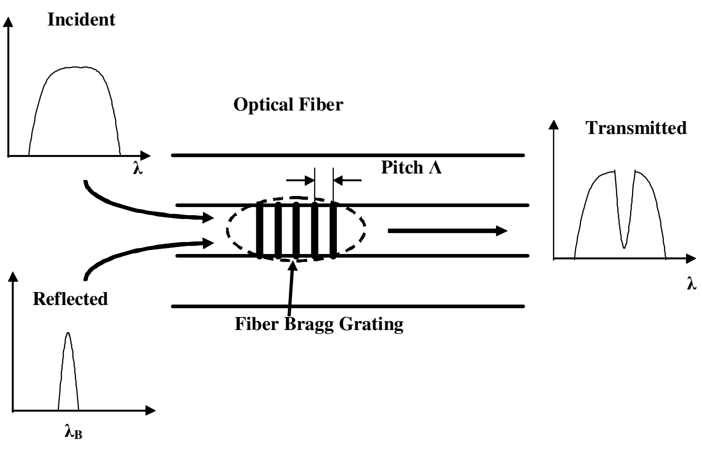

Fig. 1. Structure of the Fiber Bragg Grating.

where $\Delta\lambda_{BS}$ and $\Delta\lambda_{BT}$ are the strain and temperature induced Bragg wavelength shifts, λ_B is the Bragg wavelength, ρ_α is the photoelastic coefficient of the fiber, α is the coefficient of thermal expansion and ξ is the thermo-optic coefficient. A change in the effective refractive index and/or the grating period will cause a shift of the Bragg wavelength. Sensing principle is based on that shift of the Bragg wavelength in response to applied strain, temperature or pressure changes.

FBG sensor is one of the most attractive optical fiber sensors because of simplicity in structure and suitability for multiplexed and distributed/multipoint sensing applications, and to the fact that sensing information is encoded in an absolute parameter, namely the resonant wavelength. The measurand is transduced to the wavelength of light reflected by the FBG, an absolute parameter, eliminating errors associated with drift of the zero point of the measurement, common in strain gauge systems in which the gauge and lead wires see varying and differential thermal environments. FBG sensors exhibit many other distinguishing features such as, small size, light mass and high resolution, suitability for remote measurement. It can be used with great advantages over electronic sensors for in situ sensing to monitor or measurement in harsh environments or hazardous environment, due to its immunity against electromagnetic fields, humidity, nuclear radiation and the most chemical materials [2]. The most common advantageous application of the FBG is a smart monitoring for civil engineering, buildings and bridges; oil, gas, or electrical power generation industries [3,4]. The application to geophysical exploration/monitoring is one of the promising applications to take advantages of fiber sensors. FBGs are sensitive only to the environment experienced along the gauge length of the sensor, typically of the order of 5 – 10 mm. The small dimensions of the fiber allow the monitoring of structures with very close clearances.

This paper describes performance of a prototype of the FBG temperature sensors at temperatures up to 220°C. The system consists of fibers with FBGs and the surface parts include an optical source, detectors, optical couplers and an optical spectrum analyzer for monitoring.

2. Experiments

The FBGs were fabricated in the Institute of Materials Science (IMS in Hanoi) with reflectivity of approximately 30%, and had a Bragg wavelengths laying from 1530 nm to 1570 nm. Experimental device consists of an Erbium-doped Super Fluorescent Source (SFS), FBG sensors, a temperature controlled pad or liquid bath and temperature monitor. The FBG reflected signals is fed to an Optical Spectrum Analyzer (OSA) AGILENT 86142B to locate the Bragg wavelength and monitor wavelength shifts. A schematic of the system is shown in figure 2.

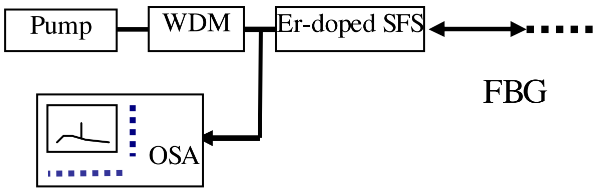

Fig. 2. A schematic of the experiment.

The SFS consists of an Erbium-doped fiber pumped by a 980 nm Laser Diode through wavelength division multiplier (WDM). The output from a SFS is coupled to a FBG sensor by fc/apc connector. The light reflected from the sensors is directed to OSA through 1550 nm output port of the WDM . The resolution of the optical spectrum analyzer was 0.06 nm, and the peak wavelength was displayed to the order of 0.001 nm. The FBG temperature was monitored by a Platinum 1000 Ω resistive thermo-sensor (Pt RTD-EPHY-MESS GmbH) with a limit deviation of 0,15°C for 0°C ÷ 100°C range and 0.25°C for a range above 100°C. A glass thermometer with graduation of 0.5°C also was used for comparison for temperature below 120°C. The tip of the thermo sensor was assembled close to the grating, so that the reading temperature in the thermo sensor indicated the actual temperature of the FBG. Both sensors then were attached to small metal strip formed a probe and placed in investigated environment. The experiments were carried out in different environments (air, solid as well as in liquid environments).

The temperature set by controlled heating source, had been tuned in small increments and fixed in about 15 min to allow achieving thermal equilibrium for measuring the sensor's characteristic. In the experiment with liquid environment, the probe containing the FBG was immersed into a water bath heated by an electrical heater, the FBG temperature changed from -6°C to 100°C. For the air environment we put the probe inside small closed oven, its temperature were changed from 20°C to 220°C. As to solid environment case we used copper pad with temperature controlled by Peltier cooler in a range -1 ÷ 60°C and by heating gun with maximum temperature up to 400°C.

3. Results and discussion

Figure 3 shows the thermal shift of the Bragg wavelength for the FBG sensor with center wavelength of 1548.61nm at 25°C, fitted by linear equation. With the increase of the FBG temperature, the Bragg wavelength shifts to the longer direction. The temperature sensitivity is 11.8 pm/°C. For all tested FBG's sensors the observed sensitivity ranged from 10.6 pm/°C to 12.0 pm/°C. The detection sensitivity of the temperature measurement using OSA demodulation is around 0.2 °C based on wavelength resolution ± 1pm of the device.

The temperature sensitivity of a FBG sensor could be enhanced by combining with the wavelength shift under strain due to thermal expansion and with the one due to temperature induced refractive index change. The FBG was embedded in the copper base of thickness 0.5 mm. The embedded length was 55mm. The copper strip then had been changed to an Aluminum alloy strip of the same 0.5 mm thickness. The result plotted in figure 4 shows the wavelength shift for a bar FBG sensor (FBG1) and those which are embedded in Cu (FBG2) and Al base (FBG3) over a temperature range of 30°C to 150°C with center wavelength of 1530.4 nm at 25°C. The wavelength shift observed for bar FBG is dominated by the thermo-optic coefficient of the fiber with a contribution the thermal contraction of the fiber itself, while for embedded FBGs the thermal expansion of the substrate is dominated over the thermal contraction of the fiber, and the wavelength shift is governed by the strain induced by the substrate thermal expansion and thermo-optic coefficient. The temperature sensitivity of embedded cases increased to 14.6 pm/°C for FBG with Cu base and 28.2 pm/°C for an Aluminum alloy base.

The theoretical wavelength shifts due to thermal expansion's strain, calculated from the thermal expansion coefficients quoted in reference [5] and from the measured wavelength shift due to strain response of the FBG are plotted for comparison in Fig.5. The data shows a reasonable agreement between the theoretical and experimental response for Cu base. For an Aluminium alloy base it deviates more. This discrepancy between the measured FBG data and the theoretical prediction may be a result of the dependence of thermal expansion coefficient of the alloy on temperature. The temperature sensitivity of the Bragg wavelength arises from the change in period associated with the thermal expansion of the fiber, coupled with a change in the refractive index arising from the thermo-optic effect. The strain sensitivity of the Bragg wavelength arises from the change in period of the fiber, coupled with a change in the refractive index arising from the strain-optic effects. So, the Bragg wavelength shifts exhibited by FBG2 and FBG3 are determined by the strain imposed by the thermal contraction of the sample to which each is attached, and by the refractive index change of the core, determined by the thermo-optic coefficient, while FBG1 wavelength shift is governed by thermal strain of the fiber and refractive index change of the core only. Some authors mentioned about a

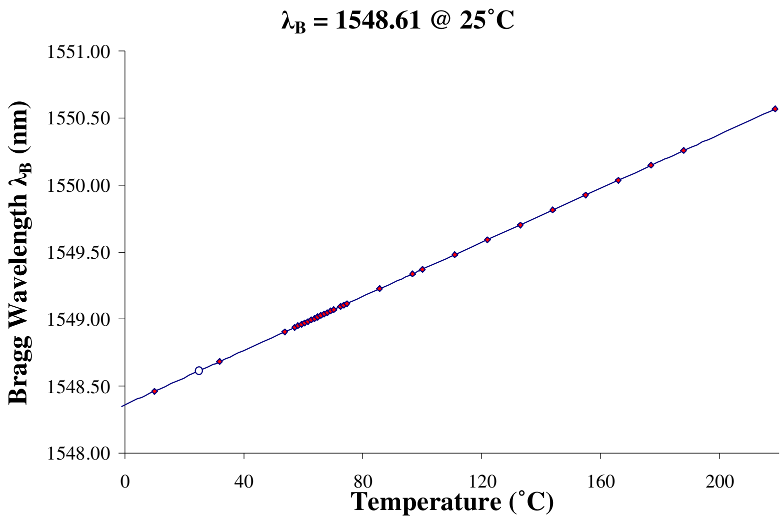

Fig. 3. The wavelength shift of the FBG sensor temperature. The experimental data set was fitted by first order equations.

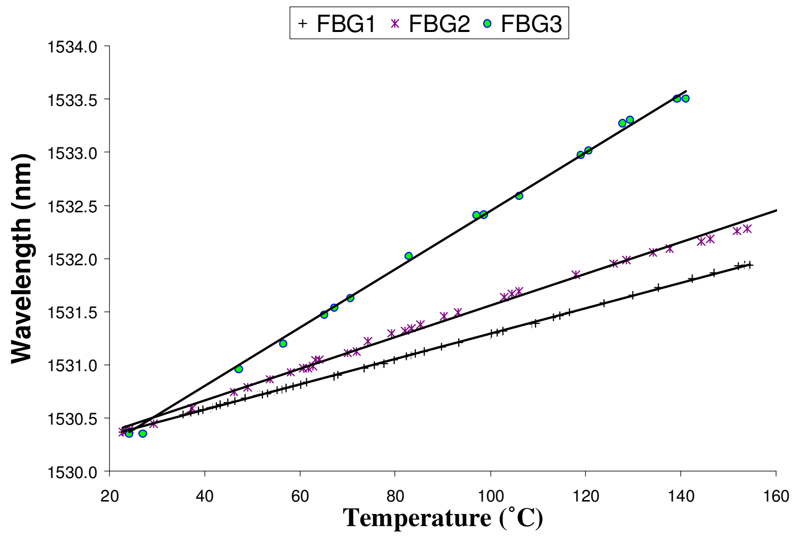

Fig. 4. The wavelength shift for a bar FBG sensor (FBG1) and those which are embedded in Cu (FBG2) and Al base (FBG3). The experimental data sets were fitted by first order equations.

thermal dependence of the strain sensitivity of an FBG, which would be a result of the temperature dependence of the stress-optic coefficient of silica glass. They found that the strain response changed on average by 0.21 ± 0.03 fm με−1 ˚C−1 over a range of temperatures between 100–400 ˚C [6]. However, this nearly negligible temperature dependence has not been observed in our experiments. The responses of the FBG to strain measured at a range of temperatures between 20°C and 180°C can be considered as temperature independent within the accuracy limits of the experiment and equals 5.247 nm/mm or 1.1 pm/με.

It was observed that the temperature dependence of the thermo-optic coefficient is linear over the temperature range 20°C to 220°C at a wavelength of 633 nm in unbuffered single-mode fiber [7]. However, the magnitude of the average thermo-optic coefficient is known to decrease at longer wavelengths, therefore it is possible that the temperature dependence of the thermo-optic coefficient will also be different at longer wavelengths. Thus it is meaningful to find out any nonlinear effect for FBG sensors at 1550 nm. A nonlinear temperature response was suggested in a study of the temperature dependence of gratings in highly doped Ge fibers [8]. The authors observed a linear temperature response over the temperature range 296–576°K, the nonlinear temperature response was indicated only by a single measurement at 77°K. The authors of Refs. 9-11 also reported measurements of hydrogenated single-mode telecommunication fiber (SMF28) fiber that suggested a nonlinear wavelength response; however, only three measurement points were presented over the temperature range 77–573°K. Therefore the origins of the nonlinearity were not clearly established. It may be the same nonlinearity at cryogenic temperatures [10].

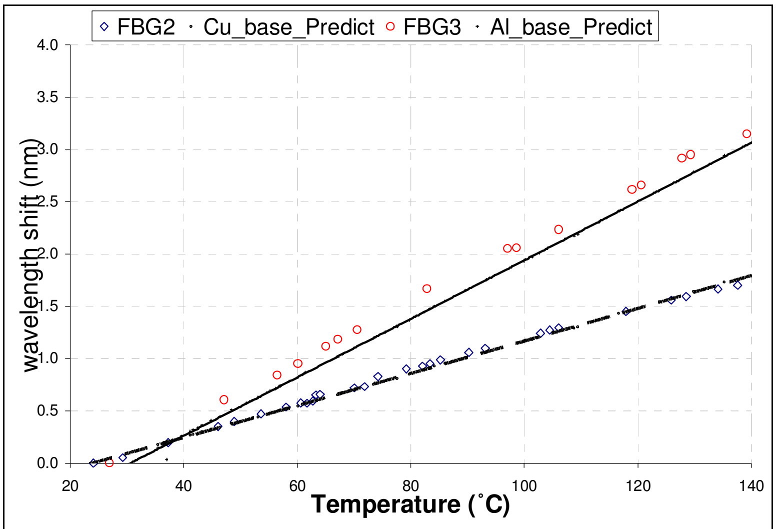

Fig. 5. The measured shift and prediction data for embedded in Cu and Al base FBG sensors.

The nonlinear temperature dependence of the Bragg wavelength is most likely due to the temperature dependence of the thermo-optic coefficient, provided that any other nonlinearity in the reported experimental systems is accounted for. Our data also showed small nonlinearity of the thermal response of the Bragg wavelength over 20°C to 180°C temperature range. The second order polynomial least-squares (SOLSQ) fit of the data gave good regression coefficient R^2 – discrepancy in the order of 10^{-4} (R^2 = 1 indicates a perfect fit). A temperature range for typical FBG sensing and communications applications is about 20°C to 80°C. Our result has showed that within this temperature range the linear fit of the data is acceptable for practical use. For the bar FBG sensor the R square value decreases less than 5.10^{-3}: $R^2 = 0.9997$ of linear fit compared to $R^2 = 0.9999$ of SOLSQ for whole 20°C to 180°C temperature range. For embedded in Cu base FBG the R^2 of linear fit is 0.9983 in 20°C to 80°C range compared to $R^2 = 0.9994$ of SOLSQ and $R^2 = 0.9963$ of linear fit for whole 20°C to 180°C. Such value may be explained by insignificant dependence of the fiber thermo-optic coefficient from temperature. For embedded sensors the temperature dependence of the thermo expansion coefficient of the base may add the extra nonlinearity in the shift. The theoretical prediction of the nonlinearity in the thermal response of the Bragg wavelength was described in [11,12]. The sensor's stability depends highly on the thermal stability of the experiment environment. Averaging over 50 events in experiment with Peltier cooler in good isolated space yielded the stability of 1 pm, which is approximately equivalent to the temperature sensitivity. In other cases the stability was of about 10 pm. This change may be addressed the thermal convention inside experiment volume.

Based on received FBG characteristics in this paper two designs of the sensor were presented: 1. a miniature tube with the sensor ends inside and 2. a Copper or Aluminum tube with the embedded sensor. These sensors can be multiplexing in line with other following FBG strain or temperature sensors.

4. Conclusion

The temperature responses of the in-fiber Bragg gratings (FBGs) have been investigated. It was found that these responses ranged from 10.6 pm/°C to 12.0 pm/°C. The temperature sensitivity of the FBGs was 0.2°C. The strain responses remained temperature independent over a temperature range of 20°C – 180°C. The results obtained are in agreement, within the experimental error, with predictions based on material parameters. Although the temperature response is nonlinear over the temperature range 20°C to 180°C, in practical systems the temperature response of the sensor may be assumed to be linear within the temperature range 20°C to 80°C.

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